Screening LCA of GHG emissions related to LNG as ship fuel

Julianne Mari Ryste

The world we created today as a result of our thinking thus far has problems which cannot be solved by thinking the way we thought when we created them

- Albert Einstein

Preface

This Master Thesis represents the culmination of the M.Sc. degree within the programme of Marine Systems at the Department of Marine Technology, Norwegian University of Science and Technology. It is written in its entirety by stud.techn. Julianne Mari Ryste, during the spring semester of 2012.

The work succeeds the Project Thesis written in the autumn semester of 2011, which was a literary study of the life cycle analysis method with application to LNG as ship fuel. The goal of this report is to perform a life cycle analysis for the process of LNG bunkering. Both the Project and Master Thesis were part of a large assignment regarding LNG as fuel, given by DNV to NTNU.

During the Project Thesis, SimaPro was selected as the expected software to be used for the analysis. However, due to some problems with SimaPro I had to change software to GaBi in mid-march. This affected the time at disposal to conduct the analysis, but luckily GaBi was relatively user-friendly, and I feel confident the model and analysis are up to par.

The scope of the Master Thesis has been altered somewhat from the original plan in the Project Thesis. Since the main interest in the thesis was to analyse the stages of the LNG value chain that have not received attention thus far, the scope of the LCA was changed to a Screening LCA (SLCA), the details of which will be described in full within the report.

I would like to extend my gratitude to my supervisor at NTNU, Professor Ingrid Bouwer Utne, for great advice and instruction in the thesis throughout this demanding semester. Thank you to my supervisors at DNV for their advice and help with data collection. Lastly, a special thanks to Katrine Strøm at DNV for providing comprehensive information regarding the bunkering process, without which the analysis would not have been successful.

The assignment has been a great learning experience, both in regards to LNG and environmental solutions for the maritime industry, and within the extensive academic field of LCA. Environmental technology is a subject scarcely addressed in the academic programme; therefore I am grateful to have been given the opportunity to write a thesis within this topic. I have gained insight in a field of great personal interest; valuable knowledge which I will make good use of in the future.

Tyholt, Trondheim 10th June 2012

_____

Julianne Mari Ryste

Executive Summary

In view of the increasingly popular climate change debate worldwide, maritime transport is under pressure to create sustainable solutions for a cleaner future.

One of these solutions is using liquefied natural gas (LNG) as ship fuel. LNG has a higher hydrogen-to-carbon ratio compared with oil-based fuels, which results in lower specific CO_2 emissions (kg CO_2/kg fuel). Other benefits of LNG are the total elimination of SO_x emissions and particulate matter, and 85-90 % reductions in NO_x emissions. DNV has estimated a net global warming benefit of 15 % with the use of LNG. However there is still a need to map the greenhouse gas emissions throughout the life cycle of LNG.

This thesis is a *Screening Life Cycle Assessment* of LNG as fuel, with the main objective to carry out a life cycle analysis of the process "Bunkering of LNG".

Screening is a simplified LCA which aims at identifying the important parts of a life cycle, or so-called hotspots. Bunkering of LNG and the bunkering facility have been chosen as the hotspots in this analysis for their uniqueness. The processes related to bunkering have not been analysed at this level of detail in published literature.

The LCA software GaBi Educational has been used to implement the bunkering model and analyse the life cycle inventory results. Processes related to energy use, manufacturing and direct emissions were included in the GaBi model.

The CML 2001 method was used to assess the *Global Warming Potential* (GWP). This is the main characterisation factor of the environmental issue climate change, which was in focus in this analysis.

The impact assessment showed that emissions related to manufacturing are the greatest contributors to the GWP, with a total GWP of 75 917 [kg CO_2-Equiv]. Energy use contributes the least, with only 0,36 ‰ of the total impact, which is considered negligible. Direct emissions stand for 7 777 [kg CO_2-Equiv] and is the only area of the bunkering life cycle where emissions can be considerably reduced. In fact, all direct emissions can be omitted by the use of BOG recovery strategies, such as vapour return.

