Master‘s thesis

# An assessment of the environmental impact of cargo transport by road and sea in Iceland

Etienne Gernez

**Advisor: Hrönn Ólína Jörunsdóttir, Ph.D, Matís**

University of Akureyri
Faculty of Business and Science
University Centre of the Westfjords
Master of Resource Management: Coastal and Marine Management

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## Supervisory Committee

Advisor:
Hrönn Ólína Jörunsdóttir, Ph.D.

Reader:
Dr. Brynhildur Davíðsdóttir, Associate Professor in Environmental Science and Natural Resource Management, University of Iceland.

Program Director:
Dagný Arnarsdóttir, MSc.

Etienne Gernez
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## Declaration

I hereby confirm that I am the sole author of this thesis and it is a product of my own academic research.

Etienne Gernez

# Abstract

The environmental impact of cargo transport is qualified and quantified in the Westfjords and Nothern regions of Iceland. A simplified Life Cycle Assessment (LCA) framework is applied to 5 transport scenarios: 1 land-based scenario reflecting the existing offer in Iceland and 4 maritime alternatives (2 sailing routes, 2 types of ships). Using a statistical energy consumption model and up-to-date emission factor databases, the results show that the best maritime alternative is the one calling at the harbours of Reykjavík, Ísafjördur and Akureyri, using a Roll On-Roll Off (Ro-Ro) ship. Compared to land-based transport, the Ro-Ro alternative has a lower impact in most categories except those related to $NO_x$ and $SO_x$ emissions. With monetisation methods used for the internalisation of external costs, we show that a modal shift from land to sea comes as an overall benefit to the Icelandic society. A Net Present Value (NPV) analysis is suggested to improve the economic calculations, as well as a context-based calculation of the value of time. Further possible improvements are advised in the emission inventory and characterisation phases. A final recommendation is issued for future transport policy in Iceland.

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# List of Abbreviations

| | |
|---|---|
| AHS | Analytic Hierarchy Survey |
| BEFR | Break Even Freight Rate |
| CLRTAP | Convention on Long Range Transboundary Air Pollution |
| ETS | Emission Trading Scheme |
| FEU | Forty feet Equivalent Unit |
| GHG | Greenhouse Gas |
| GWP | Global Warming Potential |
| HDV | Heavy Duty Vehicle |
| HFC | Hydrofluorocarbon |
| HFO | Heavy Fuel Oil |
| IMO | International Maritime Organization |
| IPCC | Intergovernmental Panel on Climate Change |
| ISK | Icelandic Krona Currency |
| ISO | International Organization for Standardization |
| LCA | Life Cycle Assessment |
| Lo-Lo | Lift on - Lift off ship |
| MARPOL | International Convention for the Prevention of Pollution from Ships |
| MCR | Maximum Continuous Rating |
| MDO | Marine Diesel Oil |
| MGO | Marine Gas Oil |
| NIS | Non Invasive Species |
| NPV | Net Present Value |
| OECD | Organization for Economic Cooperation and Development |

| | |
|---|---|
| PAH | Polycyclic Aromatic Hydrocarbon |
| PCB | Polychlorinated Biphenyl Compound |
| PFC | Perfluorocarbon |
| POP | Persistent Organic Pollutant |
| Ro-Ro | Roll in - Roll out ship |
| SECA | Special Emission Control Area |
| SED | Specific Energy Demand |
| TEU | Twenty feet Equivalent Unit |
| UNECE | United Nations Economic Commission for Europe |
| USD | United States Dollar |

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Finally, talking about transport: Pierre's bike is definitely the best vehicle, powered by Hélène's most delicious food.

# Introduction

There is an ongoing debate in Iceland about domestic cargo transport. Until December 1st 2004, both land-based and maritime transport were offered by one single operator. Heavy Duty Vehicles (HDVs, "trucks" in common terms) were utilized for fast delivery on roads of small cargo volumes, and one container ship was sailing all around Iceland for the rest of the cargo. After December 1st 2004, the coastal ship was replaced by more HDVs. Since then, wether or not to move some of the cargo from the roads to the sea is a reoccuring question in the Icelandic public agenda.

So far, the debate has been oriented on economic issues. The evolution of transport demand towards more flexible and fast deliveries, how the government money is spent in the maintenance of the different transport infrastructures (roads and harbours) and how the transport users should be charged to compensate for these costs are examined by Herbertsson (2005) [Tryggvi Þór Herbertsson, 2005]. Möller et al (2010) highlights the differences in transport needs between the different regions of Iceland depending on their connection to the international exchange markets [Möller et al., 2010]. The Westfjords and the Northern regions are found to be economically speaking the regions where maritime transport alternatives could be an interesting option. Three maritime transport routes are proposed, together with an estimation of the quantity of cargo exchanged and the type of ships needed to fulfill this mission.

"Motorways of the seas, "short-sea shipping" and "intermodal transport" are becoming recurrent terms in the European transport policy papers, advocating for a better connectivity between the different transport modes and a move of some cargo from land to sea to curb down the greenhouse gas emissions, reflecting the growing public environmental concern[CEC, 2008, CEC, 2009]. The question of the environmental impact is evoked by Herbertsson (2005), estimating the costs resulting from the pollution of transport activities, without quantifying this pollution [Tryggvi Þór Herbertsson, 2005]. Möller et al (2010) merely states that the environmental impact of the maritime alternative is lower than the land-based current offer, without any further details [Möller et al., 2010].

The purpose of the present study is to qualify in detail what is meant by "environmental impact" of a transport scenario and to quantify the impact of several transport scenarios in Iceland.

Chapter 1 establishes a list of the substances potentially released by cargo transport on road (by trucks) and at sea (by ships). Each substance emission has one or several effects on the environment, which form the basis for the definition of the environmental impact of a transport scenario.

Chapter 2 presents the theoritical framework used to compare different transport scenarios. The simplified Life Cycle Assessment (LCA) proposed by Fet et al, 2000, [Fet et al., 2000], and based on the LCA standard [ISO, 2000] is selected for its robustness and operability. Different transportation modes (planes, ships, trucks) can be compared within this framework by establishing the inventory of all the emissions to air, soil, fresh and marine water resulting from the transport of cargo from a point A to a point B, whatever the route taken. Recent and widespread emission factor databases are used to set up the emission inventories [EMEP/EEA, 2009, EMEP/EEA, 2010]. The severity of the impacts of each substance emission is characterized [Guinée et al., 2002a].

Chapter 3 presents a comparison of land-based transport and maritime alternatives following the propositions of Möller et al, 2010, [Möller et al., 2010]. A statistical model of energy consumption is used for the calculations [Kristensen, 2010a]. One maritime alternative is selected and investigated further, starting a discussion on the relative importance of different environmental side-effects.

Chapter 4 continues this discussion by ranking the different environmental side-effects according to their economical costs to the society, as advised by [Fet et al., 2000], initiated in [Tryggvi Þór Herbertsson, 2005] for the case of Iceland, and based on an international review of monetisation methods [Grangeon et al., 2010].

Chapter 5 summarizes the main results and questions raised along this study: What are the environmental impacts of transport in Iceland? Why is that an important question? What are the respective impacts of land-based and maritime-based transport scenarios? How to select the "best scenario" both in terms of an environmental and an economic perspective?

# Chapter 1

# Pollution and associated impacts from domestic cargo transport by road and sea

"Pollution" describes the damaging effects from wastes inputs in the environment. "Contamination" refers to the occurrence of these wastes, and is caused when an input from human activities increases the concentration of a substance in a particular environment [Clark, 1997].

This first chapter is an inventory of waste inputs resulting from cargo transport by trucks and ships, sorted by sources of inputs and type of damaging effect.

## 1.1 Substances released in air

The exhaust gas from fossil fuel combustion in truck and ship engines are the main source of atmospheric inputs. Some substances released in the atmosphere contribute to the greenhouse effect and to the formation of photo-oxidants, which are chemical compounds becoming highly reactive by the action of sunlight. Through the action of wind and rain, other substances are transported back to the ground, in the surface soil and water, causing acidification (decrease of pH in fresh and marine water), and eutrophication (excessive richness of nutrient causing a dense growth of plant life and death of animal life due to lack of oxygen)[Clark, 1997].

### 1.1.1 Substances contributing to acidification, eutrophication and photo-oxidation

**Nitrogen oxide $NO_x$.** During the combustion of a fuel in an engine, the organic nitrogen present in the fuel and the molecular nitrogen present in the combustion air are oxidized. Nitric oxide (NO) is formed in the combustion chamber, where oxidation of NO into nitrogen dioxide ($NO_2$) happens at ambient temperature after expulsion from the exhaust system. $NO_x$ refer to the mix of NO and $NO_2$. However, as the lifetime of NO in the atmosphere at ambient temperature is of a few hours only, it is reasonable to assume that the nitrogen oxide mix is mainly composed of $NO_2$ [Franke et al., 2009]. Dependent upon the fuel, the quantity of organic nitrogen may account for a significant proportion of the total $NO_x$ emission, particularly for engines operating on Heavy Fuel Oil (HFO), found only onboard ships [Lloyd's Register of Shipping, 1995].

$NO_x$ emissions have a triple effect. (i) A photo-oxidation effect, by favoring in two ways the formation of the main atmospheric photo-oxidant, the hydroxide ion ($OH^-$). $NO_x$ catalyzes the formation of ozone ($O_3$), which liberates highly reactive compounds [1] under the influence of sunlight (photolysis). The products of the ozone photolysis react with water vapor ($H_2O$) to form $OH^-$. In addition, the transformation of NO into $NO_2$ liberates hydroxide ions as well. (ii) A eutrophication effect, due to the presence of nitrogen (N) which ends up in surface waters when the atmospheric emissions precipitate. (iii) An acidification effect, due to the formation of nitric acid ($HNO_3^-$), from complex reactions between $NO_x$ and the highly reactive compounds formed by ozone photolysis [Eyring et al., 2010].

It is estimated that approximately 15% of $NO_x$ emissions in Iceland in 2008 came from road transport [EAI, 2010b]. Due to the international component of maritime transport, the emission from ships are omitted in the national emission inventory documents, as instructed by the guidelines from the Intergovernmental

[1] These compounds are called "free radicals". They have one un-paired electron, hence are in a very high energetic state and are willing to react with a myriad of compounds. These reactions in turn produce other reactive intermediates. An example of free radical is the $OH^{\cdot}$ radical, not to be confused with the hydroxide ion $OH^-$ which is rather stable[Eyring et al., 2010].

Panel on Climate Change [IPCC, 2006]. International emissions are reported under the Convention on Long-range Transboundary Air Pollution (CLRTAP) of the United Nations Economic Commission for Europe (UNECE). Iceland has ratified this convention, but not all the convention protocols, such as those concerning the $NO_x$ and $SO_x$ emissions [Gernez, 2010b].

**Sulfur dioxide $SO_2$** The organic sulfur in fuels is oxidized during the engine combustion. The sulfur content is high in HFO (2.7 % m/m) and very low in distillate fuels (down to 0.0008% m/m) used by truck engines, for example diesel oil[2]. Marine Diesel Oil (MDO) and Marine Gas Oil (MGO) are used only onboard ships, and have a sulfur content varying from high (2.7 % m/m) to low (0.1 % m/m) [Kristensen, 2010b].

$SO_2$ has an acidification effect. In its gas phase, it is oxidized to sulfuric acid ($H_2SO_4$) by the hydroxide ion ($OH^-$). In cloud droplets or sea-salt particles, $SO_2$ is in its aqueous phase and is oxidized to sulphate ion ($SO_4^{2-}$) by ozone ($O_3$) and the $OH^\cdot$ free radical. Sulphate reacts with the hydrogen ion ($H^+$) present in water to form sulfuric acid. As a consequence, the acidification effect of $SO_2$ is intensified by the presence of ozone and $OH^\cdot$ radicals, which are enhanced by the $NO_x$ emissions [Eyring et al., 2010].

**Ammonia $NH_3$** is produced in very small quantities during fossil fuel combustion. The presence of nitrogen makes $NH_3$ an agent of eutrophication. In addition, $NH_3$ reacts with $O_2$ in presence of a catalyzer to form nitric acid ($HNO_3$), making $NH_3$ an agent of acidification [Atkins, 1987].

**Non-Methane Volatile Organic Compounds NMVOCs** are emitted by combustion of fossil fuels and evaporation losses due to temperature variation in fuel tanks [Krzyzanowski et al., 2005]. Volatile Organic Compounds (VOCs) are organic compounds with a significant vapour pressure able to evaporate at ambient temperatures. Being naturally present in the air and not photo-reactive, methane is distinct from all the other VOCs, which are then referred to as Non-Methane VOCs. NMVOCs are taking part in ozone formation at low altitude,

[2]Sulfur content is expressed in mass percentage: 2.7 % m/m means that in 1 kg fuel, there is $2.7/100 = 0.027$ kg = 27g sulfur.

hence participating to photo-oxidant formation[Deletraz and Paul, 1998].

The road transport sector is the main source of NMVOCs in Iceland, accounting for approximately 50% of the emissions in 2008 [EAI, 2010a].

**Carbon monoxide CO** is produced during incomplete combustion, under specific temperature and pressure conditions when carbon dioxide $CO_2$ gets another carbon atom to form two CO molecules. This is particularly the case when the carburetor is not allowing enough oxygen inside the combustion chamber[Deletraz and Paul, 1998]. The $OH^{\cdot}$ radical reacts with CO to initiate the formation of ozone, making CO an agent of photo-oxidation. Road transport is the most prominent contributor to CO emissions in Iceland, accounting in 2008 for more than 90% of the emissions [EAI, 2010a].

### 1.1.2 Substances contributing to the greenhouse effect

**Carbon dioxide $CO_2$** is formed in all combustion processes in which complete or near complete combustion of a hydrocarbon fuel takes place. The quantity of $CO_2$ depends on the quantity of fuel burnt, which to a large extent is determined by the engine power required, the plant efficiency and the composition of the fuel [Kristensen, 2010a].

In Iceland, road transport accounted for approximately 20% of $CO_2$ emissions in 2008 [EAI, 2010a].

**Methane $CH_4$ and nitrous oxide $N_2O$** are produced in very small quantities during fossil fuel combustion. However, both are potent greenhouse gases, with a Global Warming Potential (GWP) respectively 25 and 300 times higher than $CO_2$ [Forster et al., 2007]. As $N_2O$ contains nitrogen, it is an agent of eutrophication as well.

Road transport is the second most important source of $N_2O$ in Iceland, accounting for 10% of the 2008 emissions. Paradoxically, the obligatory use of catalytic converters in all new vehicles starting with the 1995 models contributed significantly to an increase of $N_2O$ emissions, the contribution of road transport being only of 1% in 1990 [EAI, 2010a].

**Hydrofluorocarbons and Perfluorocarbons HFCs and PFCs** are found in refrigerating gas or liquid used to transport temperature sensitive cargo. Their GWP are generally very high: the HFC-134a gas used in refrigerated containers is 1300 times more potent as a greenhouse gas compared to $CO_2$.

### 1.1.3 Metal contamination

**Metals** are known to affect biological processes by e.g. inhibiting enzyme reactions and affect nerve development. Traces of cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), zinc (Zn) as well as lead (Pb), arsenic (As) and selenium (Se) can be found in exhaust emissions. The distribution of metals in exhaust emissions depends on their concentration in the combusted fuel. The metal composition in fuel in turn reflects the component oil blends and any elements incorporated during storage and transfer [Lloyd's Register of Shipping, 1995].

### 1.1.4 Organic pollutants contamination

**Polycyclic aromatic hydrocarbons PAHs** are a group of approximately 100 compounds, either present in oil products or formed by incomplete combustion of carbon-containing materials like coal, wood or waste. PAHs compounds are structures built on the hexagonal benzene molecule ($C_6H_6$); the benzene content of a fuel is then a good indicator of its potential risk as a source of PAHs. Some PAHs are documented to be the strongest known carcinogens, for instance the benzo-a-anthracene, chrysene, benzo-b-fluoranthene, benzo-a-pyrene, dibenz-a,h-anthracene and indeno-1,2,3,cd-pyrene.[Ravindra et al., 2008]. PAHs are not persistent; still, due to their volume and toxicity, they are usually included as organic pollution. Toxicity states how poisonous a substance is, or how large a dose is required to kill an organism; the more toxic the substance the smaller the lethal dose [Clark, 1997].

Road transport is responsible for approximately 15% of PAH emissions in Iceland, with a significant increase of 36% between 1990 and 2008 due to the expansion of the vehicle fleet[EAI, 2010b].

### 1.1.5 Particulate matters

**Soot particles** formed in incomplete combustion are found in exhaust fumes. In addition, some gaseous compounds can condensate to form solid particles: it is the case for sulphates ($SO_4^{2-}$) and nitrates ($NO_3^-$). The magnitude of particle emissions are then dependent upon the completeness of combustion (with smoke traditionally acting as a measure of combustion quality) and the composition of the fuel burnt (especially the sulfur content) [Lloyd's Register of Shipping, 1995]. These particles, referred to as **Particulate matters (PM)**, are likely to be smaller than $1\mu$m in diameter, readily transportable by air currents and are highly bioavailable through inhalation. Human epidemiological studies have identified increased risks of mortality, respiratory morbidity and allergic responses due to the exposure to a mixture of substances, including PM [Krzyzanowski et al., 2005].

The national inventories of atmospheric pollution in Iceland [EAI, 2010a, EAI, 2010b] do not report the PM emissions, because Iceland has not ratified all the protocols of the international convention on Long Range Transboundary Air Pollution [UNECE, 1979]. For comparison, the transport of freight on roads is responsible of approximately 10% of the PM emissions in France [CITEPA, 2010].

## 1.2 Substances released in sea water

These emissions are only accountable to ships.

**Oil** is released during the voluntary discharge of bilge waters, where lubricating and fuel oil leaking from engine room are accumulating. This operation can be a common practice, as shown by a satellite study in the Mediterranean sea, estimating an average of 100 000 discharges per year [Rempec, 2003]. The WWF estimates an annual release of 0.7 to 1.3 million tonne per year of oily water in European waters [WWF, 2003].

Maritime transport of oil products is also responsible of oil spills, equally distributed between accidental pollution when an oil tanker ship is spilling oil from running aground or a collision, and operational pollution when the fuel tanks are washed or filled with water to serve as ballast (a common practice for one third of the oil tanker fleet). In addition, fuel oil pollution occurs in harbours during the loading and unloading of the oil tankers [Fattal, 2006]. Only two companies import oil to Iceland: Oliudreifing and Skeljungur. The later company fuels the Shell stations in Iceland and claims a zero release of oil [Gernez, 2011c].

**Metals and biocides** are released by the paints covering the ship hulls, called antifouling paints. Any plant or animal growth on the hull increases the friction between the ship hull and the sea water, causing an increased need of energy (hence fuel consumption) to move the ship forward. If not protected, a ship can gather up to 150 kg of fouling per $m^2$ in 6 months, increasing the fuel consumption up to 40 % [IMO, 2002]. Biocides are used to prevent this marine growth and are by design toxic to the marine environment.

Tributyltin (TBT) used to be the most common biocide in antifouling paints, before it was completely prohibited as of 1 January 2008 because of its impact on the aquatic fauna, for example to oysters [Alzieu, 2000] and dogwhelk [Gibbs and Bryan, 2009]. The alternatives to TBT paints are copper (Cu) and zinc (Zn) functioning as biocides and organic "boosters" (for example zinc pyrithion, copper pyrithion, dichlofuanide, irgarol) to amplify and focus their destructive action to a few species of plants and animals growing on ship hulls [Thomas et al., 2001].

Metallic anodes protecting ship hulls against corrosion are also a source of metal contamination: aluminum (Al), cadmium (Cd), copper and zinc. The metal leaching levels from antifouling paints are comparable to those of anodes [OSPAR Commission, 2006].

**Invasive species** also referred to as **Non Indigenous Species NIS** are released by international and regional shipping due to the growing of marine life on ship hulls and the transport of large amounts of sea water as ballast. Savarese et al (2005) estimates that 90% of the invading marine species in Hawaiian waters and that 36% of invasive coastal marine species in North America could be the result of hull fouling alone, while ballast water represents 20% of new species introduction [Savarese, 2005]. NIS have an important impact on marine ecosystems where they do not have natural predators, thus becoming invasive and creating a strong trophic competition with the local species.