The conclusion drawn is that the emissions associated with bunkering of LNG is perhaps not the main issue. A more pressing issue at the moment is the low fuelling possibilities for LNG. If LNG is to become the fuel of the future, fuelling must be made more accessible and available.

Contents

List of Figures

List of Tables

Abbreviations

BOG   – Boil-off gas
CCB   – Coast centre base
CH4   – Methane
CML   – Centrum voor Milieuwetenschappen, Leiden University, NL
CO2   – Carbon dioxide
GHG   – Greenhouse gas
GTT   – Gaztransport & Technigaz
GWP   – Global warming potential
HFC   – Hydrofluorocarbons
HFO   – Heavy fuel oil
IMO   – International Maritime Organisation
IPCC   – Intergovernmental panel on climate change
ISO   – International organisation of standardisation
ITPS   – Intermediary tank-to-ship via pipeline (land-to-ship)
LCA   – Life cycle analysis
LCI   – Life cycle inventory
LCIA   – Life cycle impact assessment
LNG   – Liquefied natural gas
MDO   – Marine diesel oil
MGO   – Marine gas oil
MIP   – Mechanically insulated pipe
N2   – Nitrogen gas
NG   – Natural gas
NOX   – Nitrogen oxide
OSV   – Offshore supply vessel
PFC   – Perfluorocarbons
PSV   – Platform supply vessel
SLCA   – Screening life cycle analysis
SOX   – Sulphur oxide
STS   – Ship-to-ship (bunkering)
TTS   – Tank-to-ship (bunkering)
VIP   – Vacuum insulated pipe

1   Introduction

In view of the increasingly popular climate change debate worldwide, maritime transport is under pressure to create sustainable solutions for a cleaner future. Although international shipping is the most energy efficient mode of mass transport and only a modest contributor to overall carbon dioxide emissions (IMO 2011), action must be taken to further improve energy efficiency. As sea transport continues to grow alongside world trade, effective emission control and limitations are needed.

1.1   Background

In 2007 international shipping was estimated to have contributed about 2,7 % to the global emissions of carbon dioxide (CO_2) (IMO 2009). The Second IMO GHG Study 2009 identifies a significant potential for reduction of greenhouse gas (GHG) emissions through technical and operational measures. The study estimates that, if implemented, these measures could increase efficiency and reduce the emissions rate by 25% to 75% below the current rate at which emissions are growing (IMO 2011).

One of these solutions is using *Liquefied Natural Gas* (LNG) as an alternative fuel in the shipping industry. There are many documented benefits of LNG as fuel, among them the total elimination of SO_x emissions and particulate matter and 85-90 % reduction in NO_x emissions (Richardsen 2010). LNG has a higher hydrogen-to-carbon ratio compared with oil-based fuels, which results in lower specific CO_2 emissions (kg CO_2/kg fuel). DNV has estimated a 15-25 % reduction of CO_2 emissions with LNG. The emissions of methane (CH_4) related to LNG exhaust gas, however, reduces the net global warming benefit to a total of 15 % reduction in CO_2-equivalent emissions.

Although the numbers for LNG look promising, they are based mainly on combustion of natural gas. The environmental performance of the fuel in a life cycle perspective is not well documented, creating growing concerns and speculations about the actual net benefit of LNG.

Life Cycle Analysis (LCA) is a renowned method to assess the environmental performance at all the stages of a product or system's lifetime. A life cycle begins with the extraction of raw materials, to manufacturing and use of the product, through to repair and eventually disposal.

1.2 Objectives

The thesis is based on the screening life cycle assessment method. Screening assessments aim to identify the environmental hotspots in a product's life cycle. The first goal is therefore to establish these in the LNG value chain, not only by considering contributions to the environmental impact but also investigating areas of the LNG life cycle receiving little attention thus far.

Consequently, the main objective of this thesis is to carry out a life cycle analysis of such a hotspot, namely "Bunkering of LNG". GaBi Educational software will be used for this analysis, with an aim at making a model that can easily be adopted and developed further.

The results will be interpreted with respect to the environmental issue of climate change. Greenhouse gas emissions are therefore in focus throughout the report. The results will thereby be compared to other marine fuels such as MDO and HFO. Some suggestions of improvements in the bunkering cycle will be made accordingly.

Detailed and high quality data from reliable sources create good LCA results. Data collection is therefore an important part of this thesis, the goal being to obtain as much data as possible directly from the industry, aiming at quality datasets and minimum need for assumptions.

Last but not least, the thesis aims to create momentum around LNG as a fuel, as well as an interest for the subject of environmental issues within marine technology. Although this thesis is written in cooperation with and for DNV, it will hopefully bode for interesting reading also for fellow students, professors and others with an interest for LNG and environmental solutions for the maritime industry.

1.3 Limitations

Data collection is an extensive, time-consuming process in any LCA. Bunkering of LNG is such a concise, particular part of the LNG value chain making it even more difficult to obtain reliable data. Where data is not available, estimations based on background knowledge and possibly academic assumptions will be used.

The bunkering process is so specific that it has not been given attention in any of the environmental studies found. In addition, LCA requires that systems under subject of comparison are analysed using equivalent product systems. For these reasons, the ability to compare the results for different fuels is limited.

1.4 Structure of report

The first part of this thesis devotes some time to explain the important terms *Natural Gas*, *LNG* and *Boil-off Gas* before focusing on the SLCA methodology, with a brief description of *Life Cycle Impact Assessment* (LCIA) where the *Characterisation Factor Global Warming Potential* (GWP) will receive special attention. Following this the report will focus on the main objective, starting with a description of some stages in the LNG value chain. The bunkering process is described in detail followed by the system boundaries of the product system to be analysed. Data collection is shortly explained prior to presenting the GaBi implementation and analysis. Following this the results will be discussed before the thesis rounds off with a concluding remark and ideas for further work.

2 What is LNG

Before diving into the LNG life cycle and product system description, a short presentation of natural gas, liquefied natural gas and boil-off gas is provided. These terms will be used abundantly throughout the report. It is therefore sensible to describe these to establish a foundation for better overall understanding of the following thesis.

2.1 Natural Gas

Natural gas (NG) is a combustible mixture of hydrocarbon gases formed primarily by methane, but also including ethane, propane, butane and pentane (NaturalGas 2010). Due to its small amount of carbon atoms compared to hydrogen atoms in the molecule, natural gas contains far less carbon per content of energy. This makes it one of the world's cleanest burning fossil fuels, emitting much lower air emissions than other fossil fuels such as oil or coal (Ryste 2011). Natural gas is also one of the most energy efficient fuels, offering a specific heat of combustion of 54 [kJ/kg] compared to diesel which only has 45 [kJ/kg].

This means that natural gas offers more energy and less environmentally harmful emissions per mass than do other common fuels. It has therefore become a vital component of the world's energy supply and one of the most useful of all energy sources (NaturalGas 2010). Today approximately 25% of the world's energy demand is derived from natural gas (Linde 2012). It is widely used in industrial applications such as production of plastics, fertilizer, anti-freeze, and fabrics, but also for residential and commercial heating as well as cooking (NaturalGas 2010). In recent years, natural gas has become a popular choice as a fuel for transportation, both for trucks and buses, and now also for passenger vessels and to some extent larger sea-going vessels.

Natural gas is often called methane or just CH_4. When natural gas is utilised, it has been dried and removed of all hydrocarbons so that it is in its purest form, methane. This is known as consumer grade natural gas. Like many other forms of energy, natural gas is internationally measured and expressed in *British Thermal Units* (Btu). One Btu is the amount of natural gas that will produce enough energy to heat one pound of water by one degree at normal pressure. In Norway natural gas is often measured in [kWh] and [MJ].