The Rock crab (*Cancer irroratus*) was first spotted in South West Iceland in 2006, coming from North America. It is has now populated the West, North West and North regions of Iceland. Other examples of novel pionneers introduced in Icelandic coastal water since the first Viking navigations are e.g the Soft-shell Clam (*Mya arenaria*) and the "toothed wrack" (*Fucus serratus*) [Gíslason, 2009].

## 1.3 Substances released in soil and fresh water

These emissions are only accountable to road vehicles.

**Non-exhaust Particulate Matters** are released by resuspension of debris accumulated on the road surface, as well as brake wear, tyre wear and road wear. Non-exhaust PM are heavier and larger than exhaust PM described in section 1.1.5: approximately 10$\mu$m against 1$\mu$m. Both sizes are included in the category $PM_{10}$, encompassing all particles with a diameter less or equal 10 $\mu$m. Brake wear particles consist of metals (such as iron, copper and lead), organic material and silicon components. Tyre particles consist of various rubbers, as well as organic zinc, used in tyre production [Krzyzanowski et al., 2005].

High levels of non-exhaust PM can be expected in winter Iceland, due to the "sandpaper effect": sand aggregate is dispersed on the roads to keep the roads wet and prevent icing. As abrasion increases with moisture, the wear of road surface is 2 to 6 times larger for a wet road. In addition, the studded tyres are very abrasive[EMEP/EEA, 2009].

## 1.4 Summary of the substance emission

Table 1.1: Inventory of substances, associated main input sources and effects.

| Substance | Main source | Effects |
|---|---|---|
| | *Emissions to air* | |
| $NO_x$ | fuel combustion | Photo-oxidant formation, Eutrophication, Acidification |
| NMVOC | fuel combustion | Photo-oxidant formation |
| CO | fuel combustion | Photo-oxidant formation |
| $NH_3$ | fuel combustion | Eutrophication |
| $SO_2$ | fuel combustion | Acidification |
| $CO_2$ | fuel combustion | Greenhouse effect |
| $CH_4$ | fuel combustion | Greenhouse effect |
| $N_2O$ | fuel combustion | Greenhouse effect, Eutrophication |
| Metals | fuel combustion, road, brake and tyre abrasion | Toxic contamination |
| PAH | fuel combustion | Toxic contamination |
| $PM_{10}$ | fuel combustion, road, brake and tyre abrasion | Toxic contamination |
| | *Emissions to soil and fresh water* | |
| Metals | road, brake and tyre abrasion | Toxic contamination |
| | *Emissions to sea water* | |
| Oil discharges | voluntary discharge | Toxic contamination |
| Biocides | antifouling paint | Toxic contamination |
| Metals | antifouling paint | Toxic contamination |
| NIS | ballast water, hull fouling | Toxic contamination |

## 1.5 Pollution effects and impact categories

As defined in the very beginning of this chapter, pollution describes the damaging effects from wastes inputs in the environment. These damaging effects consist in Photo-oxidant formation, Acidification, Eutrophication, Greenhouse effect, and Toxic contamination. Each one of these effects defines a category of impact. The environmental impact of the pollution resulting from road and sea transport is then defined as the combined contribution of five impact categories. The contribution of an impact category depends on the emission of each substance associated to it:

**Photo-oxidant formation:** emissions of **$NO_x$, CO, NMVOC**

**Eutrophication:** emissions of **$NO_x$, $NH_3$, $N_2O$**

**Acidification:** emissions of **$SO_2$, $NO_x$, $NH_3$**

**Greenhouse effect:** emissions of **$CO_2$, $CH_4$, $N_2O$**

**Toxic contamination:** emissions of **PAH, $PM_{10}$, Biocides, Metals, Oil discharges, NIS**

In addition to these five categories, some impacts not related to a specific substance are considered in this study, based on results by Fet et al (2000) [Fet et al., 2000]:

**Land occupation:** area and duration of land occupation, mainly due to transport infrastructures (for instance roads and harbours).

**Noise exposition:** area and duration of exposure to levels over 55 dBA, corresponding to the maximum noise level outdoors permitting spoken conversation, and other activities such as sleeping, working and recreation, which are part of the daily human condition[US Congress, 1972].

**Energy consumption:** quantified consumption of energy (in Joules).

Finally, for practical reasons,

**HFCs and PFCs** are not included in the emission inventory in this study, due to a lack of data on the quantities and type of refrigerating gas used in the vehicles equipped with temperature controlled systems.

**NIS** are not investigated further in this study, as no simple method is available yet to quantify the associated impact. Halpern et al (2008) suggests to use the volume of ballast water transported, together with the time spent in harbours [Halpern et al., 2008].

**Toxic contamination** is further divided in four categories, to take into account the toxicity to different type of ecosystems [Guinée et al., 2002b]: **Human Toxicity**, **Marine Aquatic Ecotoxicity**, **Freshwater Aquatic Ecotoxicity** and **Terrestrial Ecotoxicity**

**Metals** taken into account are: lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), chromium (Cr), copper (Cu), nickel (Ni), selenium (Se) and zinc (Zn).

**TBT-free antifouling** paints are considered only, due to the TBT ban of 2001 entered in force in 2008 [IMO, 2001] and incorporated into EU law in 2003 [European Commission, 2003].

As summarized in Figure 1.1, the environmental impact of a transport system is defined as a combination of impacts in all these 11 categories. The calculation of the contribution to each impact category is described in the next chapter.

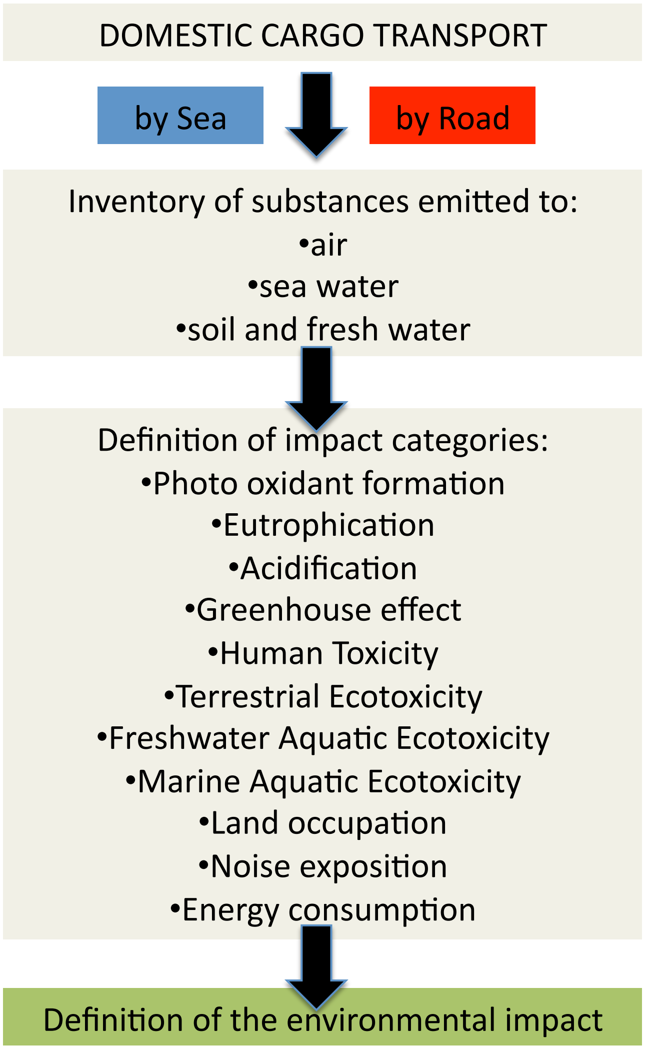



Figure 1.1: Summary of chapter 1

# Chapter 2

# Quantification of the identified impacts

## 2.1 The Life Cycle Assessment method

The objective of an LCA is explicit: to assess the environmental impact of a service, product, process, during its complete lifetime (from "cradle to grave") or part of it (from "cradle to gate") [ISO, 2000]. The main steps of an LCA are [Guinée et al., 2002a]:

**Goal and Scope definition:** the objectives and boundaries of the assessment are defined. The function of the assessed system is explicited, as well as the functional unit to which the emissions and resources consumption are related. Relevant impact categories are identified. Reference scenarios and alternatives are defined, ready for the assessment.

**Inventory analysis:** the emissions to air, fresh and sea water and soil of all the identified substances are quantified, for each scenario. The parameters affecting the quantity of substances emitted are identified to carry out uncertainty and sensitivity analyses.

**Impact assessment:** the impact of the emission of each substance is characterised using dedicated impact models. For example, the impacts of $CO_2$, $CH_4$ and $N_2O$ are weighted according to their Global Warming Potential within the Greenhouse effect impact category. This characterisation phase is the only mandatory phase of the impact assessment. Two other phases of Normalisation and Valuation can be used, to take into account some local or regional considerations for the impact (Normalisation) and to aggregate the impact of each category into one global environmental impact (Valuation). Because these two last phases are very dependent on the type of system assessed and the purpose of the assessment, no standardisation is possible [ISO, 2000].

**Interpretation:** the results are criticized based on identified uncertainties. System components responsible of high impacts can be identified and mitigations measures proposed. Economic and social implications can also be discussed.

## 2.2 Life Cycle Assessment for transportation systems

Fet et al (1998,2000) find relevant to use a LCA method for comparative impact studies of transportation systems, under specific assumptions [Fet and Sørgård, 1998, Fet et al., 2000], listed below.

### 2.2.1 Goal and scope definition

The goal in this study is to compare the environmental impact of transport scenarios. Their function is to transport general cargo between Reykjavík and Ísafjördur. The functional unit is 1 tonne general cargo transported from Reykjavík to Ísafjördur, whatever the route taken. Five transport scenarios are assessed in this study: a land-based transport scenario using Heavy Duty Vehicles (HDVs) and four maritime alternatives using either a Roll on - Roll off ship ("Ro-Ro" ship) or a Lift on - Lift off ("Lo-Lo") ship. Chapter 3 presents the assessment in details.

Defining the scope of the LCA means to decide which parts of the life cycle of the transport subsystems will be included in the assessment. For example, the life cycle of a ship goes from the building phase, to the operational phase alternated with the maintenance phase, and the scrapping phase. The main assumption according to Fet et al (2000) is to include only the operational phase of each subsystem, based on the results from a "cradle to grave" LCA of a ship [Johnsen and Fet, 1999, Fet et al., 2000]:

- The building phase is the first contributor to ozone depletion and material use.
- The operational phase is the only phase contributing with more than 10% to the overall impact with respect to most of the impact categories defined in that study: greenhouse effect, acidification, photo-oxidant formation, eutrophication, local air pollution, toxic contamination and energy use.
- The operational phase is the phase contributing the most to ecotoxicological impacts and solid waste; the maintenance and building phases come respectively in second and third.
- The scrapping phase reduces the impact in photo-oxidant formation, solid waste and material use, due to the recycling of materials.

These results are confirmed by Tincelin (2010), showing that the operational phase of a fishing vessel accounts for more than 90% of its whole life cycle environmental impact [Tincelin et al., 2010].

In addition, Johnsen (1999) quotes a "cradle to gate" LCA of the fuel used for the propulsion of a vehicle (car, truck, ship, plane) and shows that more than 90% of the impacts come from the combustion of the fuel by the vehicle engine, meaning that only the operational phase of the fuel can be considered in this study [Johnsen and Fet, 1999].

### 2.2.2 Inventory calculation

The impact categories and associated substances are explicited in section 1.5. The substance emissions are calculated by the following formulas. $E_i$ is the emission of substance $i$ per functional unit $[g/F.U]$ (1 F.U = 1 tonne transported from Reykjavík to Ísafjördur).

**Exhaust gas emission** is calculated after

$$E_i(exhaust) = FC * e_{exhaust,i}$$

where

- $FC$ is the fuel consumption per functional unit $[kg/F.U]$
- $e_{exhaust,i}$ is the exhaust emission factor for substance i $[g/kgfuel]$

The fuel consumption is calculated after

$$FC = SED * SFC * D$$

where

- $SED$ is the vehicle Specific Energy Demand [MJ/tonne cargo/km]: quantity of energy needed to move 1 tonne cargo on a distance of 1 km
- $SFC$ is the Specific Fuel Consumption [kg fuel/MJ]
- $D$ is the Trip distance [km]

**Non exhaust emission of suspended particles** is calculated after

$$E_i(non - exhaust) = D * e_{non-exhaust,i} * f_k$$

where

- $f_k$ is the kilometric fuel consumption $[kgfuel/km]$ (only for land-based vehicles)
- $e_{non-exhaust,i}$ is the kilometric non exhaust emission factor for substance i $[g/km]$

**Leaching from ship antifouling** of substance i is calculated after

$$E_i(leaching) = T * S_w * e_{leaching,i}/C$$

where

- $T$ is the exposition time $[h]$
- $S_w$ is the ship hull wetted surface $[m^2]$

- $e_{leaching,i}$ is the leaching rate of substance i $[g/m^2h]$
- $C$ is the exploited capacity of the ship $[tonne]$

The calculation of the **land occupation** is based on the area occupied during the transport and the duration of this occupation [Karlsen and Angelfoss, 2000]:

$$LO = (B + S_B) * (L + S_L) * T_l/C$$

where

- $LO$ is the land occupation $[m^2h/F.U]$
- $B$ is the transport mean breadth (road breadth or quay breadth) $[m]$
- $S_B$ is the safety distance in breadth direction for the transport mean[1] $[m]$
- $L$ is the length of transport mean $[m]$
- $S_L$ is the safety distance in length direction for the transport mean[2] $[m]$
- $T_l$ is the land occupation time $[h]$

The calculation of the **noise exposition** is based on the area exposed to noise levels above 55 dBA and the duration of this exposition[Karlsen and Angelfoss, 2000]:

$$NE = A_{>55dBA} * T_n/C$$

where

- $NE$ is the noise exposition $[m^2h/F.U]$
- $A_{>55dBA}$ is the average area exposed to a noise over 55 dBA $[m^2]$. A minimum distance of 325 m and 288 m is necessary to reach noise levels lower than 55 dBA for trucks and ships, respectively[Karlsen and Angelfoss, 2000].

[1] Only for road transport. A value of 2m is used [Karlsen and Angelfoss, 2000]

[2] Only for road transport. A value of 62.5m is used [Karlsen and Angelfoss, 2000]. An example of emission inventory calculation for road transport is given at the very end of the document for illustration purposes.

- $T_n$ is the noise exposition $[h]$

The calculation of the **energy** is based on the energy consumed by the main and auxiliary engines of the transport vehicles to realise the transport function. The energy consumed to maintain the cargo at a specific temperature (for fresh and frozen cargo) is not included.

Lo-Lo and Ro-Ro ships usually have different types of engines and use different types of fuel:

**Lo-Lo** ships have a slow-speed engine running on Heavy Fuel Oil (HFO), releasing important emissions of $SO_2$ and PM due to the elevated sulfur content of this type of fuel. In addition, emissions of $NO_x$, metals and PAHs can be expected to be important [Lloyd's Register of Shipping, 1995].

**Ro-Ro** ships have a medium-speed engine running on Marine Diesel Oil or Marine Gas Oil (MDO/MGO). Burning such fuel results in lower emissions than with HFO. However, medium-speed engines are less fuel efficient than slow-speed engines [Kristensen, 2010a].

Heavy Duty Vehicles differ by the emission standard they follow, called EURO norms. The more recent the norm, the lower the maximum level of emissions authorized: the EURO IV and V norms for HDVs built respectively after 2005 and 2008 are much stricter than the original EURO I norm from 1991. Only the emissions of $NO_x$, $SO_x$ and PM are regulated by the EURO norms [Kristensen, 2010a].

The emission factor tables below show the differences in exhaust emissions, between the different types of HDVs (Table 2.1) and ships (Table 2.3). For instance the $NO_2$ and $SO_2$ emission factors are much lower for HDVs than for ships. A variety of metals is released in the atmosphere, with a dominance of copper and zinc for HDVs, and nickel for ships. The metal and PAH emission levels are always much lower than the other substances, by a factor 1000 in average.

The metals released in soil and freshwater by HDVs are shown in Table 2.2, those released at sea by ships in Table 2.4. Note that metal emissions from ship anodes are not included due to a lack of emission factor data. As mentioned in

Chapter 1, the levels of metal leaching from anodes are comparable to those of antifouling paints [OSPAR Commission, 2006].

Table 2.1: Emission factors for Heavy Duty Vehicles - part I

| EURO norm[a] | EURO I | EURO IV | EURO V | Unit | Source |
|---|---|---|---|---|---|
| Fuel | Diesel Oil | Diesel Oil | Diesel Oil | [-] | [EMEP/EEA, 2009] |
| Sulfur content | 0.03 | 0.004 | 0.0008 | $\%m/m$ | [EMEP/EEA, 2009] |
| Calorific value | 42.8 | 42.8 | 42.8 | $MJ/kgfuel$ | [Kristensen, 2010a] |
| Oil consumption | 0.200 | 0.200 | 0.200 | $kg/kWh$ | [Kristensen, 2010a] |
| | | | *Emission to air - from exhaust fumes* | | |
| $NO_2$ | 35.81 | 18.24 | 10.38 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| NMVOC | 2.14 | 0.05 | 0.05 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| CO | 7.38 | 0.50 | 0.50 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| $NH_3$ | 0.01 | 0.01 | 0.01 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| $SO_2$ | 0.60 | 0.08 | 0.02 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| $CO_2$ | 3171 | 3171 | 3171 | $g/kgfuel$ | [IPCC, 2006] |
| $CH_4$ | 0.38 | 0.38 | 0.38 | $g/kgfuel$ | [IPCC, 2006] |
| $N_2O$ | 0.04 | 0.06 | 0.16 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| $PM_{10}$ | 1.41 | 0.11 | 0.11 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| PAH[b] | 7.62E-03 | 7.62E-03 | 7.62E-03 | $g/kgfuel$ | [Ravindra et al., 2008] |
| Pb | 3.38E-05 | 3.15E-05 | 3.15E-05 | $g/kgfuel$ | [EMEP/EEA, 2009] |
| Cd | 1.00E-05 | 1.00E-05 | 1.00E-05 | $g/kgfuel$ | [EMEP/EEA, 2009] |
| Hg | 1.00E-05 | 1.00E-05 | 1.00E-05 | $g/kgfuel$ | [EMEP/EEA, 2009] |
| As | 1.00E-05 | 1.00E-05 | 1.00E-05 | $g/kgfuel$ | [EMEP/EEA, 2009] |
| Cr | 5.00E-05 | 5.00E-05 | 5.00E-05 | $g/kgfuel$ | [EMEP/EEA, 2009] |
| Cu | 1.70E-03 | 1.70E-03 | 1.70E-03 | $g/kgfuel$ | [EMEP/EEA, 2009] |
| Ni | 7.00E-05 | 7.00E-05 | 7.00E-05 | $g/kgfuel$ | [EMEP/EEA, 2009] |
| Se | 1.00E-05 | 1.00E-05 | 1.00E-05 | $g/kgfuel$ | [EMEP/EEA, 2009] |
| Zn | 1.00E-03 | 1.00E-03 | 1.00E-03 | $g/kgfuel$ | [EMEP/EEA, 2009] |

[a] The EURO norms apply to the European Economic Area (EEA), hence to Iceland, according to Directives 1991/542/EEC I (EURO I)and 1999/96/EC (EURO IV and V) adopted by Decision of the EEA Joint Committee No 72/2000.

[b] Accounting for a group of 29 PAH species [Ravindra et al., 2008].