Norway is the seventh largest natural gas producer in the world (Statistics Norway 2011). Norway is, however, not a big consumer of natural gas, using only around seven % of the total natural gas produced on the Norwegian continental shelf. Most of the natural gas is exported, mainly to The United Kingdom, Germany and France, as Figure 1 demonstrates.
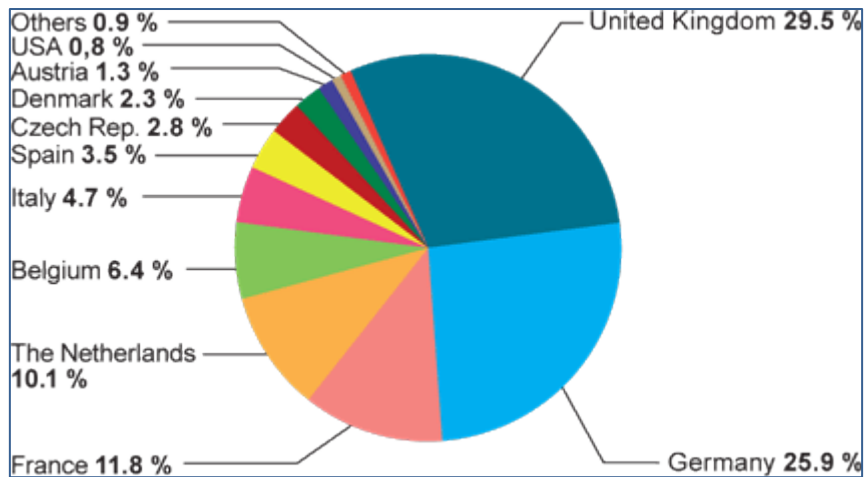
Figure 1- Norwegian natural gas exports by country, 2010

2.2 Liquefied Natural Gas

There are four main ways in which gaseous fossil fuels can be retained (Gassteknikk Ltd. 2012):

- Compressed gas: Gases are compressed by pressure in suitable containers. Examples are *Compressed Natural Gas* (CNG) and air.

- Condensed gas: Gases that become fluid when pressurised in a container. Examples are carbon dioxide (CO_2) and *Liquefied Petroleum Gases* (LPG) such as propane and butane.

- Dissolved gas: Gases that are dissolved in another medium, such as acetylene which can be dissolved in acetone under low pressures in a pressurised container.

- Cryogenic gas: Gases that are cooled to sub-zero temperatures in a specially designed thermos. Examples are *Liquefied Nitrogen* (LIN), *Liquefied Oxygen* (LOX) and finally *Liquefied Natural Gas* (LNG).

Cryogenics is the science and technology of very low temperatures; traditionally the field of cryogenics is taken to start at temperatures below -150°C (Ursan 2011). LNG is formed at low temperatures of -162°C and is classified as a cryogenic fluid.

Liquefied natural gas takes up about one six hundredth the volume of gaseous natural gas, making it much easier to transport, store and use when in liquid form. Since 1964 LNG has been transported in specially designed LNG carriers (the first being MV *Methane Princess*) (Curt 2004). This made LNG much more accessible, and it could be transported by ship to areas where pipeline transportation was uneconomical or impossible. Since then, LNG has been the preferred form of natural gas.

Before it is liquefied, natural gas must be purified and dried to remove all components that can interfere with the liquefaction process. First of all it is purified by removing all carbon dioxide, mercury, hydrogen sulphide and oxygen residues, making it almost 100 % methane. The gas is then dried by removing all condensate and helium (Linde 2012). Finally the gas is cooled to approximately -162°C in stages, at normal pressure, which results in the condensation of the gas into liquid form. The process is shown in Figure 2 (Linde 2012). Quantities of LNG are measured in standard cubic meters, scm or simply $[m^3]$.
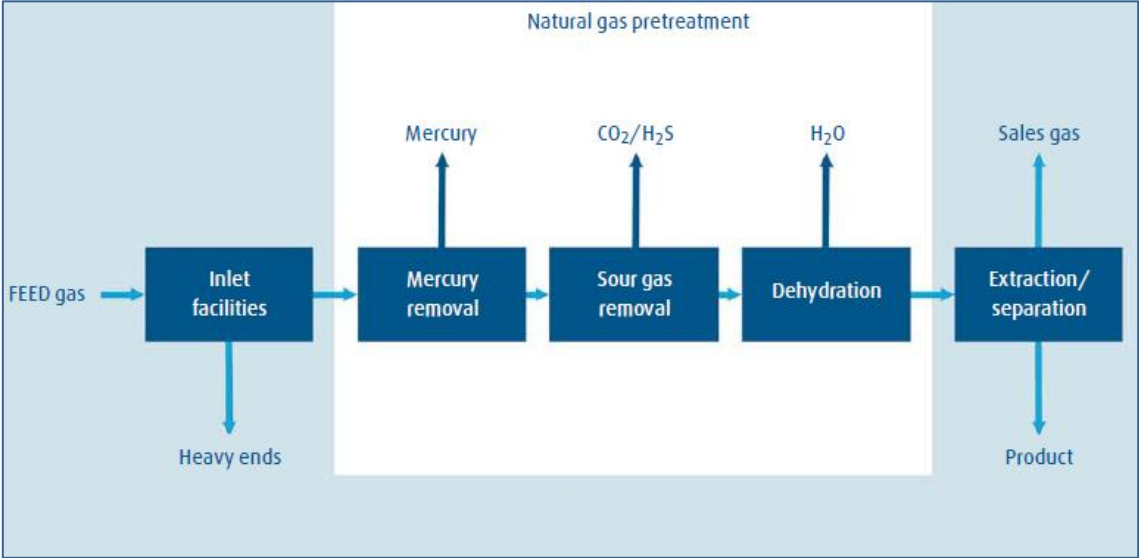
Figure 2 - Liquefaction process of LNG

LNG is a clean fuel containing no sulphur; this eliminates the SO_X and particulate matter emissions. Additionally, the NO_X emissions are reduced by up to 90% due to reduced peak temperatures in the combustion process. Due to its low hydrogen-to-carbon ratio compared with oil-based fuels, results in lower specific CO_2 emissions [kg of CO_2/kg of fuel]. Unfortunately, the emissions of methane in the exhaust gas reduces the net environmental benefit of LNG (IMO 2009).

LNG has been used as a fuel on passenger ferries and other small scale vessels in Norway since 2000, with a fleet of 16 ferries today (Haugstad 2012). The world's first LNG fuelled ferry was the MF *Glutra*, operating along the Norwegian coast (Skipsrevyen 2000).

LNG is now becoming a popular subject when discussing environmentally friendly fuels also for medium to large scale vessels such as *Offshore Supply Vessels* (OSV) and cargo ships. Norway is a pioneer within LNG technology, with five LNG-fuelled OSVs in operation already and several newbuildings on the way (Haugstad 2012).

2.3 Boil-off Gas

To remain a liquid, LNG must be kept refrigerated at approximately -162°C at all times. This is done, predominantly by the use of efficient insulation in all tanks, pipes and transfer units. There is, however, no such thing as perfect insulation, and LNG that is kept stored over a period of time will inevitably be influenced by heat exchange into the containment vessel. When the temperature of the fluid increases due to heat exchange, the fluid begins to boil to maintain a constant pressure in the liquid.

However, LNG expands 600 times from liquid to gas form, meaning that BOG must be vented out of the containment vessel to keep the volume constant. Thereby the BOG retains the heat input and keeps the fluid at constant temperature. The resulting phenomenon is called *Auto Refrigeration* and is used in all cryogenic technologies

If a substantial amount of BOG is produced, this should be recovered to avoid emissions directly to the surroundings. Solutions for BOG recovery are explained in chapter 4.2.