Table 2.2: Emission factors for Heavy Duty Vehicles - part II

| EURO norm | EURO I | EURO IV | EURO V | Unit | Source |
|---|---|---|---|---|---|
| | | *Emission to air from road, tyre and brake abrasion*[b] | | | |
| $PM_{10}$ | 6.2E-02 | 6.2E-02 | 6.2E-02 | $g/km$ | [Spielmann et al., 2007] |
| Pb | 6.85E-05 | 6.85E-05 | 6.85E-05 | $g/km$ | [Spielmann et al., 2007] |
| Zn | 1.37E-02 | 1.37E-02 | 1.37E-02 | $g/km$ | [Spielmann et al., 2007] |
| Cu | 2.74E-04 | 2.74E-04 | 2.74E-04 | $g/km$ | [Spielmann et al., 2007] |
| Cd | 1.37E-05 | 1.37E-05 | 1.37E-05 | $g/km$ | [Spielmann et al., 2007] |
| Cr | 1.23E-04 | 1.23E-04 | 1.23E-04 | $g/km$ | [Spielmann et al., 2007] |
| Ni | 1.10E-04 | 1.10E-04 | 1.10E-04 | $g/km$ | [Spielmann et al., 2007] |
| | | *Emissions to soil from road, tyre and brake abrasion*[b] | | | |
| Pb | 3.43E-05 | 3.43E-05 | 3.43E-05 | $g/km$ | [Spielmann et al., 2007] |
| Zn | 6.85E-03 | 6.85E-03 | 6.85E-03 | $g/km$ | [Spielmann et al., 2007] |
| Cu | 1.37E-04 | 1.37E-04 | 1.37E-04 | $g/km$ | [Spielmann et al., 2007] |
| Cd | 6.85E-06 | 6.85E-06 | 6.85E-06 | $g/km$ | [Spielmann et al., 2007] |
| Cr | 6.17E-05 | 6.17E-05 | 6.17E-05 | $g/km$ | [Spielmann et al., 2007] |
| Ni | 5.48E-05 | 5.48E-05 | 5.48E-05 | $g/km$ | [Spielmann et al., 2007] |
| | | *Emissions to fresh water from road, tyre and brake abrasion*[b] | | | |
| Pb | 3.43E-05 | 3.43E-05 | 3.43E-05 | $g/km$ | [Spielmann et al., 2007] |
| Zn | 6.85E-03 | 6.85E-03 | 6.85E-03 | $g/km$ | [Spielmann et al., 2007] |
| Cu | 1.37E-04 | 1.37E-04 | 1.37E-04 | $g/km$ | [Spielmann et al., 2007] |
| Cd | 6.85E-06 | 6.85E-06 | 6.85E-06 | $g/km$ | [Spielmann et al., 2007] |
| Cr | 6.17E-05 | 6.17E-05 | 6.17E-05 | $g/km$ | [Spielmann et al., 2007] |
| Ni | 5.48E-05 | 5.48E-05 | 5.48E-05 | $g/km$ | [Spielmann et al., 2007] |

[b] Based on the assumption that half of the airborne particulate emissions from road abrasion, tyre and brake wear ($PM_{10}$ in this table) are released back into the soil, and the other half into fresh water [Spielmann et al., 2007]. The speciation of airborne particles into the different metals is given in the same reference.

Table 2.3: Emission factors for Lo-Lo and Ro-Ro ships - part I

| Ship type | Lo-Lo ship | Ro-Ro ship | Unit | Source |
|---|---|---|---|---|
| Engine speed | Slow speed | Medium speed | [-] | [Kristensen, 2010a] |
| Fuel type | HFO | MDO | [-] | [Kristensen, 2010a] |
| Sulfur content[a] | 3 | 0.1 | $\%m/m$ | [Kristensen, 2010a] |
| Calorific value | 40.5 | 42.8 | $MJ/kgfuel$ | [Kristensen, 2010a] |
| Oil consumption | 0.195 | 0.210 | $kg/kWh$ | [Kristensen, 2010a] |
| | | *Emission to air* | | |
| $NO_x$[b] | 89.7 | 63.1 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| NMVOC | 3.0 | 2.3 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| CO | 7.4 | 7.4 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| $NH_3$ | 0.022 | 0.027 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| $SO_2$ | 60.0 | 2.0 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| $CO_2$ | 3179 | 3179 | $g/kgfuel$ | [IPCC, 2006] |
| $CH_4$ | 0.28 | 0.30 | $g/kgfuel$ | [IPCC, 2006] |
| $N_2O$ | 0.08 | 0.09 | $g/kgfuel$ | [IPCC, 2006] |
| $PM_{10}$ | 7.8 | 1.5 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| PAH[c] | 2.50E-03 | 5.00E-04 | $g/kgfuel$ | [Ravindra et al., 2008] |
| Pb | 1.80E-04 | 1.30E-04 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| Cd | 2.00E-05 | 1.00E-05 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| Hg | 2.00E-05 | 3.00E-05 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| As | 6.80E-04 | 4.00E-05 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| Cr | 7.20E-04 | 5.00E-05 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| Cu | 1.25E-03 | 8.80E-04 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| Ni | 3.20E-02 | 1.00E-03 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| Se | 2.10E-04 | 1.00E-04 | $g/kgfuel$ | [EMEP/EEA, 2010] |
| Zn | 1.20E-03 | 1.20E-03 | $g/kgfuel$ | [EMEP/EEA, 2010] |

[a] The maximum sulfur content allowed by Marpol Annex VI for HFO is 4.5 %m/m until 2012, 3.5 %m/m then[IMO, 1978]. The MDO sold inside the EU has a maximum sulfur content of 0.1 %m/m since 2008, according to Directive 2005/33/EC adopted in Iceland through the European Economic Area (EEA) Joint Committee Decision 49/2006.



[b] Expressed in $NO_2$ equivalents.

[c] Accounting for a group of 29 PAH species. The HFO value is calculated as 5 times the MDO value, based on the large difference in sulfur content of HFO and MDO [Cooper, 2003].

Table 2.4: Emission factors for Lo-Lo and Ro-Ro ships - part II

| Ship type | Lo-Lo | Ro-Ro | Unit | Source |
|---|---|---|---|---|
| | | *Emission to sea water* | | |
| Cu[a] | 4.86E-05 | 4.86E-05 | $g/cm^2/day$ | [Finnie, 2006] |

[a] Copper leaching rate obtained with the ISO method, shown to overestimate by approximately a factor 10 the actual copper leaching rate of antifouling paintings [Finnie, 2006]. A copper leaching rate of 1E-06 $g/cm^2/day$ is estimated to be the minimum level for an antifouling paint to be effective [Gernez, 2010c].

### 2.2.3 Impact assessment: Characterisation

The method used to characterise the impact of the emission of each substance is the CML 2001 method developed at the University of Leiden, Netherlands [Guinée et al., 2002b]. This method is also used by Tincelin (2010) and Prinąud (2010) [Tincelin et al., 2010, Prinçaud et al., 2010]. For each impact category, a characterisation factor and the associated unit are given and compiled in Tables 2.5 and 2.6.

The impact of each category is calculated as:

$$Impact = \sum_i E_i * CF_i$$

where:

- $i$ is the substance contributing to the calculated impact category
- $E_i$ is the emission of substance i [g/F.U]
- $CF_i$ is the characterisation factor of substance i

**Photo-oxidant formation** is strongly connected to the formation of ozone, as explained in Chapter 1. The impact of each substance contributing to the formation of ozone ($NO_x$, CO and NMVOC emitted into the air) is characterised by a photochemical ozone creation potential (POCP) expressed in kg ethylene equivalent per kg emission [Derwent et al., 1998, Jenkin and Hayman, 1999].

**Eutrophication:** similarly, an eutrophication potential (EP) is calculated for each eutrophying emission to air, water and soil of $NO_2$, $NH_3$ and $N_2O$, expressed in kg Phosphate ion ($PO_4^{3-}$) equivalent per kg emission. With nitrogen, phosphorus (P) is the other main agent of eutrophication [Heijungs et al., 1992].

**Acidification:** an acidification potential (AP) is calculated for each acidifying emission to the air of $SO_2$, $NO_2$ and $NH_3$, expressed in kg $SO_2$ equivalent per kg emission [Huijbregts, 1999a].

**Greenhouse effect:** the global warming potential for a 100-year time horizon (GWP100) is calculated for each greenhouse gas emission to air of $CO_2$, $CH_4$ and $N_2O$, expressed in kg $CO_2$ equivalent per kg emission. The GWP of a greenhouse gas is an indication of how much its man-made emission can change the heat radiation absorption ("radiative forcing") of the atmosphere [Forster et al., 2007].

**Human toxicity:** a human-toxicity potential (HTP) is calculated for each emission of a toxic substance to air, water/and or soil (in kg 1,4-dichlorobenzene [1,4-DB] equivalent per kg emission). The HTP takes into account the fate, exposure and effects of toxic substances to human health. 1,4-DB is a carcinogenic substance [Huijbregts, 1999b, Huijbregts, 2000], classified as possibly carcinogenic to humans (Group 2B) [IARC, 1999].

**Marine aquatic ecotoxicity:** a marine aquatic ecotoxicity potential (MAETP) is calculated for each emission of a toxic substance to air, water/and or soil (in kg 1,4-DB equivalent per kg emission) [Huijbregts, 1999b, Huijbregts, 2000].

**Freshwater aquatic ecotoxicity:** a freshwater aquatic ecotoxicity potential (FAETP) is calculated for each emission of a toxic substance to air, water/and or soil (in kg 1,4-DB equivalent per kg emission) [Huijbregts, 1999b, Huijbregts, 2000].

**Terrestrial ecotoxicity:** a terrestrial ecotoxicity potential (TETP) is calculated for each emission of a toxic substance to air, water/and or soil (in kg 1,4-DB equivalent per kg emission) [Huijbregts, 1999b, Huijbregts, 2000].

**Noise exposition, Land occupation and Energy:** no weighting factor is necessary, as these impact categories are constituted of one parameter each (Noise exposition area, Land occupation area and Energy consumption).

Table 2.5: Characterisation factors - part I.

| Photo-oxidant formation | POCP | [kg ethylene eq / kg] |
|---|---|---|
| $NO_2$ | 0.028 | [Jenkin and Hayman, 1999] |
| NMVOC | several | [Derwent et al., 1998] |
| CO | 0.027 | |
| Eutrophication | EP | [kg $PO_4^{3-}$ eq / kg] |
| $NO_2$ | 0.13 | [Heijungs et al., 1992] |
| $NH_3$ | 0.35 | |
| $N_2O$ | 0.27 | |
| Acidification | AP | [kg $SO_2$ eq / kg] |
| $SO_2$ | 1.2 | [Huijbregts, 1999a] |
| $NO_2$ | 0.5 | |
| $NH_3$ | 1.6 | |
| Greenhouse effect | GWP100 | [kg $CO_2$ eq/ kg] |
| $CO_2$ | 1 | [Forster et al., 2007] |
| $CH_4$ | 25 | |
| $N_2O$ | 300 | |
| Land occupation | 1 | |
| Noise exposition | 1 | |
| Energy | 1 | |

Table 2.6: Characterisation factors - part II [kg 1.4-DB eq / kg] [Huijbregts, 1999b, Huijbregts, 2000]

| Emission to air | HTP | FAETP | MAETP | TETP |
|---|---|---|---|---|
| PAH (29 species) | 5.72E+05 | 1.72E+02 | 4.26E+03 | 1.02E+00 |
| Pb (Metal) | 4.77E+02 | 2.40E+00 | 7.05E+03 | 1.57E+01 |
| Cd (Metal) | 1.45E+05 | 2.89E+02 | 1.11E+06 | 8.12E+01 |
| Hg (Metal) | 6.01E+03 | 3.17E+02 | 1.20E+06 | 2.83E+04 |
| As (Metal) | 3.48E+05 | 4.95E+01 | 2.31E+05 | 1.61E+03 |
| Cr (Chromium VI) | 3.43E+06 | 7.69E+00 | 2.10E+04 | 3.03E+03 |
| Cr (Chromium III) | 6.47E+02 | 1.92E+00 | 5.24E+03 | 3.03E+03 |
| Cu (Metal) | 4.30E+03 | 2.22E+02 | 8.93E+05 | 6.99E+00 |
| Ni (Metal) | 3.50E+04 | 6.29E+02 | 3.76E+06 | 1.16E+02 |
| Se (Metal) | 4.77E+04 | 5.46E+02 | 2.12E+07 | 5.35E+01 |
| Zn (Metal) | 1.04E+02 | 1.78E+01 | 6.73E+04 | 1.20E+01 |
| $PM_{10}$ | 8.20E-01 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Emission to soil | HTP | FAETP | MAETP | TETP |
| Pb (Metal) | 3.28E+03 | 6.53E+00 | 7.53E+02 | 3.25E+01 |
| Zn (Metal) | 6.37E+01 | 4.77E+01 | 7.21E+03 | 2.46E+01 |
| Cu (Metal) | 9.39E+01 | 5.95E+02 | 1.20E+05 | 1.44E+01 |
| Cd (Metal) | 1.96E+04 | 7.76E+02 | 1.12E+05 | 1.67E+02 |
| Cr (Chromium VI) | 5.00E+02 | 2.10E+01 | 2.62E+03 | 6.30E+03 |
| Cr (Chromium III) | 3.00E+02 | 5.25E+00 | 6.54E+02 | 6.30E+03 |
| Ni (Metal) | 2.68E+03 | 1.69E+03 | 1.17E+06 | 2.39E+02 |
| Emission to fresh water | HTP | FAETP | MAETP | TETP |
| Pb (Lead II) | 1.23E+01 | 9.62E+00 | 1.11E+03 | 4.77E-22 |
| Zn (Zinc II) | 5.84E-01 | 9.17E+01 | 1.38E+04 | 2.53E-21 |
| Cu (Copper II) | 1.34E+00 | 1.16E+03 | 2.33E+05 | 4.06E-21 |
| Cd (Cadmium II) | 2.29E+01 | 1.52E+03 | 2.20E+05 | 1.42E-20 |
| Cr (Chromium VI) | 3.42E+00 | 2.77E+01 | 3.44E+03 | 2.27E-19 |
| Cr (Chromium III) | 2.05E+00 | 6.91E+00 | 8.61E+02 | 2.27E-19 |
| Ni (Nickel II) | 3.31E+02 | 3.24E+03 | 2.25E+06 | 1.03E-18 |
| Emission to sea water | HTP | FAETP | MAETP | TETP |
| Cu (Copper II) | 1.36E+05 | 4.11E-20 | 1.48E+06 | 2.48E-20 |

Table 2.6 shows the assumed form under which metallic substances are released: metal form when released into the air and into the soil (for example Pb for lead); ionic form when released into water (for example $Pb^{2+}$) [Guinée et al., 2002b]. In addition, two ionic forms are given for the Chromium ion, Chromium VI being more toxic than Chromium III (higher characterisation factors). A 50-50% split is assumed for Chromium III and VI due to a lack of information on the emission magnitude of each. Finally, there is no generic characterisation factor for the NMVOC emissions, as they are constituted of several compounds. An average value between the $NO_2$ and the CO photochemical ozone creation potential is assumed. All these assumptions are highly discussable, yet the discussion involves specialist knowledge in Aquatic and Atmospheric chemistry and go beyond the knowledge of the author and the scope of the study.

### 2.2.4 Impact assessment: Normalisation and Valuation

Normalisation and Valuation are facultative in the LCA method [ISO, 2000]. Normalisation is not considered in this study. Valuation can be used for comparing the relative importance of different environmental impact categories, or to derive a single index for comparison of the environmental performance of alternative systems when a decision with conflicting environmental targets is to be taken [Fet et al., 2000]. This approach is discussed in Chapter 4.

## 2.3 Discussion: limitations to the LCA method

### 2.3.1 Scope: impact of transport infrastructures

Because of the scope limitation to the operational phase only, the transport infrastructures considered in this study are the roads and harbours used by the HDVs and ships. All the infrastructures involved in transforming and storing the cargo before its transport are not considered, nor are the loading and unloading infrastructures (cranes, loading vehicles).

The impact of roads and harbours are accounted for through the categories of

Noise exposition and Land occupation. Because the roads and the harbours are open to several users, the impacts have to be allocated to the transport function defined in this study. This allocation is based on the time spent by each vehicle using the infrastructures to fullfill the transport function. For roads it is the HDVs driving time, for harbours the time needed to load and unload the cargo on ships.

Vogtlander (2004) proposes to look at the (specific) biodiversity erosion and the rarity of ecosystems to assess the impact of land-use [Vogtländer et al., 2004]. Bagoulla (2008) proposes a detailed list of dedicated indicators for the environmental impact of harbours: presence of ship waste treatment facilities, existence of a risk contingency plan, number of complaints from the neighbouring population [Bagoulla et al., 2008].

### 2.3.2 Inventory analysis: uncertainties related to emission factors

All emission calculations in this study are based on emission factors. These factors are sensitive to several parameters. For instance the exhaust emission factors depend on the vehicle type, the fuel type, the engine type, the age and maintenance of the vehicle, the speed, the slope of the road (or the presence of wind and waves for ships), the air combustion temperature (cold/hot start), the ambient air temperature[Deletraz and Paul, 1998]. In this study, one main source compiling a number of existing research is used ([EMEP/EEA, 2010] for ships and [EMEP/EEA, 2009] for HDVs), in order to prevent too much heterogeneity. The same level of details ("Tier 2 approach") is used for both ships and HDVs, considering only the type of vehicle, engine, and fuel used.

The uncertainty in ships emission factors lies within a 95% confidence intervals in [EMEP/EEA, 2010]. If an emission factor is given with a 95% confidence interval of 10 to 20 %, it means that 95% of the emission calculation will lie within 10 to 20 % of the "real value". For road vehicles emission factors, the uncertainty is qualitative, based on the quality of the data assessed to compute the emission factors: grade A ("Statistically significant emission factors based on sufficiently large set of measured and evaluated data"), grade B ("Emission factors non statistically significant based on a small set of measured re-evaluated data"), grade

C (“Emission factors estimated on the basis of available literature”) and grade D (“Emission factors estimated applying similarity considerations and/or extrapolation”) [EMEP/EEA, 2009].

A qualitative method is used in this study to combine these two approaches. A grade is given to the uncertainty associated with the emission factors:

**Low uncertainty:** values lying within a 0 to 20% interval of 95 % confidence and data of quality A and B.

**Medium uncertainty:** values lying within a 20 to 50 % interval of 95% confidence and data of quality C.

**High uncertainty:** values lying within a 50 to 100 % interval of 95% confidence and data of quality D.

The uncertainty grades are presented in Table 2.7. High uncertainty concerns only the emission of metal and PAH: emitted in much smaller quantities than the other substances, they are much more sensitive to the measurement variability.

Table 2.7: Uncertainties associated with emission factors. The sources are the same as the emission factors, see Table 2.1, 2.2, 2.3 and 2.4

| Emission factor | Ship | Truck |
|---|---|---|
| | *Emission to air* | |
| $NO_2$ | low | low |
| NMVOC | low | low |
| CO | low | low |
| $NH_3$ | medium | low |
| $SO_2$ | medium | low |
| $CO_2$ | low | low |
| $CH_4$ | medium | low |
| $N_2O$ | medium | low |
| $PM_{10}$ | high | medium |
| PAH | high | high |
| Metals | high | high |
| | *Emission to fresh water and soil* | |
| $PM_{10}$ | Not Applicable | high |
| Metals | Not Applicable | high |
| | *Emission to sea water* | |
| Cu | high | Not Applicable |

### 2.3.3 Impact assessment: uncertainties related to characterisation factors

The characterisation calculation has to be treated with care for the impact categories containing substances with some uncertainty in the emission factor. This is particularly the case for all the toxicity impact categories: Human Toxicity, Freshwater Aquatic Toxicity, Marine Aquatic Toxicity, and Terrestrial Toxicity.

In addition, characterisation factors have some inherent uncertainty, as they are based on generic models taking into account the fate of the substances and their exposure in different types of environments. In that sense, the Marine aquatic ecotoxicity characterisation factors are not considered as reliable by some LCA experts [Gernez, 2010a].

### 2.3.4 Life Cycle Impact assessment: not a risk assessment

The main limitation in using a LCA for assessing the environmental impact resulting from a process or system is that localised impacts cannot be addressed, for example identifying which impacts can be expected due to the functioning of a facility in a specific locality [Guinée et al., 2002a]. This is not however the scope of this study, which is to compare the impact resulting from different scenarios for transportation. The LCA method is used in this case as the framework for the comparison.

The notion of impact combines a hazard (for example the emission of a substance, reaching higher levels than background concentrations) and a vulnerability to this hazard (for instance how much of the substance can be absorbed and tolerated by an ecosystem) [Fattal, 2006]. In that sense, assessing an environmental impact means to assess a risk, which is the combination of a probability (the hazard) and its consequence (the vulnerability). Hence, assessing an impact with a LCA means to assess a potential impact, rather than a real risk.

Under this assumption, several processes influencing the impact severity are not considered in this study:

**Transport of substances:** as shown in Figure 2.1 the substances emitted in the atmosphere can be transported over long distances and redeposited on the ground as wet (for example acid rain) or dry deposition. When absorbed in the soil, they can percolate to watersheds and end up in the ocean.

Pollution deposition is measured in a few air quality monitoring stations in Iceland and expressed in concentrations of $NO_x$, $SO_x$ and NMVOCs per cubic metre at ground level, showing important seasonal variability [EEA, 2010]. Occurrence of pollutants in the marine environment is ultimately monitored under the OSPAR Commission [OSPAR Commission, 2005] and performed by the Icelandic food and biotech company Matís, looking at traces of POPs, PAHs and heavy metals in Icelandic seafood [Jörundsdóttir et al., 2010].

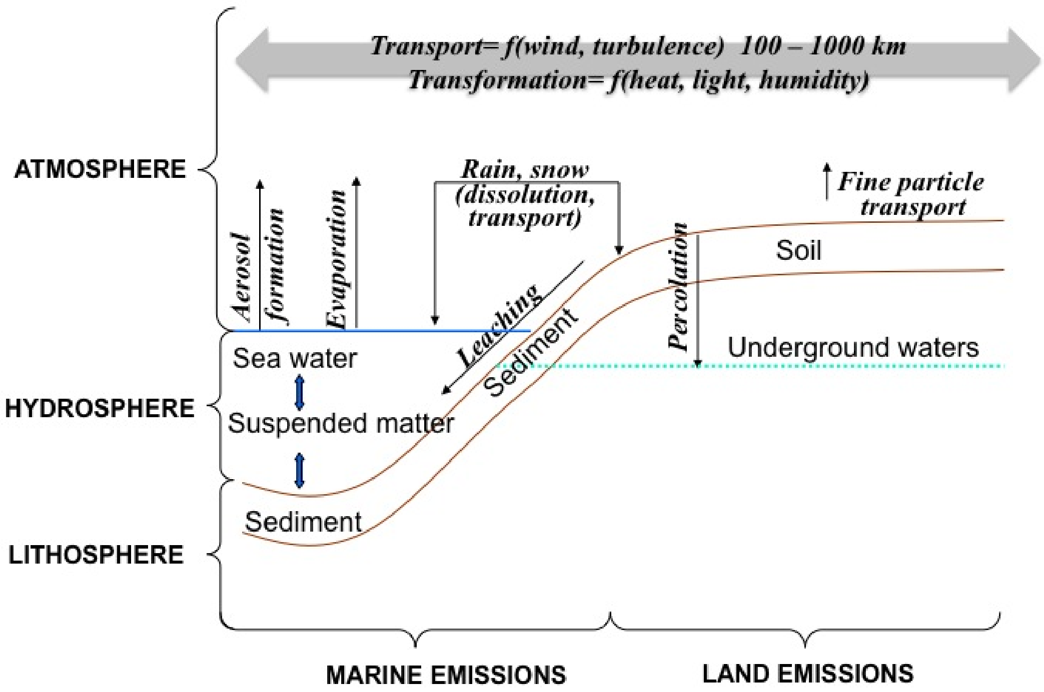



Figure 2.1: Transport of substances released in air, soil and water [Gernez, 2011b]

**Ecosystems vulnerability** depends on several factors. For example the type of habitat (habitats like fjords where the residence time of water is relatively long are under the influence of trapped substances for a long time); the season of the emission (if it happens during the reproduction season, or at an early evolution stage when a fish population for example is particularly weak and sensitive). The sensitivity of coastal ecosystems is especially true for Iceland where most of the road network and the population is along the shore.

Deletraz (2003) gives the example of two mountain ecosystems in France subject to $NO_2$ emissions from road transport, mapping the $NO_2$ deposition on the ground as well as the vulnerability of each ecosystem based on the type of soil and vegetation [Deletraz, 2003]. It is shown that the environmental risk is higher for the site with the lowest traffic and lowest $NO_2$ emissions but higher sensitivity.

Prinąud (2010) proposes a new method to calculate the impact of toxic substances emission on the marine aquatic environment [Prinçaud et al., 2010]. A list of possible toxic substances is created (containing approximately 180 elements) and given a toxicity potential (from 1 to 4). This substance toxicity potential is then weighted by the vulnerability of the type of coastal ecosystem where it is released, based on the Environmental Sensibility Index used for oil spills by the NOAA (National Oceanic and Atmospheric Administration). On this index, Coastal wetlands are the most sensitive areas, Gyre areas the least. The ship sailing profile gives the distribution of the vulnerability of water encountered during the ship operation. In order to be used for a comparison of road versus sea transportation, this approach should however be adapted as well to road transport. A sensitivity index of the ecosystems neighboring the road should be developed. In Iceland where most of the roads are very close to the shore (especially in the Westfjords region), the same Environmental Sensibility Index could almost be used for both road and sea transport!

## 2.4 Chapter conclusion

The main assumption of this chapter is to use a LCA method reduced to the operational phase of the vehicles to compare the impact of transport scenarios. The calculation procedure and background data are given for the inventory of substances emitted and the characterisation of their impact. Uncertainties of the approach is discussed and qualified, showing that the impact categories related to toxicity (to humans, terrestrial ecosystems, freshwater and sea water ecosystems) have to be analysed with special care.

The calculation process illustrated in Figure 2.2 is applied to a case study in the next chapter.

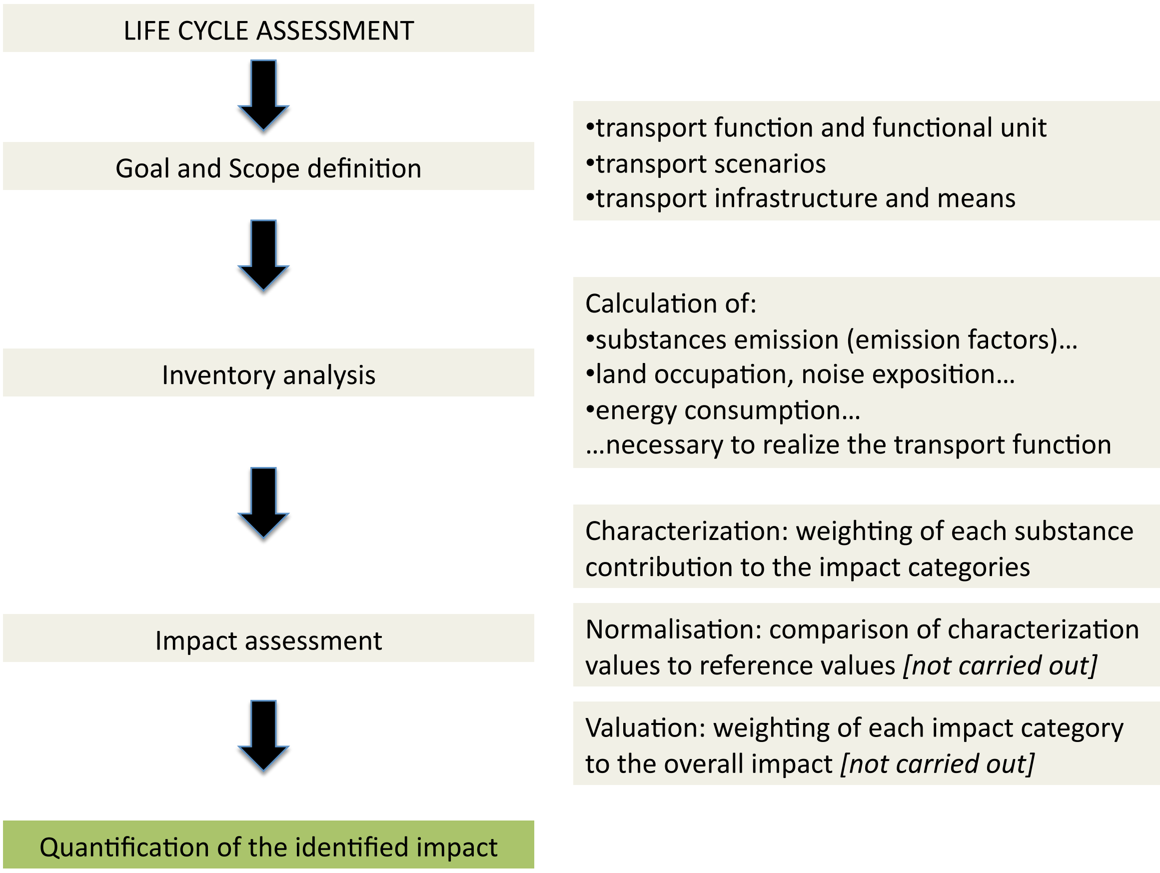



Figure 2.2: Summary of Chapter 2

# Chapter 3

# Comparative impact of transporting 1 tonne cargo from Reykjavík to Ísafjördur

## 3.1 Transport demand in the Westfjords and Northern regions

Ísafjördur is the main town (approximately 4000 inhabitants) of the Westfjords region (7400 inhab.), located in the North West of Iceland. Reykjavík (200 000 inhab. including the neighbouring areas) is the capital of Iceland (320 000 inhab.).

All international traffic to Iceland goes through either Keflavik airport (located some 50 km South West of Reykjavík) or the harbours of Reykjavík and Reydarfjördur on the East coast (and the Vestman Islands, located on the sailing routes to Europe). The connection between Reykjavík and Ísafjördur is essential to:

- provide the Westfjords with commodities (fresh products) and raw materials (wood, steel,etc.), as very few are produced locally
- export the important fish production from the Westfjords to the international market (mostly Europe and North America)

The situation is the same in the North of Iceland in the region around Akureyri (approx. 18000 inhab.). The Westfjords and the Northern regions are seen as the two only regions where maritime transport could be used as an alternative to land transport [Möller et al., 2010].

Figure 3.1 shows the demand for domestic transport between Reykjavík and the Westfjords region on one hand, and Reykjavík and the Northern region on the other hand, roughly estimated to a total of 180 000 tonne cargo per year between Reykjavík, Ísafjördur and Akureyri: 80 000 leaving Reykjavík to the Westfjords and Northern region, and 100 000 coming back to the capital region [Möller et al., 2010]. The traffic to the Westfjords is balanced (40 000 tonne each way), but not to the Northern region, with a surplus coming from Akureyri, to the capital.

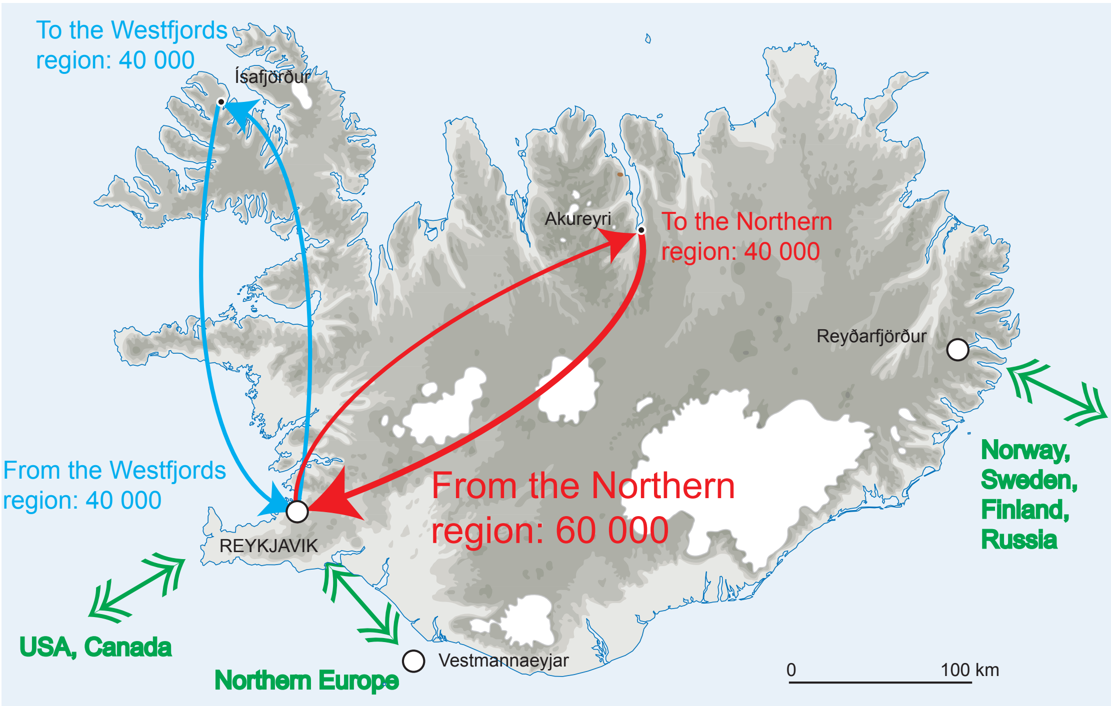



Figure 3.1: Transport demand in tonne cargo per year between the capital and the Westfjords and Northern regions.

## 3.2 Transport offer

### 3.2.1 Reference scenario

Since December 2004, cargo transport in Iceland is land-based only, using HDVs.

**Transport mean.** HDV composed of a tractor pulling a semi-trailer. The semi-trailer is assumed to be a forty feet container (12.20 m long), carrying a maximum load of 26 tonnes (ISO Norm 668). Including the tractor, the HDV is 18m and can weigh up to 40 tonne. The exploited capacity is assumed to be 22 tonne. Depending on the construction year of the tractor, it has to respect one of the EURO norms. The Euro IV norm (HDV built after 2005) is assumed by default. The speed is limited to 80km/h on asphalt roads for heavy vehicles (Umferdastofa - Road traffic directorate).

**Transport infrastructure.** Asphalt road between Reykjavík and Ísafjördur: 497 km. The first third is the Icelandic main road (Road 1) and the two last thirds consist in a smaller road (Road 61) snaking around 8 fjords.

### 3.2.2 Maritime alternatives

Two maritime alternatives using two types of ships are proposed by Möller et al (2010); the ship minimum capacity is estimated to be 1800 tonne [Möller et al., 2010].

**Lift on - Lift off cargo ship** with a 1800 tonne capacity. The ship is loaded with containers of twenty or forty feet long, with 1 Forty feet Equivalent Unit (1 FEU) = 2 Twenty Equivalent Units (2 TEU) = 20 tonne payload in average [Kristensen, 2010a]. The containers are lifted on (loading) and off (unloading) the ship with a crane, usually located on the ship itself, reducing the infrastructures needed at quay. Based on the ship capacity, it is assumed to sail at 14 knots [Kristensen, 2010a].

**Roll on - Roll off cargo ship** of 1800 tonne, no passengers. The cargo is rolled in (loading) and rolled out (unloading) the ship from the quay. The ship height relative to the quay is varying according to the tide, so that a special platform is needed to drive in and out the ship at any time of the day.The capacity of a Ro-Ro ship is usually expressed in lane meters. The quantity of cargo loaded per lane meter is the key parameter determining the ship transport efficiency. Based on an extensive study of a large fleet of Ro-Ro ships (more than 700), Kristensen (2010) estimates that 3.375 tonne cargo can be loaded per lane meter on a Ro-Ro, assuming that (i) the ship carrying capacity (also called "deadweight", including cargo, fuel, ballast water, crew, provisions) is 4.5 tonne per lane meter and that (ii) the cargo itself ("payload") represents 75% of the deadweight [Kristensen, 2010a]. With this assumption, the Ro-Ro ship examined in the present study has a 533 lane meter capacity and it sails at 14 knots [Kristensen, 2010a].

**Transport infrastructures** Lo-Lo and Ro-Ro ship terminals in the harbours where the ship is calling at.

Two sailing routes are proposed (Figure 3.2). A route sailing all around Iceland was operated until December 2004, with two container ships sailing in opposite direction, calling at many small harbours. The situation has changed since the development of the harbour of Reydarfjördur in the East. As explained in Section 3.1 the transport demand is now focused on the Westfjords and Northern regions:

**Direct Route** Penduling between Reykjavík and Ísafjördur, with one departure per week. In that case, no cargo can be delivered to Akureyri. The transport demand is then much lower, and the ship capacity is underused.

**Indirect Route** Reykjavi - Ísafjördur - Akureyri service with one departure per week from Reykjavík. Both demands for the Westfjords and Northern regions can be satisfied, and the ship is better exploited.

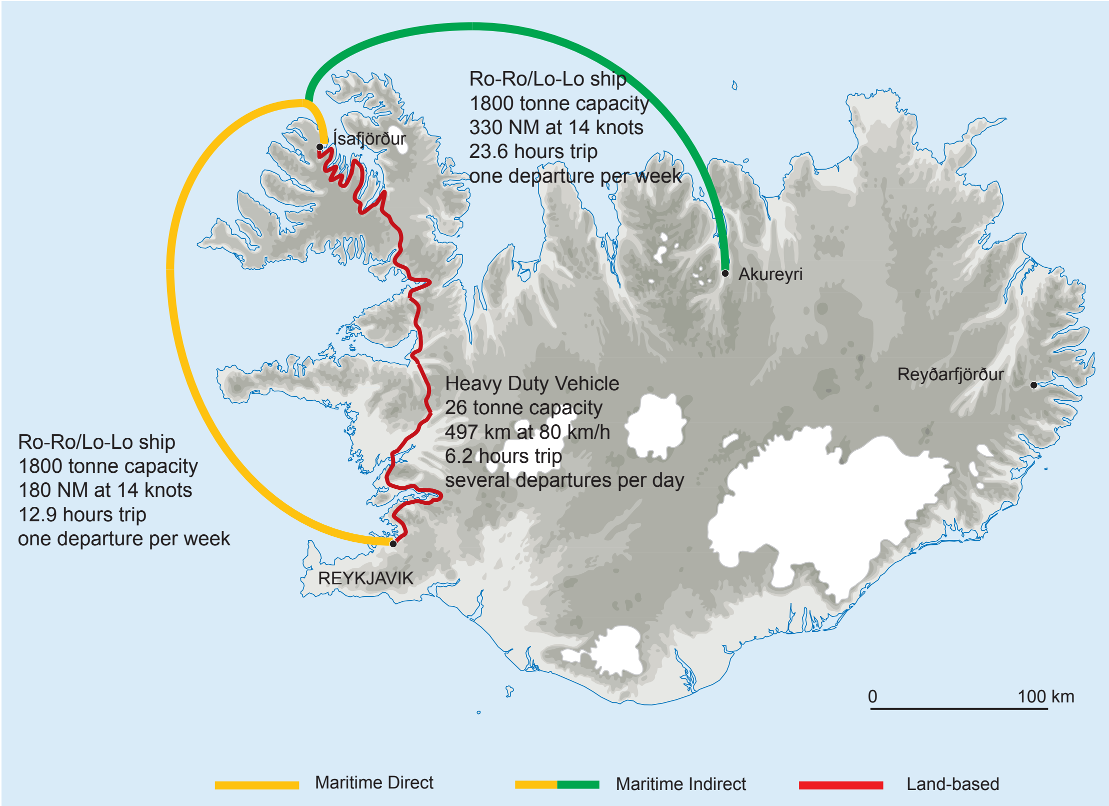



Figure 3.2: Transport offer: land-based and maritime alternatives.

Assuming that the transport service can be delivered 48 weeks per year (taking out holidays), and guaranteeing a steady demand for 80% of the estimated 180 000 tonne cargo, the yearly demand for transport is converted into weekly demand and distributed on the different routes (land-based and maritime alternatives) in Figure 3.3.