3 LCA

The following will provide a brief explanation of the LCA methodology, focusing on application to the LNG analysis. The chapter begins with a description of the screening method, including some elements of the simplifications applied to the analysis. Further, the elements of LCI and LCIA relevant to the product system and interpretation of *Global Warming Potential* are presented.

3.1 Screening LCA

There are three basic levels of LCA (Hochschorner and Finnveden 2003)

- A matrix LCA

- A screening LCA

- A full LCA

There are many barriers to completing a full LCA, such as inadequate data, inaccuracy, cut-offs, estimations and limitations. All these barriers narrow the scope and cause uncertainties and inconsistency in an analysis. A perfect LCA is in practice impossible, and some go as far as to say that a full LCA has never been accomplished due to the severity of these barriers (Hur, Lee et al. 2004).

Simplified versions are therefore available to examine certain environmental aspects and characteristics of the product system, without the need to fully comply with the LCA ISO standards.

There is not *one* defined recipe one can follow to carry out a simplified LCA, the simplifications are individual to each project. Simplifications can be done in two main ways: By reducing the scope of the study, i.e. by cutting out unit processes or analysing only certain parts of the life cycle; Or by reducing the data requirements, i.e. substituting with surrogates where data is not readily available (Hur, Lee et al. 2004).

The two most significant barriers are data and time availability. For these exact reasons, the LCA in this thesis is limited to what is called a *Screening Life Cycle Assessment* (SLCA).

Screening is a simplified LCA which aims at identifying the important parts of a life cycle, or those that require attention due to data gaps or assumptions (WG Environment 2004).

Hotspot Assessment is another name for a screening, because it intends to identify so-called hotspots in the product life cycle which pose special interest to the practitioner. Hotspots may be stages in the life cycle which have not previously been analysed, or stages that present opportunities for improvement.

This particular analysis has been simplified by seeking out the stages of the life cycle that have received little or no attention and choosing a hotspot among these. Steps that are well-documented and analysed in other studies have been excluded. Production, purification, liquefaction and pipeline distribution and combustion are all parts of the LNG life cycle that are well-documented, for example in the TNO-report "Environmental aspects of using LNG as fuel" (TNO 2011). Transportation, delivery and storage at terminal, bunkering, and storage on board were identified in the preceding project thesis as the stages often left out of LCAs (Ryste 2011).

Bunkering of LNG and the bunkering facility are not big contributors to the total environmental impact, but have been chosen as the hotspots in this analysis for their uniqueness. No documentation has been found that these stages have been analysed in any detail before. Choosing them for the screening will therefore provide a great supplement to other life cycle studies and create a better overall picture of the LNG life cycle.

The greenhouse gases carbon dioxide and methane are the main components of LNG emissions. They primarily contribute to air pollution which leads to the environmental concern of climate change. Focusing on the *Impact Category* global warming potential only in the LCIA is therefore an additional simplification.

Further, the product system for Bunkering of LNG will be simplified by setting system boundaries. This will be discussed later, but mainly consists of excluding some of the processes and equipment due to lack of information.

3.2 LCI

Life Cycle Inventory is a compilation and quantification of the inputs and outputs that flow through the product system. Inputs are the systems resources and are defined in three groups; materials, energy, and intermediates. These travel through the product system where material and energy flows are connected to produce a product or service. The outputs are defined in the groups; product, by-product, waste, intermediates and emissions. Figure 3 shows a simplified version of a product system.

Resources → Process → **Product A** (0.9 kg, 99 MJ, 99 $)

Product B (0.1 kg, 1MJ, 1 $)

Emissions
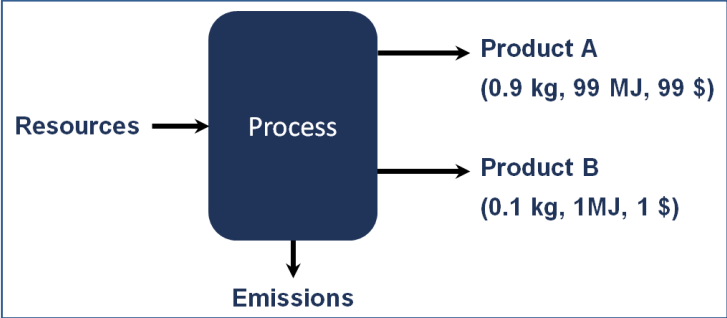
Figure 3 - A simple product system

Each product system is based on the *Unit Processes* required in order for it to perform or deliver the function or product that defines the system. Unit processes are defined by the resources that go into it, the emissions it produces and the product it produces. Figure 4 shows a detailed picture of what goes on in a typical unit process.