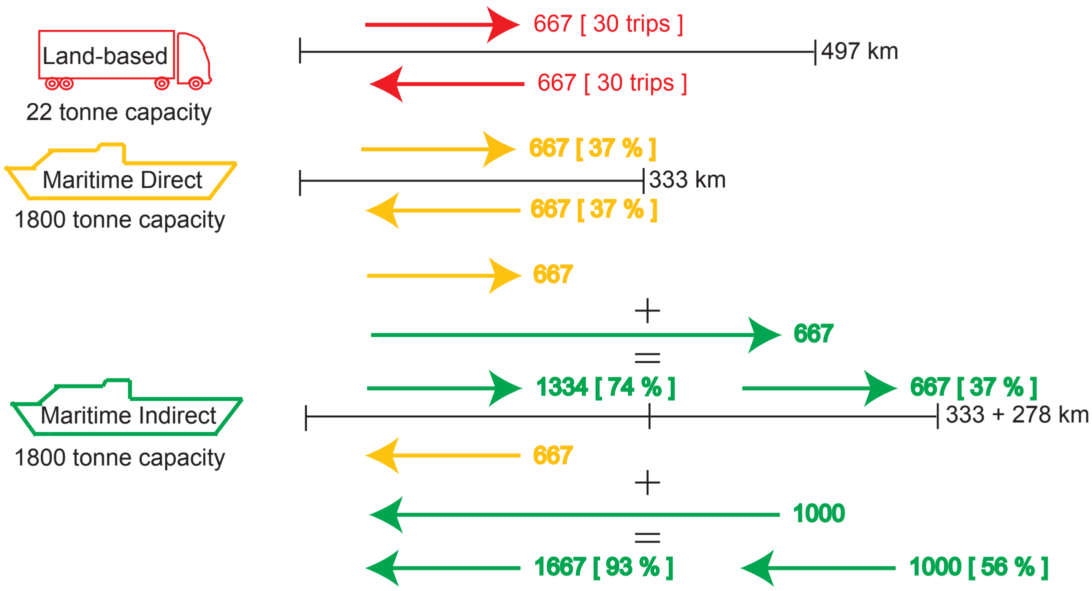



Figure 3.3: Exploited capacities for the different transport alternatives: in number of single trips for land-based transport, and % of ship capacity occupied for the maritime alternatives. Note that for the Indirect route, the transport demand for the Westfjords and Northern regions are adding up.

## 3.3 Calculation assumptions

### 3.3.1 Allocation

In order to satisfy the transport demand every day (for HDVs) and every week (for ships), each vehicle has to come back to its departure point once the delivery is made. The emissions released on the return trip have to be taken into account somehow. In terms of LCA, allocation rules for the return trip emissions have to be set. The allocation rules are based on the balance of the traffic and on the contribution of the vehicle to the function realisation: to transport 1 tonne cargo from Reykjavík to Ísafjördur.

**Land-based transport:** the traffic is balanced (same amount of cargo transported each way) and only Reykjavík and Ísafjördur are deserved. No extra distance is made to realise the function, so the return trip emissions are not accounted for.

**Maritime, Direct alternative:** same situation, no allocation of the return trip emissions.

**Maritime, Indirect alternative:** some of the cargo on the ship is not bound to Ísafjördur, and the ship is sailing all the way up to Akureyri before sailing back to Reykjavík, implying two allocations:

1. The emissions on the way Reykjavík to Ísafjördur are weighted by the volume of cargo bound to Ísafjördur over the total volume transported: $667/1334 = 0.5$ (see Figure 3.3).
2. On the way back, the return trip emissions are calculated by adding the emissions of the 3 segments Ísafjördur to Akureyri, Akureyri back to Ísafjördur and Ísafjördur back to Reykjavík. Again, these emissions are weighted by the volume of cargo bound from Ísafjördur to Reykjavík, over the total cargo transported on the 3 segments: $667/(667 + 1000 + 1667) = 0.20$.

### 3.3.2 Specific energy demand, speed and exploited capacity

For a given vehicle, the specific energy demand (SED) depends on the speed and the exploited capacity.

For ships, there is often a difference between the service speed and its actual sailing speed. The engine power P is proportional to the ship speed V to the third power, so the variation of engine power is proportional to the ship speed variation squared:

$$\text{if } P = \alpha V^3 \text{ then } \frac{\Delta P}{\Delta V} = \beta V^2$$

with $\alpha$ and $\beta$ proportionality coefficients. Allowing for a speed variation of [-10%;+10%], the SED should vary within [-1.10*1.10;1.10*1.10]=[-1.21;+1.21] i.e [-21%;+21%]. The same uncertainty interval is allowed for HDVs, assuming that the speed limitation of 80km/h is not always the actual speed.

When the vehicle is not fully loaded, the SED increases according to

$$SED_X = (100/X) * SED_{100} * C$$

with

- $SED_X$: Specific energy demand for a loading of X % [MJ/tonne cargo/km]
- $SED_{100}$: Specific energy demand at full load [ MJ/tonne cargo/km]
- $C$: correcting factor, as a ship not fully loaded will be higher on the water and offer less wetted surface, lowering its water resistance to forward movement. For a Ro-Ro ship, C is taken as 0.95 (5% resistance reduction), 0.9 for a Lo-Lo ship (10% reduction) and 1 for a HDV (no correction).

Figure 3.4 shows the SED at full load for the three vehicles examined in this study, and how it increases when the exploited capacity decreases.The Lo-Lo ship has the lowest SED (0.28 [MJ/tonne/km] at full load), followed by the Ro-Ro ship (0.33 [MJ/tonne/km]) and the HDV (0.69 [MJ/tonne/km]). The error bars represent the uncertainty due to variations in speed.

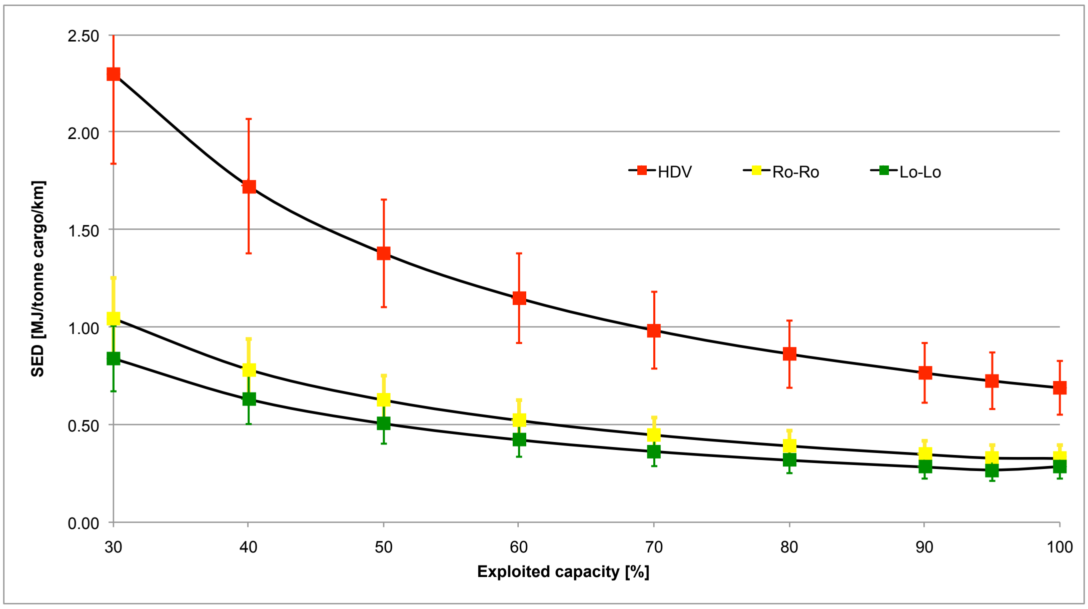



Figure 3.4: Specific energy demand of the HDV, Ro-Ro and Lo-Lo ships, as a function of the vehicle exploited capacity, and a [-10%;+10%] variation of speed.

The exploited capacity depends on the cargo dimensions and weight. The default exploited capacity of the HDV is assumed to be 85% (22 out of 26 tonne). For Lo-Los, cargo is loaded in containers, and the default weight per TEU is assumed to be 10 tonne. For Ro-Ro ships, the capacity is expressed in lane meters, and the exploited capacity depends on the loaded weight per lane meter. A default loading of 3.375 tonne/lane meter is assumed, and if the 533 lane meters of the Ro-Ro ship are loaded this way, the exploited capacity is 100%. However, if the Ro-Ro is loaded with complete HDVs of 15m long and 22 tonne payload, the loading becomes less than 1.5 tonne/lane meter, and the exploited capacity less than 50%, leading to a more than doubled SED. A better unit for the SED for Ro-Ro ships is the MJ/ lane meter/ km; the Ro-Ro used in this study have a SED of 1.10 MJ/ lane meter/km [Kristensen, 2010a].

From Figure 3.4, the minimum loading density for a Ro-Ro ship to stay competitive with a HDV in terms of energy efficiency is:

$$\frac{\text{Ro-Ro full load SED}}{\text{Minimum HDV SED}} = \frac{1.10\ \text{MJ/lane meter/km}}{0.55\ \text{MJ/ tonne/km}} = 2\ \text{tonne/lane meter}$$

On the other hand, if the Ro-Ro is loaded with at least 3.375 tonne/lane meter, it is almost as energy efficient as a Lo-Lo ship.

### 3.3.3 Land occupation and Noise exposition durations

Land occupation and Noise exposition depend on the trip duration for the HDV, that is, on the speed and distance. For the ships, they are based on the time spent at quay during cargo handling (loading and unloading), and the quay and ship dimensions.

For a Ro-Ro ship, full HDVs (tractor and semi-trailer) directly drive into the ship (with the disadvantage of occupying a large room) or only the trailer only is driven in (which takes a bit more time, but occupies less room). Cargo not brought on trucks can be loaded as well using dedicated rolling vehicles. The cargo handling rate is estimated at 500 tonne per hour [Gernez, 2011e].

For a Lo-Lo ship, the containers are lifted off the ship and laid on the quay, before being moved horizontally by a special lifter. The handling rate is much slower, estimated at 250 tonne per hour [Gernez, 2011e].

The handling time is also coming into the equation of the emissions to sea-water: the quantity of copper released by the antifouling paint on ship hulls is calculated based on the time the ship is spending in the harbours. It is assumed that this time corresponds to the handling time, i.e neglecting the time during which the ship stays idle (not sailing, nor being loaded or unloaded). The emissions of copper are then largely underestimated.

## 3.4 Results

Five scenarios are compared: the land-based reference, and the four maritime alternatives (two ship types and two sailing routes) in Figures 3.5 and 3.6.

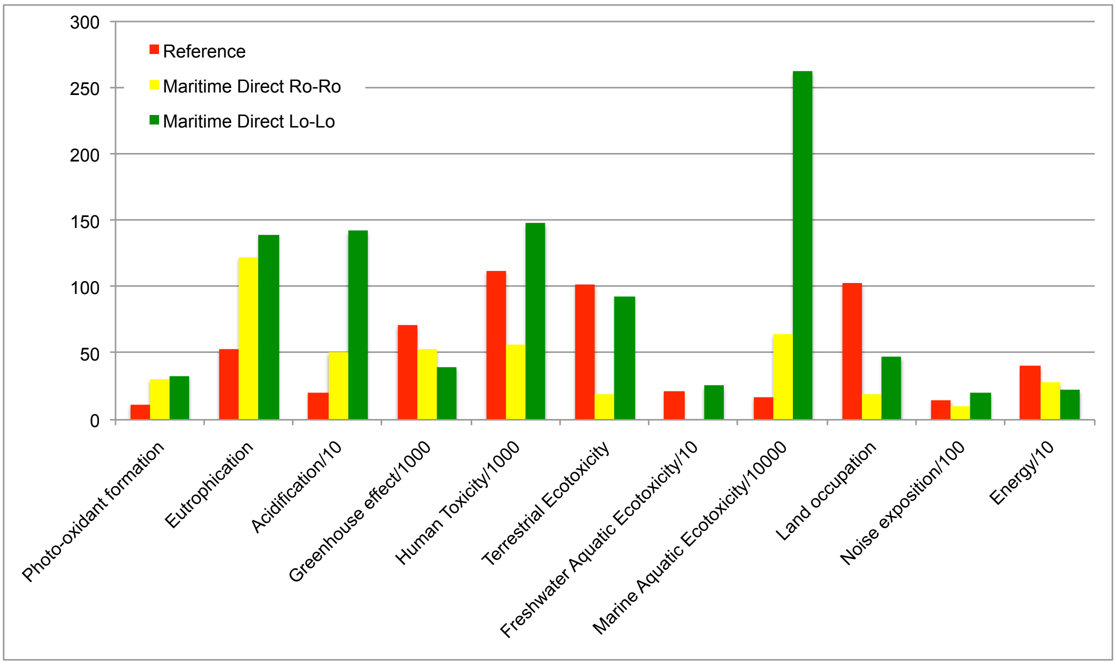



Figure 3.5: Environmental impact per impact category: Reference scenario, Maritime Direct (Ro-Ro and Lo-Lo). Note that the results for some impacts categories are scaled down. The environmental impacts are dimensionless. The values are used for relative comparison.

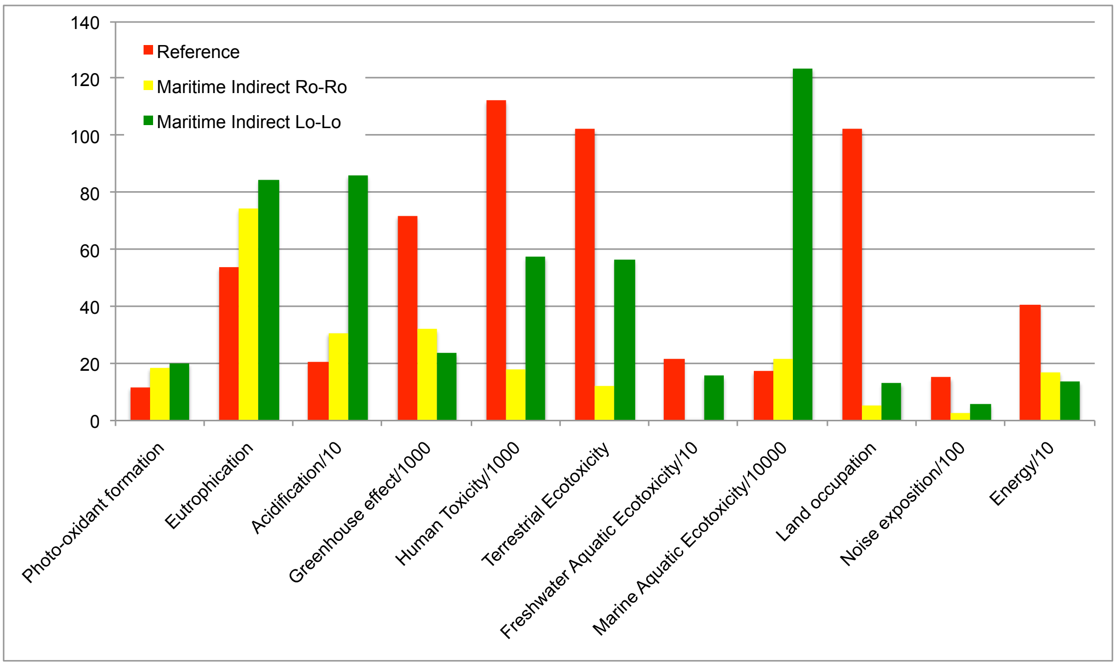



Figure 3.6: Environmental impact per impact category: Reference scenario, Maritime Indirect (Ro-Ro and Lo-Lo). Note that the results for some impacts categories are scaled down.

The alternative scenarios are then compared to the reference scenario by calculating a percentage impact difference for each impact category:

$$\Delta Alternative[\%] = \frac{Alternative - Reference}{Reference} * 100$$

For each impact cateogry, the sign of $\Delta$ tells if the impact of the alternative scenario is more important ($\Delta > 0$) or less important ($\Delta < 0$) than the reference.

Table 3.1: Environmental impact per impact category: Maritime Direct (Ro-Ro and Lo-Lo) and Indirect (Ro-Ro and Lo-Lo) alternatives compared to the reference scenario. The shaded cells highlight the alternative with the lowest environmental impact compared to the reference scenario.

| Impact category | Δ Direct Ro-Ro [%] | Δ Direct Lo-Lo [%] | Δ Indirect Ro-Ro [%] | Δ Indirect Lo-Lo [%] |
|---|---|---|---|---|
| Photo-oxidant formation | 159 | 183 | 57 | 72 |
| Eutrophication | 128 | 160 | 38 | 57 |
| Acidification | 145 | 584 | 49 | 315 |
| Greenhouse effect | -27 | -45 | -55 | -67 |
| Human Toxicity | -50 | 32 | -84 | -49 |
| Terrestrial Ecotoxicity | -81 | -9 | -88 | -45 |
| Freshwater Ecotoxicity | -92 | 18 | -95 | -28 |
| Marine Ecotoxicity | 271 | 1404 | 24 | 610 |
| Land occupation | -81 | -53 | -95 | -87 |
| Noise exposition | -32 | 37 | -81 | -62 |
| Energy | -30 | -44 | -58 | -66 |

Two conclusions can already be drawn from these results:

1. **If a maritime alternative is to be selected, it clearly should be the Maritime Indirect route, with a Ro-Ro ship.** (i) The Indirect route is longer but exploits better the ship capacity, by adding up the transport demand to the Westfjords and the Northern regions. (ii) The higher emissions of $NO_x$, $SO_x$ and PM of the Lo-Lo due to the high sulfur content of the Heavy Fuel Oil (HFO) have a direct impact on the Photo-oxidant formation, Eutrophication, and Acidification. In addition, burning HFO leads to higher PAH and metal emissions, which results in a higher impact in all toxicity categories. The only advantage of the Lo-Lo ship over a Ro-Ro is its fuel efficiency, as shown by the Greenhouse effect and Energy categories.

2. **However, when compared to the land-based reference scenario, the maritime alternative does not always have a lower impact**. Table 3.2 presents the emissions calculated over one year for the land-based transport scenario, for the maritime indirect alternative with a Ro-Ro ship, and the difference between the two scenarios.

   **Photo-oxidant formation, Eutrophication and Acidification** are increased, because of the stricter emission standards of road vehicles compared to ships: the HDVs have been subjected to the EURO norms since 1991, reducing several times the maximum allowed levels of $NO_x$, $SO_2$ and PM. The ships will be subjected to $NO_x$ limitations in the next 10 years, but not in Icelandic territorial waters, as Iceland has not ratified Annex VI of the Marpol Convention [IMO, 1978]. This issue is discussed further in sections 3.4.1 and 3.4.2.

   **Greenhouse effect and Energy impacts are reduced** because of the superior energy efficiency of ships: more cargo per trip, which means less fuel consumed per cargo transported.

   **Human Toxicity, Terrestrial and Freshwater Ecotoxicity impacts are reduced** because of higher metal emission of the land-based scenario, both from exhaust fumes and abrasion of the road, as well as brake pads. The emitted quantities are quite small as shown on Table 3.2 and there are some uncertainties attached to the emission calculation and the characterisation of the toxic substances (see sections 2.3.2 and 2.3.3).

   **Marine Ecotoxicity impacts are increased** because of the release of copper from ship antifouling paints. As mentioned in Section 3.3.3, the copper emissions are underestimated, so that the Marine Ecotoxicity impact increase could be even higher than calculated.

   **Land occupation and Noise exposition impacts are reduced** because of the important quantity of cargo moved in one trip by the ships, but for a single trip, the land occupation and the noise exposition are more important for the ships than for a HDV.

Table 3.2: Balance of yearly emissions when shifting all the cargo to the Westfjords and Northern regions from land-based transport to the maritime indirect alternative on a Ro-Ro ship.

| | Land-based | Maritime alternative | Maritime alternative MINUS Land-based | |
|---|---|---|---|---|
| | | *Emission to air* | | |
| $NO_2$ | 65 | 110 | 45 | tonne |
| NMVOC | 0 | 4 | 4 | tonne |
| CO | 2 | 14 | 12 | tonne |
| $NH_3$ | 49 | 42 | -7 | kg |
| $SO_2$ | 0 | 4 | 4 | tonne |
| $CO_2$ | 11259 | 6126 | -5133 | tonne |
| $CH_4$ | 1352 | 577 | -775 | kg |
| $N_2O$ | 203 | 165 | -38 | kg |
| PAH | 27 | 1 | -26 | kg |
| Cd | 151 | 19 | -132 | g |
| Cr | 1 | 0 | -1 | kg |
| Cu | 8 | 2 | -6 | kg |
| Pb | 691 | 251 | -440 | g |
| Zn | 119 | 2 | -117 | kg |
| $PM_{10}$ | 1452 | 2120 | 668 | kg |
| | | *Emission to soil* | | |
| Cd | 1158 | 0 | -1158 | g |
| Cr | 1 | 0 | -1 | kg |
| Cu | 2 | 0 | -2 | kg |
| Ni | 1 | 0 | -1 | kg |
| Pb | 1 | 0 | -1 | kg |
| Zn | 116 | 0 | -116 | kg |
| | | *Emission to fresh* and marine water*** | | |
| Cd* | 116 | 0 | -116 | g |
| Cr* | 1 | 0 | -1 | kg |
| Cu* | 2 | 0 | -2 | kg |
| Cu** | 0 | 20 | 20 | kg |
| Ni* | 1 | 0 | -1 | kg |
| Pb* | 579 | 0 | -579 | g |
| Zn* | 116 | 0 | -116 | kg |

### 3.4.1 Sensitivity to HDV fleet composition

As explained in Section 2.2.2, the exhaust emissions in $NO_x$, $SO_2$ and PM for HDVs are regulated by air quality norms: Euro I for vehicles built after 1991, Euro IV after 2005 and Euro V after 2008. A discussion is currently underway concerning the Euro VI emission standards, to be introduced in 2014. The European Commission proposal calls for 50 % reduction in PM and a further 80 % reduction in $NO_x$ over Euro V. This would necessitate the use of diesel particle filters, engine tuning, and $NO_x$ exhaust after-treatment to meet the regulations [EMEP/EEA, 2009].

The composition of the HDV fleet used for land transport will have an influence on the environmental performance of the land-based scenario.Three scenarios are compared:

**Reference scenario:** the whole HDV fleet is composed of Euro IV vehicles.

**Mixed scenario:** the fleet is composed of 25% Euro I, 50% Euro IV and 25% Euro V vehicles. It is probably a more realistic scenario than the Reference scenario.

**Future scenario:** the fleet is composed of 25% Euro IV, 25% Euro V and 50% Euro VI vehicles.

The impacts in Photo-oxidant formation, Eutrophication and Acidification are presented in Table 3.3. The Mixed fleet scenario shows an increase in the three impact categories, however not as much as the levels of a the Ro-Ro, Maritime Indirect scenario (see Table 3.1). The future scenario shows an important decrease.

Table 3.3: Sensitivity to HDV fleet composition

| Impact category | Reference | Mixed | Future | Δ Mixed | Δ Future |
|---|---|---|---|---|---|
| Photo-ox. form. | 12 | 15 | 5 | 25 | -54 |
| Eutrophication | 54 | 61 | 25 | 13 | -54 |
| Acidification | 208 | 238 | 94 | 15 | -55 |

### 3.4.2 Sensitivity to international regulations on shipping emissions of $NO_x$ and $SO_2$

The marine emissions of $NO_x$ and $SO_2$ are regulated internationally by the International Maritime Organization (IMO) and regionally in Special Emission Control Areas (SECAs). Three SECAs regulated by the Annex VI of Marpol Convention exist already in the North Sea and the Baltic Sea, as well as in North America, including most of US and Canadian coasts [IMO, 1978]. Europe is discussing the adoption of a SECA on its territorial waters [Gernez, 2010b]. In that case, Iceland could be obliged to enter this SECA[1].

Two scenarios are compared to the land-based reference scenario. Both use a Ro-Ro ship on the Maritime Indirect route. The emission regulations differ for each type of fuel and engine; in that case it will only lead to a reduction in $NO_x$.

**Maritime 2010:** with the current regulation.

**Ratification of Marpol VI:** with a reduction of 20% of the $NO_x$ emission levels compared to 2010.

**Ratification of Marpol VI and inclusion of Iceland in a SECA:** with a $NO_x$ reduction of 80 % compared to 2010.

The impacts in Photo-oxidant formation, Eutrophication and Acidification are presented in Table 3.4. Compared to Table 3.3 it shows that the ratification of Marpol Convention Annex VI would lead to an impact similar to the mixed HDV fleet scenario. In addition, the ratification of Marpol VI combined with the creation of a SECA in Iceland would lead to an impact comparable with the future land-based scenario.

[1] A prior condition would however be the ratification of the Annex VI of Marpol Convention, still not ratified by Iceland, and the signature of a EEA joint agreement between Iceland and Europe on the limits of the potential European SECA.

Table 3.4: Sensitivity to international shipping regulation.

| Impact category | Reference | Marpol VI | Marpol VI +SECA | $\Delta$(Marpol VI) | $\Delta$(Marpol VI +SECA) |
|---|---|---|---|---|---|
| Photo-ox. form. | 12 | 15 | 6 | 30 | -51 |
| Eutrophication | 54 | 60 | 15 | 11 | -72 |
| Acidification | 208 | 252 | 81 | 21 | -61 |

In conclusion, the $NO_x$ emissions of ships needs to be reduced by at least 20% to be competitive with the land-based reference scenario in the Photo oxidant formation, Eutrophication and Acidification impact categories. Operational and technological solutions are available to achieve such an objective [Eyring et al., 2005].

## 3.5 Discussion: which scenario has the lowest environmental impact?

Switching to a maritime transport scenario is improving the environmental impact of cargo transport in 7 out of 11 impact categories. Is it possible to conclude that maritime transport has a lower environmental impact than land-based transport? In an attempt to answer this question, we discuss below:

**The comparison unit:** Does the transport unit used in this report reflect well the specificities of each transport scenario?

**The subjective nature of impacts:** Every impact represents a different threat and concern to the whole society. What are the concerns of the Icelandic society e.g, in regard to ocean acidification? to the greenhouse effect? Is one side-effect more important than the other?

**The construction of a single environmental performance index:** How to build a single indicator to rank the environmental impacts of different scenarios? Is that a good idea?

### 3.5.1 Transport comparison unit

The unit commonly used for comparing two transport services is the tonne*kilometer. It assumes the equivalency of two transport services as long as the same weight of cargo is carried on the same distance [Prud'homme et al., 1999].

From one transportation mode to another, the distance travelled can differ and result in a significantly different environmental performance [Fet et al., 2001]. In this study, only the weight equivalency is assumed: all the impacts are calculated for 1 tonne cargo transported from Reykjavík to Ísafjördur independently of the route taken and the travelled distance.

A transport service is not sold for the sake of moving cargo from a point A to a point B. Transport is always a part of a supply chain. Different transport services are needed for different types of cargo: for example temperature sensitive cargo needs to be refrigerated. Other important parameters are the delivery speed (80 km/h for HDVs, 30km/h for Ro-Ro and Lo-Lo ships), frequency (several departures per day, 1 per week), breaks of load (number of loading/unloading operations needed to transport the cargo from door to door). One way to solve this problem is to use additional indicators to compare different transport scenarios. For example, Iqbal (2001) suggests to add a "Customer service" index based on the time needed to deliver the cargo to the customer [Iqbal and Hasegawa, 2001].

What happens "before" the transport of cargo in Iceland (importation through a harbour or local production) and "after" (exportation or local consumption) is not part of the scope of this study. In terms of environmental impact, all imported cargo have the same initial infrastructure impact (coming in Reykjavík or Reydarfjördur harbour), regardless of the way they are transported later on. For exported cargo, the way they are transported away from Iceland will influence strongly their environmental impact, or "footprint". In order to take these aspects into account, the scope needs to be changed to the LCA of a product in its complete supply chain, including several phases of transport.

### 3.5.2 Local and global impacts

How can a citizen be more concerned by one type of environmental impact rather than another? It is a complex problem with many factors involved. The importance of the spatial and temporal scales of each impact category is discussed below.

**Photo-oxidant formation, Human toxicity** are indicators of local, short-term air quality. In addition to Noise exposition, this is a concern for urban areas, where highest emission levels are measured [EEA, 2010]. The vast majority of people living in the capital region (200 000 inhab.) and the Westfjords are located in urban centres, so this should be an important concern. However these urban areas are not densely populated, and urbanisation is not a major threat in Iceland. The public interest to these impacts changes a lot with time, for example with the daily news: in February 2011 the focus is on cow milk contaminated with dioxins released by waste incinerators [Iceland Review Online, 2011].

**Eutrophication, Acidification, Terrestrial and Freshwater Ecotoxicity** are indicators of regional, mid-term ecosystem health. The impact on crops, animal breeding, and freshwater resources should be a concern for the people depending on such resources for their income, and for the people consuming these resources. This adds up to a large number of people - even if Icelandic products are not the only one available on the market.

**Marine ecotoxicity** is an indicator of regional, long-term marine ecosystem health, together with all the previous impact categories. The Icelandic proverb "Hafid tekur endalaust vid" (approximate translation: "The Ocean can receive infinitely") would suggest that the release of toxic susbtances to the sea is not a major concern in Iceland.

**Land occupation** is an indicator of local, long-term nature artificialisation. The construction of important energy infrastructures has started passionate debates in Iceland; on one side there is the concern to preserve Iceland's pristine nature, and on the other the need to develop its industry [Magnason, 2006]. Such nationwide debate has not been held during the construction of roads and harbours, but the question still holds.

**Greenhouse effect** is an indicator of long-term, global climate change. The Kyoto protocol has been ratified by Iceland in 2005, allowing a 10% increase of the GHG emissions from the 1990 levels. Due to the scale of the country and the development of energy-intensive industry, this goal can be very quickly reached: a single aluminum plant can add more than 15% to the country's total greenhouse gas emissions [Ministry for the Environment in Iceland, 2006]. Together, the Fishery and Transport sectors contribute to half of the GHG emissions, so that there is a real interest in reducing the emissions from domestic cargo transport.

**Energy** is an indicator of dependency to imported fossil fuels. One ambition of the Icelandic government is to phase out fossil fuels and switch to other energy sources like electricity, hydrogen, methane gas, synthetic and bio fuels[Júlíusdóttir, 2010]. Technological breakthroughs are needed to go beyond a simple reduction in fossil fuel consumption.

A non exhaustive list of international conventions is presented in Table 3.5 as an attempt to illustrate the priorities of the Icelandic environmental policies. While the protection of endangered species and sensitive ecosystems is covered by a number of legal instruments (e.g CITES, Ramsar, Bern, OSPAR Conventions), there is a patent lack of legislation regarding air pollution of $NO_x$ and $SO_x$ (dedicated CLRTAP Protocols and Marpol Annex VI). According to a representative of the Environmental Agency in Iceland, the greenhouse effect and persistent organic pollutants are "the highest priority. [...] Iceland is not concerned with general eutrophication of the ocean around the island. Acidification from $SO_x$ and $NO_x$ is not regarded as a problem [...] The ocean acidification that is of concern is in relation to increase of $CO_2$ in the atmosphere leading to increased absorption by the ocean resulting lower pH." [Gernez, 2011d].

Table 3.5: Legal instruments in place in Iceland [Cauhépé, 2006] and non ratified international Conventions on environmental protection, as of February 2011.

| **Legal instrument** | **In force in Iceland?** |
|---|---|
| Stockholm Convention on POPs | since 2004 |
| Protocol to the Regional UNECE Convention on Long Range Transboundary Air Pollution (CLRTAP) on POPs | since 2003 |
| CLRTAP Protocol for the European Monitoring and Evaluation Programme (EMEP) (1984) | Not ratified |
| CLRTAP Sulfur Protocol (1985) | Not ratified |
| CLRTAP $NO_x$ Protocol (1988) | Not ratified |
| CLRTAP VOC Protocol (1991) | Not ratified |
| CLRTAP Further reduction in Sulfur Protocol (1994) | Not ratified |
| CLRTAP Heavy metals Protocol (1998) | Signed on 24/06/1998 |
| CLRTAP Multi effect Protocol: Acidification, Eutrophication and Ground level Ozone (1999) | Not ratified |
| Marpol Convention Annex VI: Air pollution from ships | Not ratified |
| UN Framework Convention on Climate Change & Kyoto Protocol | since 2005 |
| UN Convention on Biological Diversity | since 1994 |
| UN Convention on the Law of the Sea | since 1983 |
| Convention for the Protection of the Marine Environment of the North East Atlantic (OSPAR) | since 1998 |
| UN Agreement on Straddling Fish Stocks and Highly Migratory Fish Stocks | since 1995 |
| UN Convention to Combat Desertification | since 1997 |
| Convention on International Trade in Endangered Species (CITES) | since 2000 |
| Ramsar Convention on Wetlands | since 1978 |
| Bern Convention on the Conservation of European Wildlife and Natural Habitats | since 1982 |

### 3.5.3 Toward a single environmental performance index?

Calculating a single environmental performance index means to weight the concerns of the Icelandic society for each of the impact categories:

$$Single\ Environmental\ index = \Sigma\ Impact\ Category\ Score * Category\ Weighing$$

In terms of LCA, it corresponds to the Valuation phase, presented in Section 2.1.

The weighing can be for example based on opinion surveys treated with the Analytic Hierarchy Survey (AHS) method, where people are asked to compare the different impact categories two by two, judging wich one is absolutely/very strongly/strongly/ weakly dominant over the other (or wether both affect the environment equally) [Iqbal and Hasegawa, 2001]. The survey is representative of the nation opinion only if a large number of people, from different socio-professional categories are interrogated.

Inspired by Deletraz (2003) and Prinçaud (2010), the weighing could be based on the sensitivity of the exposed ecosystems [Deletraz, 2003, Prinçaud et al., 2010]. The weighing can also be a reflection of national policy. Fet et al (2000) shows the result of single index calculations according to OECD emission reduction targets: the larger the reduction target, the more concern, hence the more weight given to the corresponding substance or impact category. After reviewing six different weighing techniques, Prof A.M. Fet highlights the subjectivity of such an approach and the lack of standard method for weighing factors calculation in the LCA framework [Fet et al., 2000, ISO, 2000]. In next chapter, a method to overcome the subjectivity of the Valuation phase is presented. It is based on the monetisation of the different environmental side effects. This approach is recommended by Prof A.M. Fet [Fet et al., 2000, ISO, 2000]. This approach is presented in the form of a discussion, because of the uncertainties and possible bias lying in the monetisation methods used.

# Chapter 4

# Discussion: The economic perspective

This chapter presents a method to weight the different impact categories into a single environmental performance index. The results obtained for each impact category are commented and discussed individually. The aim of this chapter is to tentatively answer the following: How do the environmental impacts translate into economical costs and benefits? Who pays for the costs and who gets the benefits back? The references used for this chapter are mainly international literature reviews carried out for government agencies.

From a broad perspective, the costs of shifting cargo from land-based to maritime transport alternative have two components:

**Private costs:** the costs paid by the users of the transport service. They are set by the transport service provider based on the spending (costs) and earnings (revenue).

**External costs:** the combination of all the costs to the society, not paid by the transport service provider nor the transport user. These are e.g the costs of pollution, congestion, accidents, health, supported by the whole society in Iceland, as a result of the transport activity.

The sum of the private and external costs is called the social costs. First the private costs are examined, and then the external costs.

## 4.1 Private costs

In this section the point of view of an independent transport service provider is assumed, operating a Ro-Ro ship on the line Reykjavík - Ísafjördur - Akureyri. The costs of running the Ro-Ro ship are calculated and a break-even freight rate is derived, for which the revenues are matching the costs. The break-even freight rate of running a ship is compared to the rates offered by the existing main transport operator in Iceland.

An emphasis is put on the term "independent" transport service provider. Until December 2004 the same company was running a coastal ship all around Iceland for maritime freight, while offering land-based transport services as well. In that case the competition between the land-based and maritime transport alternatives is internal to the transport company. The revenue lost by shifting some cargo from trucks to ships can be recovered with the ship earnings if the freight rates are competitive, and vice versa.

### 4.1.1 The costs of running a ship

Möller et al (2010) estimates the total running costs for a Lo-Lo ship operating on the Maritime Indirect scenario [Möller et al., 2010]. It is assumed that the costs of manning, insurance and maintenance are the same for a Ro-Ro ship of a similar size. All the values from the Möller report are checked against the maritime economics reference book by Stopford (2009) and updated with a 5% inflation rate from 2010 to 2011 before being used [Stopford, 2009, Fedec and Sousa, 2011]. The cost of fuel are recalculated based on the Ro-Ro fuel consumption. An exchange rate of 116.12 ISK-USD is used [XE, 2011].

1. Capital costs: assuming that the Ro-Ro ship is rented in a bare boat charter contract, the ship owner finances the vessel and rents it to an operator who pays for the running costs. Therefore there are no capital costs for the ship operator. In the case that the ship operator owns the boat as well, the capital cost could account for up to 40% of the running costs in the form of interests and capital payment on debt.

2. Operating costs: fixed costs including the ship hire costs according to the charter terms, as well as maintenance, manning, stores, insurance and general costs. Charter rates are volatile on the market, a value of 5000$/day for a 1800 tonne capacity Ro-Ro is assumed [Gernez, 2011a]. In comparison, Möller et al (2010) assumes a 9000 $/day bare boat charter rate for a 230 TEU Lo-Lo [Möller et al., 2010]. For maintenance, manning and insurance, the value from Möller et al (2010) is used.

3. Voyage costs: variable costs such as fuel costs and port charges. 1 tonne MDO costs 877$ [Bunkerworld, 2011], port charges are assumed to represent 36% of fuel costs[Stopford, 2009]. Fuel consumption is calculated based on the quantity of transport needed to satisfy the demand in the Maritime indirect scenario, as shown in Figure 3.3 in previous chapter.

4. Cargo-handling costs: variable costs, depending on the amount of cargo loaded and unloaded. According to Möller et al (2010) and Stopford (2009) a cost of 3$ per tonne exchanged is used [Möller et al., 2010, Stopford, 2009].

Table 4.1: Total costs for the ship manager in thousand ISK per year for the Maritime Indirect scenario, using a Ro-Ro ship.

| Item | Sub item | Value | Source |
|---|---:|---:|---|
| Operating costs | Ship hire | 211919 | [Gernez, 2011a] |
| | Maintenance | 38325 | [Möller et al., 2010] |
| | Manning | 84000 | [Möller et al., 2010] |
| | Insurance | 19178 | [Möller et al., 2010] |
| | General costs | 26250 | [Möller et al., 2010] |
| Voyage costs | Fuel | 245236 | |
| | Port charges | 88285 | [Stopford, 2009] |
| | Cargo-handling | 97541 | [Möller et al., 2010] |
| Total running costs | | 810733 | for 180 000 tonne sold |

### 4.1.2 Break-even freight rate

The revenue of operating the ship is the quantity of transport sold times the price of transport. The price for which the total revenue equals the total costs is the break-even freight rate (BEFR). Table 4.2 presents the BEFR calculation in the case of the Ro-Ro ship on the line Reykjavík-Ísafjördur-Akureyri. It is compared to the calculation for a Lo-Lo on the same line, and the HDV freight rates presented by Möller et al (2010) with a 5% inflation rate and assuming that 1 FEU = 20 tonne [Möller et al., 2010].

Table 4.2: Running cost and break-even freight rate for a Ro-Ro ship, a Lo-Lo ship and a HDV on the routes Reykjavík to Ísafjördur and Reykjavík to Akureyri.

| | | |
|---|---|---|
| Ro-Ro Total running costs | 810733 | [1000 ISK per year] |
| Quantity of transport sold | 180 000 | [tonne per year] |
| BEFR per tonne for a Ro-Ro | 4500 | [ISK per tonne] |
| BEFR per tonne for a Lo-Lo | 7300 | [ISK per tonne] |
| HDV freight rate Reykjavík-Ísafjördur | 12600 | [ISK per tonne] |
| HDV freight rate Reykjavík-Akureyri | 9450 | [ISK per tonne] |

This table shows that with the calculation assumptions used in this study, the BEFR for a Ro-Ro or a Lo-Lo ship are well under the HDV freight rates, which include an operating margin. The difference in the Ro-Ro and Lo-Lo BEFR comes from the difference in fuel consumption, bare boat charter rates and port dues calculation assumptions between this study and Möller's. Still, the calculated values do not take into account the capital costs (debt, interests). A Net Present Value (NPV) calculation is needed to have the complete picture. Finally, the BEFRs are calculated over the total demand for transport, and do not reflect the difference in distances between the two destinations of Ísafjördur and Akureyri.