Input:

Polypropylene scrap
500 kg

Thermal energy
712 MJ

Power
74.5 kWh

Process water
4,800 kg

Process:

Washing and drying of PP scrap

Output:

PP scrap (washed)
495 kg

PP (consumer waste)
5 kg

Waste water
4,800 kg

- What is the weight of one complete battery housing?
  500 g
- Which material inputs are used (specification)?
  Used battery housings made of polypropylene
- How is the cooling water treated (closed or open loop)?
  No cooling water necessary
- Compressed air: power demand of the compressor, air pressure?
  Don't know the power demand, air pressure is 7 bar STP
- Generation of thermal energy (which kind of fuel is used)?
  Natural gas

materials, energy, operating mat. → process → waste, losses, emissions, products, by-products

Figure 4 - Details of a Unit Process

A product system is defined by its *Functional Unit* (FU), the reference unit to which input and output data are normalised. The functional unit must be consistent with the goal and scope of the study and should be clearly defined and measurable. The FU for bunkering will be discussed in chapter 6.4.

LCI is largely dependent on data collection to quantify the input and outputs so that the product system can be analysed. When sufficient data is gathered, the product system is implemented as a model in the chosen LCA software and the data values are inserted.

When the model is finished, the software calculates a temporary inventory result, also called a *Balance*. This represents the total amounts of materials and energy used by the system and the actual emissions related. An LCA can stop here if one is only after the amount of emissions. To further interpret the results based on environmental impact, Life cycle impact assessment is used.

Life cycle inventory was presented in detail in the project thesis, and will therefore not be described further here. For more information please refer to chapter 4.2 in the project thesis (Ryste 2011).

3.3 LCIA

Life cycle impact assessment is a helpful tool to interpret the LCI results. It is defined as the phase in the LCA aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system (Pré Consultants 2010).

LCIA models selected environmental issues, called impact categories, and uses *Category Indicators* to condense and explain the LCI results. The category indicators are intended to reflect the aggregate emissions for each impact category, and represent the potential environmental impacts.

To do this, LCIA contains a number of *Impact Assessment Methods* that aim to place the results into environmental context. Each method is based on a particular *Environmental Mechanism*. The methods are distinguished by the impact categories included in the mechanism and the characterisation factors used to calculate these categories. The method used is chosen according to the environmental mechanism that best suits the scope of the analysis.

There is also a broad field of assessment elements that aim to evaluate the significance of the results and their accuracy. The elements are voluntary, chosen individually for each project depending on the purpose of the LCA.

The scope of this analysis is to calculate the greenhouse gas emissions only. This implies that the LCA could stop at the LCI results. Using LCIA does, however, ensure the analysis is more complete and will make the results easier to use in relation to other studies. The following will therefore describe some elements of the LCIA relevant to GHGs.

3.3.1 Impact categories

An Impact category is defined as an environmental issue of concern, such as global warming or ecotoxicity. To make sense of the LCI results they are assigned to the relevant impact category for further interpretation.

Categories are divided into *Midpoints* and *Endpoints*, which represent each their stage in the environmental mechanism. Choosing whether to interpret the results at endpoint or midpoint determines which LCIA method is used.