### 4.1.3 Benefits of GHG emission savings

One of the reasons commonly put forward to justify a shift of land-based transport into maritime transport are the savings of GHG emissions [Prud'homme et al., 1999]. A market has been created in the European union to exchange these emissions. What is the benefit of selling the abated $CO_2$ for the transport operator? Does it have any effect on the BEFR?

The total GHG emissions of transporting 180 000 tonne cargo with a Ro-Ro ship on the Maritime Indirect route are calculated based on the results from Chapter 3 (Table 3.2). The calculation is also made using a HDV driving on the roads Reykjavík-Ísafjördur and Reykjavík-Akureyri. A price of 4000 ISK per tonne abated is assumed [Prud'homme et al., 1999]. The results are presented in Table 4.3.

Table 4.3: Effect of GHG emission savings on the BEFR

| | | |
|---|---|---|
| Total GHG: Ro-Ro, Maritime Indirect | 6190 | [tonne $CO_2$ eq] |
| Total GHG: HDV, Land-based | 11353 | [tonne $CO_2$ eq] |
| Total GHG savings | 5163 | [tonne $CO_2$ eq] |
| Price per $CO_2$ tonne | 4000 | [ISK per tonne $CO_2$ eq] |
| Total GHG saving benefit | 20384 | [1000 ISK] |
| BEFR without GHG saving | 4500 | [ISK per tonne] |
| BEFR with GHG saving | 4390 | [ISK per tonne] |

### 4.1.4 Summary of private costs dicussion

When looking at the break-even freight rates, the modal shift from land to sea transport appears as a benefit for the transport operator, who can lower its running costs. The transport user can also expect the transport operator to lower his rate and save some money as well.

However, this not what happened historically: the transport operator has shut down its maritime transport operation in 2004 in order to save on the running costs, and has argued since then that operating a ship would be too expensive[Granholm, 2011]. This is purely economic cost and benefit. The emission savings of 5000 tonne GHG do not translate into siginificant economic benefits for the transport operator. What about the other substances emissions? This is investigated in the next sections.

## 4.2 External costs

The external costs are all the costs not paid by the private user, left for someone to pay anyhow. How much should be paid to compensate the effects of e.g ocean acidification from the emissions of transport? Who should pay? To whom?

The challenge is to estimate these costs and to redistribute them. The estimation phase uses mainly 3 pricing methods:

**Damage cost:** how much does it cost to repair the damages due to an environmental impact, once the damage is done?

**Abatement cost:** how much does it cost to avoid the damages of an impact, before the damage is done?

**Protection cost:** how much would someone be ready to pay not to be subjected to an environmental impact?

Once a value is calculated, the external cost can be redistributed to:

**the private user:** following the principle that the polluter pays. In that case, the external costs are "internalised".

**the society:** the most frequent case, in the form of taxes, which are used to pay for medical care, road maintenance, harbour construction, etc.

Another important distinction exists between the marginal costs (cost for one additional unit of pollution) and the average costs (total cost divided by the number of pollution units): external costs for one extra vehicle in the fleet (marginal cost), or for the fleet as a whole, divided by the number of vehicles (average cost).

The next sections are presenting a few examples of pricing methods applied to the external costs of transport, based on an international review prepared for the French Ministry of Transportation [Grangeon et al., 2010]. Note that the calculations should be considered with care and are meant to be illustrative, because of important differences in context (France, United Kingdom, Switzerland have different population density and infrastructures than Iceland) and method disparity (damage, abatement and protection; marginal and average) and transport modes (see the discussion on unit in section ). Icelandic readers are referred to a detailed analysis of external cost for transport in Iceland by Herbertsson (2005) [Tryggvi Þór Herbertsson, 2005].

For each impact category, the external cost of land-based transport is compared to the maritime alternative. The difference in cost is calculated as:

$$\Delta = \text{External cost of Maritime alternative} - \text{External cost of Land-based reference}$$

Then if $\Delta > 0$ the Maritime alternative is more costly for the society, otherwise $\Delta < 0$ and the Maritime alternative is beneficiary the society.

### 4.2.1 Pricing of air pollution externalities

Air pollution refers here to the emissions of $NO_x$, $SO_2$ and $PM_{10}$. The method used is the Impact Pathway Approach [Watkiss et al., 2006]. The general principle is to follow the emission of a substance from its source to its final destination, assuming that its impact can be be expressed as:

$$\text{impact} = \text{pollution} * \text{stock at risk} * \text{response function}$$

where:

**pollution** is the initial emission of a substance, calculated by a bottom-up approach: the single vehicle emissions (marginal emission calculation) are added up to get the emissions from the whole transport sector.

**stock at risk** represents the population, crops or buildings exposed to the pollution.

**response function** expresses how the exposed stock will react to the pollution. When a population is exposed to a substance, epidemiological studies are carried out to calculate a dose/response for this substance in order to calculate the physical impact on humans.

This conception of impacts is similar to the definition presented in Chapter 2: impact = hazard * vulnerability; with hazard=pollution and vulnerability=stock at risk*response function. Once the impact is calculated, the economic damage is calculated as a marginal, damage cost:

$$\text{economic damage} = \text{impact} * \text{unit value of impact}$$

where the unit value of impact is calculated differently depending on the type of impact:

**impact on human health:** cost of Respiratory and Cardiovascular hospital admissions, cost of medicine.

**impact on crops:** yield loss * crop market price for a wide variety of crops[1].

**impact on buildings:** repairing costs of acidic deposition and corrosion of building materials; cleaning costs of dirt deposition.

Table 4.4: External costs of air pollution: marginal damage cost [Watkiss et al., 2006]. Emission calculation based on Table 3.2.

| | Cost per tonne [ISK] | | | Δ Emission | Δ External cost [ISK 2011] | | |
|---|---|---|---|---|---|---|---|
| | Min | Max | Average | [tonne] | Min | Max | Average |
| $NO_x$ | 3.66E+04 | 4.23E+05 | 1.87E+05 | 45 | 1.65E+06 | 1.90E+07 | 8.41E+06 |
| $SO_2$ | 1.02E+05 | 6.75E+05 | 3.19E+05 | 4 | 4.07E+05 | 2.70E+06 | 1.28E+06 |
| $PM_{10}$ | 6.00E+05 | 7.58E+06 | 2.94E+06 | 0.67 | 4.01E+05 | 5.07E+06 | 1.96E+06 |
| | | | | Total | 2.45E+06 | 2.68E+07 | 1.16E+07 |

[1] Barley, cotton, fruit, grape, hops, millet, maize, oats, olive, potato, pulses, rapeseed, rice, rye, seed cotton, soybean, sugar beet, sunflower seed, tobacco and wheat[Watkiss et al., 2006].

The external costs are calculated in Table 4.4 following the Impact Pathway Approach. Because the emissions of $NO_x$, $SO_2$ and $PM_{10}$ are higher in the maritime alternative, the Δ External cost is positive: the maritime alternative comes as an added cost to the Icelandic society.

These results are to be considered with care, because of two discussable assumptions:

1. The pollution deposition ("pollution" in the impact calculation) is assumed to be the same in the land-based and maritime scenario. This does not take into account the effect of pollution dispersion, as discussed already on section 2.3.4.

2. The pricing calculations are assumed to be valid for the Icelandic context whereas the original calculations are carried out in the United Kingdom: population, building and crop density, as well as meteorological conditions are very different [Watkiss et al., 2006].

### 4.2.2 Pricing of noise exposition externalities

Shreyer et al (2004) calculates the price of noise exposition to humans, combining a Protection cost approach (i.e how much would you pay not to be disturbed by noise?) and a Damage cost approach (i.e cost of hospital admission and medical treatment) [Shreyer et al., 2004].

The costs are calculated as marginal cost per vehicle*km. They only apply to road vehicles, so that the Δ External cost is automatically negative: shifting from land-based to maritime alternative transport comes as a benefit to the society.

The difference in vehicle*km is calculated by counting the number of HDVs necessary to transport 80 000 tonne between Reykjavík and Ísafjördur (497 km) and 100 000 tonne between Reykjavík and Akureyri (386km) assuming that each HDV can carry 22 tonne maximum. Half of the HDVs is assumed to drive at night, the other one during daytime. As most of the trip happens outside the urban centres, only the pricing values for countryside are considered. The calculations are summed up in Table 4.5

Table 4.5: External costs of noise exposition: marginal damage cost[Shreyer et al., 2004].

| | Cost [ISK per vehicle*km] | | | Δ Vehicle*km | ΔExternal cost [ISK] | | |
|---|---|---|---|---|---|---|---|
| | Min | Max | Average | | Min | Max | Average |
| Night | 2.18E-01 | 4.55E-01 | 3.36E-01 | -1.78E+06 | -4.E+05 | -8.E+05 | -6.E+05 |
| Day | 1.19E-01 | 2.57E-01 | 1.88E-01 | -1.78E+06 | -2.E+05 | -5.E+05 | -3.E+05 |
| | | | | Total | -6.E+05 | -1.E+06 | - 9.E+05 |

Discussion:

1. The noise generated by the ship engines in the harbour is not accounted for. Harbours are generally not densely populated areas and harbour workers often wear acoustic protection gear, so this assumption seems valid. Note that the external cost for urban areas are 5 to 10 times larger than the countryside values [Shreyer et al., 2004].

2. Noise impacts regroup a variety of effects: sanitary effects (stress, sleeping problems, fatigue) and inconvenience (disturbance to talk, think, i.e to work); one single event or long term exposition; high or low noise frequency.

### 4.2.3 Pricing of greenhouse effect externalities

Contrary to air pollution through $NO_x$, $SO_2$ and $PM_{10}$ there is no discussion on the atmospheric dispersion for GHG emissions, as they all have the same GWP regardless where they are released on the planet [Forster et al., 2007]. The price of a $CO_2$ equivalent tonne, which weights approximately 3.33 times more than a "Carbon tonne", can be theoretically calculated in two ways [Grangeon et al., 2010]:

**Damage cost:** based on the estimation of long term $CO_2$ emission levels (after 2030) and the associated losses in harvest, real estate, quality of life. There are several uncertainties: the technical innovation after 2030 ($CO_2$ capture technology maturity, use of non fossil fuels), the level of international cooperation, the severity of impacts, the level at which the discount rate should be set[2].

**Abatement cost:** an objective of emission reduction is fixed for a time horizon and a price for the $CO_2$ tonne is estimated to reach this objective. The parties of the Kyoto Protocol agreed to reduce their emissions by 5.2% in average in 2020, compared to the 1990 levels [EEA, 2011].

In Europe there is a market for trading $CO_2$ emissions, and Iceland is a part of this Emission Trading Scheme (ETS) since 2008. The $CO_2$ price per tonne used in this report is corresponding to historical minimum, maximum and average values of the $CO_2$ tonne under the ETS for the period 2005 to 2008 [Convery et al., 2008]. The Δ GHG Emission is calculated already in section 4.1.3 above, the Δ External costs is caculated in Table 4.6 below:

Table 4.6: External costs of greenhouse effect according to the European Emission Trading Scheme market prices [Convery et al., 2008].

| Cost [ISK per $CO_2$ tonne] | | | Δ GHG | ΔExternal cost [ISK] | | |
|---|---|---|---|---|---|---|
| Min | Max | Average | [tonne] | Min | Max | Average |
| 2.56E+03 | 5.13E+03 | 3.42E+03 | -5163 | -1.32E+07 | -2.65E+07 | -1.77E+07 |

Because the GHG emissions of the maritime alternative are smaller than the land-based reference scenario, Δ GHG Emission and Δ External costs are negative: the maritime alternative comes as a benefit to the society. There is an approximate reduction of 5000 tonne GHG sold for 10 to 30 Million ISK.

[2]The discount rate indicates how the financial depollution efforts are distributed over time. A high discount rate dismisses the depollution effort to future generations. The Stern report is famous for using a low discount rate of 1.4%, as opposed to other studies using a rate up to 8% [Sir Nicholas Stern, 2006].

### 4.2.4 Pricing of biodiversity erosion, soil and water pollution

Shreyer et al (2004) calculates a habitat restoration cost per square meter for artificial surfaces: unsealing costs, target biotopes restoration and soil replacement [Shreyer et al., 2004]. This average damage cost evaluation is applied to the transport case study in Table 4.7 by calculating the difference in Land occupation between the road reference and the maritime alternative, based on the results of section 3.4.

Table 4.7: External costs of biodiversity erosion, soil and water pollution [Shreyer et al., 2004]. Only an average figure is available.

| Cost [ISK per $m^2$] | $\Delta$ Land Occupation | $\Delta$ External cost [ISK ] |
|---|---|---|
| 1.38E+04 | -9.70E+01 | -1.34E+06 |

The need for artificial surfaces is reduced in the case of maritime transportation, so that the maritime alternative comes as a benefit to the society. However, maritime transport alternatives will always need roads and HDVs to transport cargo from the origin to its final destination. What is actually decreasing between the land-based and maritime alternative is the temporal duration of the land occupation. The calculated external cost is in addition very low, compared for example to the external cost of GHG emissions. Finally, an important part of habitat restoration costs is usually already included in the investment cost of new constructions: polluted water retention basins, soil waterproofing, etc. In that case, the external costs are partly internalised and transfered to the private costs as investment costs.

### 4.2.5 Road accidents

Kristensen (2010) uses a pricing of road accidents externalities based on marginal damage costs (cost/km) [Kristensen, 2010a]. Accidents at sea happen too but they have not been translated into external cost so far [de Palma et al., 2010], so that the calculations presented in Table 4.8 automatically show a benefit to shift from the land-based transport to maritime alternative.

Table 4.8: External costs of road accidents [Kristensen, 2010a].

| Cost [ISK per km] | | | Δ km | ΔExternal cost [ISK ] | | |
|---|---|---|---|---|---|---|
| Min | Max | Average | | Min | Max | Average |
| 4 | 25 | 19 | -3.56E+06 | -1.45E+07 | -8.97E+07 | -6.84E+07 |

### 4.2.6 Value of time

The value of time in transport is a key parameter for customer satisfaction. For fresh fish caught in the Westfjords away from the fish markets, a fast delivery is of great importance, as the value of fresh fish on the market decreases with time. However, in certain conditions, fresh fish can tolerate a slow transport: (i) fresh fish caught in the Westfjords is often delivered by the fishing vessels directly to Reykjavík, (ii) fresh fish is often exported to the Northern Europe markets by ships instead of planes. For the French market, the trip takes 3 days from Reykjavík to Rotterdam by ship plus a few hours to Boulogne by HDV, compared to 3 hours by plane from Keflavik to Liège (plus a few hours to Boulogne by HDV). Fresh fish travels on ship when the air freights are too expensive [Gernez, 2010d].

The value of time in transport should reflect the quality of the whole transport service, from door to door. The satisfaction of the customer depends on parameters such as reliability, flexibility, schedule integrity, frequency, minimum risk of cargo loss and damage, cargo tracking, information transparency. Giving a value to the time means to account for all these parameters, without any double counting. The value given to these parameters will differ from one type of cargo to another: paper bulk is not treated with the same care as fresh fish. Therefore the value of time in freight transport depends on the type of cargo transported rather than the transportation mode.

No external cost calculation related to transportation time is carried out in this report due to the lack of detailed information available on (i) the type of cargo transported between the Westfjords and the Northern regions and on (ii) the time constraints of the transport service users. Grangeon et al (2010) highlights that the value of time accounts for the biggest share of external costs in most studies [Grangeon et al., 2010].

### 4.2.7 Employment

Möller et al (2010) estimates that 14 jobs can be created by operating a ship between Reykjavík, Ísafjördur and Akureyri: 9 crew on the ship, and 5 in an office [Möller et al., 2010]. Assuming that 1500 tonne cargo need to be delivered per week and that a single HDV can carry 22 tonne, approximately 10 HDVs are needed every day, hence 10 drivers. Whatever the result of this simplified calculation, the point is that a job is not equivalent to another. Is that a satisfaction for someone losing his job that another job has been created at the same occasion? It is however important to note that the main transport operator in Iceland has the double competence of land and maritime transport, so that the same employees could be affected to another position without necessary losing their job.

### 4.2.8 Fuel taxes, road maintenance, port investments and revenue

According to Möller et al (2010), the loss for the government in fuel taxes payment if the maritime alternative is selected lies between 88 and 110 Million ISK (in 2010) [Möller et al., 2010]. On the other hand, benefits from the decrease in road maintenance cost are estimated to be between 100 and 200 Million ISK, due to the reduction of Heavy Duty Vehicle traffic.

In order to deal with an increase in maritime traffic, the harbours of Ísafjördur and Akureyri would need to invest in some infrastructure: 30-35 Million ISK2010 in Ísafjördur and 340 Million in Akureyri. On the other hand, the harbours would increase their revenue by 161 Million ISK if the maritime alternative is selected [Möller et al., 2010] .

### 4.2.9 Summary of external cost discussion

All the external costs are added up to see how they compare to each other and to the investment costs of shifting from land-based transport to maritime transport.

Table 4.9: Cost-Benefit analysis of shifting all the cargo from land-based to maritime transport, from a public perspective, in ISK.

| | Min | Max | Average | Ratio to total absolute benefit | |
|---|---|---|---|---|---|
| Air pollution | 2.45E+06 | 2.68E+07 | 1.16E+07 | 3 % | [0;7] |
| Noise | -1.20E+06 | -2.54E+06 | -1.87E+06 | 1 % | [0;0] |
| GH Effect | -1.32E+07 | -2.65E+07 | -1.77E+07 | 5 % | [3;7] |
| Soil and water pollution | -1.34E+06 | -1.34E+06 | -1.34E+06 | 0 % | [0;0] |
| Road accidents | -1.45E+07 | -8.97E+07 | -6.84E+07 | 19 % | [3;24] |
| Fuel taxes | 9.24E+07 | 1.17E+08 | 1.04E+08 | 29 % | [25;32] |
| Road maintenance | -1.05E+08 | -2.10E+08 | -1.58E+08 | 43 % | [28;57] |
| Total absolute benefit[a] | 2.30E+08 | 4.73E+08 | 3.63E+08 | 100 % | [63;130] |
| Net benefit[b] | -4.04E+07 | -1.87E+08 | -1.31E+08 | | |
| Total investment[c] | 3.89E+08 | 3.94E+08 | 3.91E+08 | | |
| Benefit per unit investment[d] | 0.1 | 0.5 | 0.3 | | |
| Yearly Benefit / Cost[e] | 2.0 | 9.4 | 6.6 | | |

[a] Sum of external costs (positive value) and benefits (negative value) in absolute value.
[b] Net sum of external costs and benefits.
[c] Investment costs of Ísafjördur and Akureyri harbours.
[d] Absolute value of Net benefit divided by Total investment.
[e] Same as above but the Total investment is distributed into 20 yearly periods.

The Net benefit of shifting from land-based transport to the maritime alternative is negative, meaning that this modal shift comes as an overall benefit for the society, from the economic perspective. This result is based on the pricing methods described in the previous sections, each one with its uncertainties and discussed drawbacks. It nevertheless shows how the environmental impact of two transport scenarios can be compared by pricing their external cost.

The benefits to the society of shifting to the maritime alternative in terms of externalities are counterbalanced by the total costs of investment. It is very important to note that these investment costs are the total investment cost, so that in reality they are not accounted at once but spread over 20 or 30 years. The calculated benefits are yearly benefits and depend on the yearly demand for transport. When the total investment costs are distributed into 20 equal yearly periods, the yearly benefits represent two to ten times the investment costs (last line of Table 4.9). A Net Present Value (NPV) analysis is needed to see how the investment costs can be financed over 20 or 30 years (i.e at what discount rate?) and projections for the evolution of the transport demand with time need to be made at the horizon 2020-2030 to see how the externalities are changing.

## 4.3 Investment risks

This last section touches briefly upon the investment risks associated with the different transport scenarios. The high investment costs of the maritime alternative represent high investment risks. The economies of scale apply to ship transport compared to road transport, but what to do with the ship if the demand for transport surges or plunges? For a transport system based only on HDVs, it is easy to adapt the capacity by buying or selling a HDV. In a single-ship transport system, the operating cost quickly overcome the revenue if the ship is not loaded to a minimum. In addition, the ship can only be sold if it can be used in another market. The same applies to the port infrastructures: what happens if they are under-used, or if another cargo handling method is required, for example if investments are made for a Ro-Ro terminal and a Lo-Lo ship ends up being selected ?

One interesting possiblity for the development of maritime transport in Iceland is its integration within the North Atlantic region: Northern Norway, Sweden, Finland and Russia on the East, United States and Canada on the West. With the development of Oil & Gas activities in the Arctic, as well as the use of Northern Shipping Route (from Europe to Asia through the Arctic), there might be an increased demand for transport in the North Atlantic and Iceland could be at the centre of a hub an spokes network.

## 4.4 Chapter conclusion

When translating the environmental impacts into economic costs and benefits, the emission savings of modal shift from land to sea transport do not appear as a significant benefit to the transport operator and the private user. However from the public perspective, this modal shift comes as a real benefit to the whole society. The increased costs associated to air pollution are balanced by the benefits of noise exposition reduction, GHG emission saving, soil and water pollution, accidents reduction. Fuel taxes losses are compensated by savings in road maintenance. The benefits to the society should come in the form of reduced taxes, as well as an increased quality of life overall.

# Conclusion

## What are the environmental impacts of transport in Iceland?

| Substance | Main source | Effects |
|---|---|---|
| | *Emissions to air* | |
| $NO_x$ | fuel combustion | Photo-oxidant formation, Eutrophication, Acidification |
| NMVOC, CO | fuel combustion | Photo-oxidant formation |
| $NH_3$ | fuel combustion | Eutrophication |
| $SO_2$ | fuel combustion | Acidification |
| $CO_2$, $CH_4$ | fuel combustion | Greenhouse effect |
| $N_2O$ | fuel combustion | Greenhouse effect, Eutrophication |
| Metals, PAH, $PM_{10}$ | fuel combustion, road, brake and tyre abrasion | Toxic contamination |
| | *Emissions to soil and fresh water* | |
| Metals | road, brake and tyre abrasion | Toxic contamination |
| | *Emissions to sea water* | |
| Oil discharges | voluntary discharge | Toxic contamination |
| Biocides, Metals | antifouling paint | Toxic contamination |
| Non Indigenous Species | ballast water, hull fouling | Toxic contamination |

## Why is that an important question?

There is no doubt that each one of the environmental side-effects of transport has a negative impact on the environment. The severity of these impacts, if not directly calculated, is compared between the different transport scenarios in the next question.

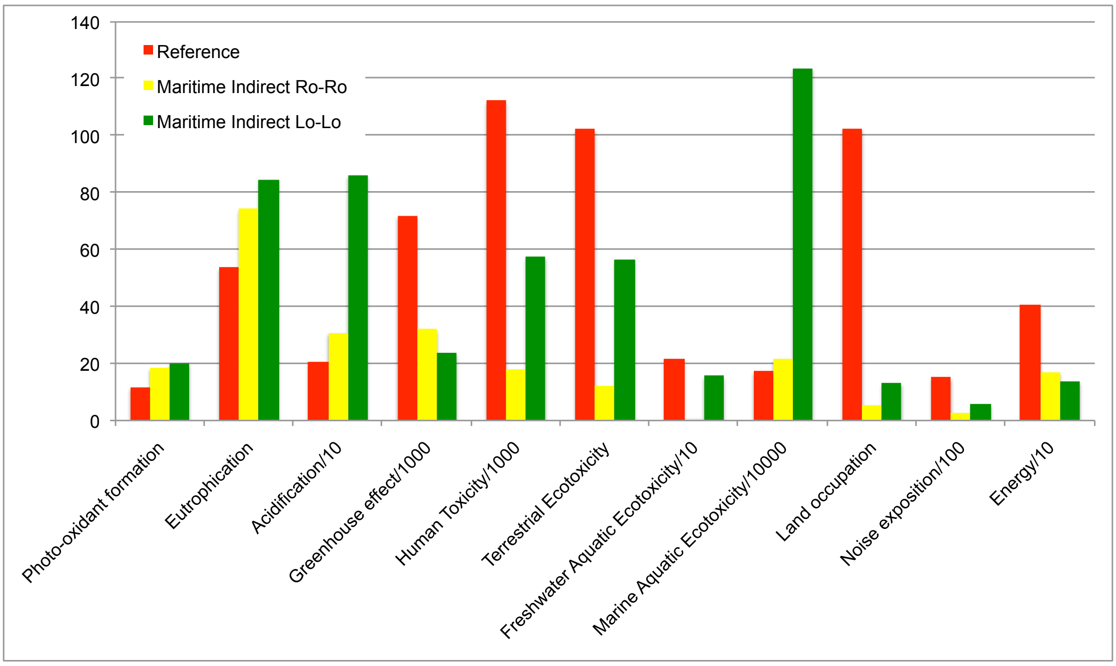
There are other reasons why looking into the environmental impact of transport is a relevant question in Iceland:

**Coastal and marine resources:** both maritime and land-based transport in Iceland are operated very close to the coast, due to the high population density on the coast. Any substance emitted in the atmosphere, on the soil or in rivers is very likely to end up in the coastal marine environment. Because a large part of the Icelandic economic resources are coastal and marine resources, it is very important to monitor the impact of all sectors of activities located close to the coast.

**Legal instruments:** the $SO_x$ and $NO_x$ protocols of the Convention on Long-range Transboundary Air Pollution (CLRTAP) are not ratified, nor is Annex VI on Air pollution from ships to the Marpol Convention. According to the Environment Agency of Iceland, there is currently no concern regarding Eutrophication and Acidification [Gernez, 2011d]. This might change in the future, with a possible intensification of industrial activities along the coast, and the associated increase in transport demand.

**New transport policies, new technologies:** at the European level the need to reduce the GHG emissions is put forward [CEC, 2009], as well as in Iceland (yet for a different reason) [Gernez, 2011d]. Investing in research to reduce the environmental impact of transport is a way for Iceland to strengthen the innovation in the energy sector and present serious arguments for more energy independency. The existing competence in hydrogen fuel in Iceland is one example (together with methane gas, synthetic and bio fuels) of the way ahead [Júlíusdóttir, 2010].

What are the respective impacts of land-based and maritime-based transport scenarios?




Environmental impact per impact category: Reference scenario, Maritime Indirect (Ro-Ro and Lo-Lo ship). This figure is a repetition of Figure 3.5 from Chapter 3.

The Maritime Indirect scenario with a Ro-Ro ship calling at Reykjavík, Ísafjördur and Akureyri is the best maritime alternative to the land-based reference scenario. A container ship (Lo-Lo ship) has the best energy efficiency of all transportation modes, but is burning very low quality fuel, resulting in a strongly negative impact in most categories. When compared to the land-based scenario, the Ro-Ro maritime alternative comes first in all categories except Photo-oxidant formation, Eutrophication, Acidification and Marine Aquatic Ecotoxicity. If Iceland is really not concerned with Eutrophication and Acidification, then the Ro-Ro maritime alternative could be a way to reduce to environmental impact of transport in Iceland.

Balance of yearly emissions when shifting all the cargo to the Westfjords and Northern regions from land-based transport to the maritime indirect alternative on a Ro-Ro ship.

| | Land-based | Maritime alternative | Maritime alternative MINUS Land-based | |
|---|---|---|---|---|
| | | *Emission to air* | | |
| $NO_2$ | 65 | 110 | 45 | tonne |
| NMVOC | 0 | 4 | 4 | tonne |
| CO | 2 | 14 | 12 | tonne |
| $NH_3$ | 49 | 42 | -7 | kg |
| $SO_2$ | 0 | 4 | 4 | tonne |
| $CO_2$ | 11259 | 6126 | -5133 | tonne |
| $CH_4$ | 1352 | 577 | -775 | kg |
| $N_2O$ | 203 | 165 | -38 | kg |
| PAH | 27 | 1 | -26 | kg |
| Cd | 151 | 19 | -132 | g |
| Cr | 1 | 0 | -1 | kg |
| Cu | 8 | 2 | -6 | kg |
| Pb | 691 | 251 | -440 | g |
| Zn | 119 | 2 | -117 | kg |
| $PM_{10}$ | 1452 | 2120 | 668 | kg |
| | | *Emission to soil* | | |
| Cd | 1158 | 0 | -1158 | g |
| Cr | 1 | 0 | -1 | kg |
| Cu | 2 | 0 | -2 | kg |
| Ni | 1 | 0 | -1 | kg |
| Pb | 1 | 0 | -1 | kg |
| Zn | 116 | 0 | -116 | kg |
| | | *Emission to fresh* and marine water*** | | |
| Cd* | 116 | 0 | -116 | g |
| Cr* | 1 | 0 | -1 | kg |
| Cu* | 2 | 0 | -2 | kg |
| Cu** | 0 | 20 | 20 | kg |
| Ni* | 1 | 0 | -1 | kg |
| Pb* | 579 | 0 | -579 | g |
| Zn* | 116 | 0 | -116 | kg |

### How to select the "best scenario" both in terms both of an environmental and an economic perspective?

A first method consists in weighing all the individual category impacts to obtain an overall environmental performance. In terms of LCA, this is the valuation phase. The weighing factors can be based on surveys, or corresponding to political goals (emission reduction targets). Fet et al (2000) experiments with 6 different valuation methods and highlights the subjectivity of this approach and the lack of standard method [Fet et al., 2000]. Iqbal (2001) combines the overall environmental performance with a Customer service index and an Economic index to obtain one single performance per transport scenario [Iqbal and Hasegawa, 2001].

Another approach is used in this study. The different impacts are translated into economic costs and benefits using pricing or monetisation methods. Based on the efforts for internalising the external costs of transport, these methods have the main advantage to express the different impacts in one single, monetary unit, which permits the direct combination of the impacts and the comparison to indicators of economic performance. The main drawback of these methods is again the lack of standard for the monetisation phase. However, there are only a few methods available (damage cost, abatement cost and protection cost) and they can be (or rather: need to be) fine-tuned to the local context.

Using a review of pricing methods, the damage costs associated with the modal shift from land-based transport to the selected maritime alternative are calculated [Grangeon et al., 2010]. Despite the increased emissions in $NO_2$, $SO_2$, CO and $PM_{10}$, the cumulated impacts result in an overall benefit for the Icelandic society, from the public perspective (external costs). In terms of private perspective (internal costs), the break-even costs of running a ship service are estimated to be much lower than the rates (which include an operating margin) currently offered by the land transport operator in Iceland. In both private and public perspectives, these economic calculations are very much simplified, because the financing costs (cost of debt and interests) are not taken into account. Finally, the question of the value of time is not resolved.

## Weaknesses of the study and need for further research

This study is exploring the question of LCA Valuation by the economic angle in Chapter 4. As stated in that chapter, the references used are not coming directly from the academic literature, but are rather a review of the existing literature. The economic approach could benefit from more solid academic grounds, especially literature dealing specifically with the Icelandic context.

The need for further research covers several areas:

**Emission Inventory:** more substances can be included, for instance Polychlorinated biphenyl compounds (PCBs) and Dioxins. Both might only be released as traces, but they are highly toxic. Hydrofluorocarbons and Perfluorocarbons (HFCs and PFCs) could form an important part of the GHG emissions, because of the important part of refrigerated cargo transport. Zinc (Zn) and other metals emitted by ship anodes could be looked at, in addition to a more detailed list of compounds released by antifouling paints. Finally, the emission calculation can be improved by taking into account more details in the engine loads: speed and cold/hot start for HDVs, level of Maximum Continuous Rating (MCR) and at sea/in harbour differentiation for ships.

**Characterisation:** all toxicity impacts are associated with some uncertainties in the calculation of the characterisation factors based on fate, exposure and effect models [Huijbregts, 2000]. A new approach developed by Prinçaud (2010) calculates the characterisation factors using a ranking of the compounds toxicity and the sensitivity of the ecosystem where the compounds are released [Prinçaud et al., 2010]. This approach has the merit of calculating a more locally detailed impact, which can not be done with a traditional LCA [Guinée et al., 2002b].

**Non Indigenous Species (NIS):** the impact of the introduction of these new species carried by the ship ballast waters and antifouling paints has not been qualified nor quantified in this study. This is a serious threat and a complex problem. Some economic impact models exist [S.J et al., 2006].

**Dispersion studies** are needed to see where the ship emissions at sea are going, and if the harbour emissions only could be considered. Dispersion models or local measurement campaigns are needed [Hanna et al., 1985, Deletraz, 2003, Vutukuru and Dabdub, 2008].

## Final recommendations

The transport demand figures given by Möller (2010) should be refined per type of cargo (temperature sensitive, urgent,etc.) in order to determine the best transport service to offer [Möller et al., 2010]. If the demand holds with important volumes and if the speed of delivery and flexibility are not the main concerns of the transport users, then the maritime alternative presented in this study should be considered.

Looking at the Norwegian market as done by Herbertsson (2005) gives an example of maritime coastal transport with small, reefed (for temperature sensitive cargo), multi-purpose vessels (combining some room for containers on the deck and a garage under the deck to roll some cargo in and out), self-geared (with cranes on board to move the containers on/off the ship) with side door to access easily the cargo stored in the garage [Tryggvi Þór Herbertsson, 2005]. Such ships operate along the Norwegian West Coast, with similar geographical patterns (rocky coasts, deep fjords), meteorological conditions (small tides, often rough weather) and population density (spread all along the coast in small isolated towns). The Norwegian company Norlines is for example operating the MS Nordkinn on a 21 days route, calling at 60 harbours (with up to 8 calls per day). The specifications of MS Nordkinn are given in next page [Norlines, 2011], showing that this vessel would fit perfectly with the Maritime alternative scenario with an estimated capacity of 1800 tonne and a Specific Energy Demand of 0.32 MJ/tonne payload/km], the same as the Ro-Ro ship considered in this study [Gernez, 2011f].

Finally it is interesting to note that Eimskip CTG, the Norwegian branch of the Icelandic main transport operator has been operating the sistership of MS Nordkinn, before selling it to Nordlines. What would happen in Iceland if there was more competition in the transport sector?

## M/V "NORDKINN"
## Special Purpose Container / Reefer Vessel


**- Flexible multi purpose cargo/reefer vessel**
**- Very favourable fuel economy**


**Contact:**
Mobile phone +47 47 48 47 67
Fax +47 47 48 47 70
E-mail: nordkinn@norlines.no


IMO nr: 9333644
Callsign: OZ2080
Flag: Faroe Island
Homeport: Torshavn

**Main Dimensions:**

| | |
|---|---|
| LOA | 79,99 m |
| Length between PP | 78,15 m |
| Breadth Moulded | 16,00 m |
| Depth Moulded Shelter Deck | 9,10 m |
| Depth Moulded Main Deck | 6,10 m |
| Scantling Water Line | 6,10 m |
| Design Water Line | 5,75 m |

**Tank capacities:**

| | |
|---|---|
| Fuel Oil | 303 m3 |
| Fresh Water | 52 m3 |
| Water Ballast | 1091 m3 |

**Propulsion Machinery:**

| | |
|---|---|
| 1x medium speed main eng. | 3060 kW |
| 1x reduction Gear with PTO | 140 rpm |
| 1x large diameter DP propeller | |

**Electrical System:**
Derric: SWL 75 tons / 19m
2 cargo lifts: SWL 4 tons
4 fork lifts: 2 x 5,0 tons / 4,0 tons / 3,0 tons

**Net cargo hold areas:**

| | |
|---|---|
| Cargo hold 1 | 471 m2 |
| Cargo hold 2 | 252 m2 |
| Cargo hold 3 | 503 m2 |
| Cargo hold 4 | 395 m2 |
| Shelter Deck | 550 m2 |
| Boat Deck | 225 m2 |

**Accommodation:**

| | |
|---|---|
| Cabins | 10 |

**Capasities:**

| | |
|---|---|
| Deadweight | 2737 t |
| Gross tonnage | 2991 t |
| Deck Load (conts) | 1250 t |
| Cargo Hold Capasity (4 holds) | 4150 m3 |
| Speed | 16 knots |

**Class:**
DNV 1A1, Reefer (-27 gr C / +32 gr C)
Container, Ice C, EO
IMO: 9333644
Call sign: OZ 2080
Flag: Faroese (The Faroe Islands, Torshavn)

**Manoeuvring:**
1x high lift flap rudder
1x electrohydr. steering gear
1x C.P. sie thruster aft
1x C.P. side thruster forward

**Container/deck crane:**
50 t - 16 m / 27 t - 21 m / 12,5 t - 24 m

**2 cargo lifts:**
Platform size: 3,05x1,40 m
Lifting capacity: 4,1 t at 24 m/min.

**Container capacities:**

| | |
|---|---|
| 20' shelter deck | 2 (26) |
| 40' shelter deck | 20 |
| 40' boat deck | 8 |

**Example of emission invnetory calculation for Road transport**

| | | | |
|---|---|---|---|
| 1 | Background info | | |
| | origin | Isafjordur harbour | |
| | destination | Reykjavik harbour | |
| | specific energy demand | 0.33 | MJ/tonne truck load/l |
| | corrected SED for loading | 0.8472973 | MJ/tonne truck load/l |
| | specific fuel consumption | 0.21 | kg fuel/kWh |
| | specific energy demand | 0.23536036 | kWh/tonne truck loac |
| | fuel consumption | 16.4765432 | kg fuel/F.U |
| | | | |
| 2 | Summary of input parameters | | |
| | Route | Direct | |
| | Return trip exploited capa | 100 | % |
| | Total sailing distance | 180 | NM |
| | Total sailing distance | 333.36 | km |
| | Speed | 14 | knots |
| | Roro model | Current | |
| | Exploited capacity | 37 | % |
| | Truck load | 9.62 | tonne |
| | Total ship capacity | 533 | lane meter |
| | Exploited capacity | 666 | tonne |
| | | | |
| 3 | Exhaust Emissions | g/F.U | variable name |
| | NO2 | 939.162965 | R_nox |
| | NMVOCs | 37.8960495 | R_nmvocs |
| | CO | 121.92642 | R_co |
| | NH3 | 0.36248395 | R_nh3 |
| | SO2 | 32.9530865 | R_so2 |
| | CO2 | 52378.931 | R_co2 |
| | CH4 | 4.93637236 | R_ch4 |
| | N2O | 1.4103921 | R_n2o |
| | PAH | 0.00823827 | R_pah |
| | Pb | 0.00214195 | R_pba |
| | Cd | 0.00016477 | R_cda |
| | Hg | 0.0004943 | R_hga |
| | As | 0.00065906 | R_asa |
| | Cr | 0.00082383 | R_cra |
| | Cu | 0.01449936 | R_cua |
| | Ni | 0.01647654 | R_nia |
| | Se | 0.00164765 | R_sea |
| | Zn | 0.01977185 | R_zna |
| | TSP | 18.1241976 | R_tsp |
| | | | |
| 4 | Marine Emissions in harbours | | R_cuw |
| | | | |
| | Ship hull surface | 22512000 | cm2 |
| | Trip duration | 0.08333333 | days |
| | Marine Cu emissions | 1.37E-01 | g Cu /F.U |
| | | | |
| 5 | Land occupation | according to Fet 2000 | |
| | Ship length | 100 | m |
| | Total Loading and Unloadi | 2 | hours |

| | | | |
|---|---|---|---|
| | Quay breadth in all harbou | 25 | m |
| | Total land occupation | 5000 | m2h |
| | Land occupation | 7.50750751 | m2h/F.U |
| | | | |
| 6 | Noise | according to Fet 2000 | |
| | Distance to noise < 55 dB | 288 | m |
| | Semi disc area exposed to | 130288.131 | m2 |
| | Total quay occupation | 2 | h |
| | Total Noise Exposition | 260576.261 | |
| | Total Noise Exposition | 391.255647 | m2h/F.U |
| | | | |
| 7 | Energy | 282.455027 | MJ/F.U |

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