Midpoint categories represent concrete environmental issues such as smog, human health and climate change. In the environmental mechanism they precede the endpoint categories which represent a concrete consequence of the environmental issues, such as cancer and extinction of species. Figure 5 demonstrates the environmental mechanism with examples of mid- and endpoints.
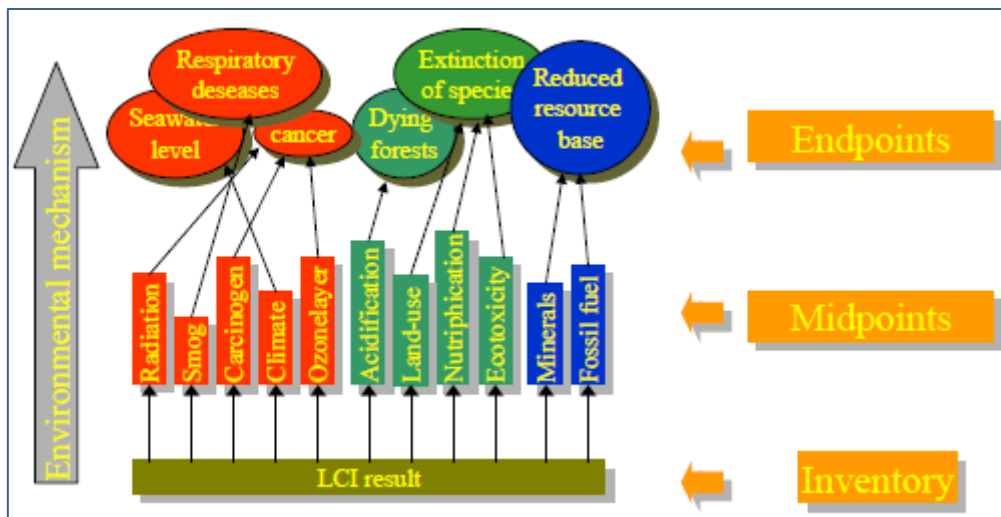
Figure 5 - Midpoint and endpoint categories in an environmental mechanism

To reach a midpoint category, only a small part of the environmental mechanism needs to be modelled, whilst indicators at endpoint level require additional steps of modelling and interpretation. Indicators close to the inventory results are therefore subject to lower uncertainty in interpretation perspectives than endpoints.

Each impact category is linked to the mid-/endpoints by what is called an *Impact Category Indicator*. To convert the indicator to a common, understandable unit, a *Characterisation Model* is used to describe the relationship between the LCI results, the category indicators and the category endpoints. From this model a *Characterisation Factor* is derived.

Characterisation factors should reflect the relative contribution of an LCI result to the impact category. For instance, contribution of 1 kg CH_4 to global warming is 25 times higher than the emissions of 1 kg CO_2. The characterisation factor of CH_4 is therefore 25.

To clarify this, an example is given: The LCI results CO_2 and CH_4 are assigned to the impact category Climate change which is calculated by the indicator *Radiative Forcing* [W/m^2]. Then the characterisation factor converts the result into global warming potential, which is defined as the *Impact Category Indicator Result* [kg CO_2-Equivalent]. The indicator result represents the potential environmental impact and is intended to reflect the aggregate emissions for each impact category.

12

Figure 6 below depicts the steps of a characterisation model.

| | IMPACT | | |
| LCI | CATEGORIES | FACTORS | LCIA |

Emissions to air

CO_2 1.3 kg
CO   3 kg
CH_4 6 kg

GWP

1.3 kg CO_2 * 1
3 kg CO * 3
6 kg CH_4 * 25

160.3 kg CO_2Eq.

SO_2 0.001 kg
NO_x 0.08 kg
HCl   0.9 kg

AP

0.001 kg SO_2 * 1
0.08 kg NO_x * 0.7
0.9 kg HCl * 0.88

0.849 kg SO_2Eq.

Emissions to water

PO_4 2 kg
NH_3 0.1 kg

EP

0.08 kg NO_x * 0.13
2kg PO_4 * 1
0.1 kg NH_3 * 0.33

2.043 kg PO_4Eq.

CLASSIFICATION   CHARACTERISATION
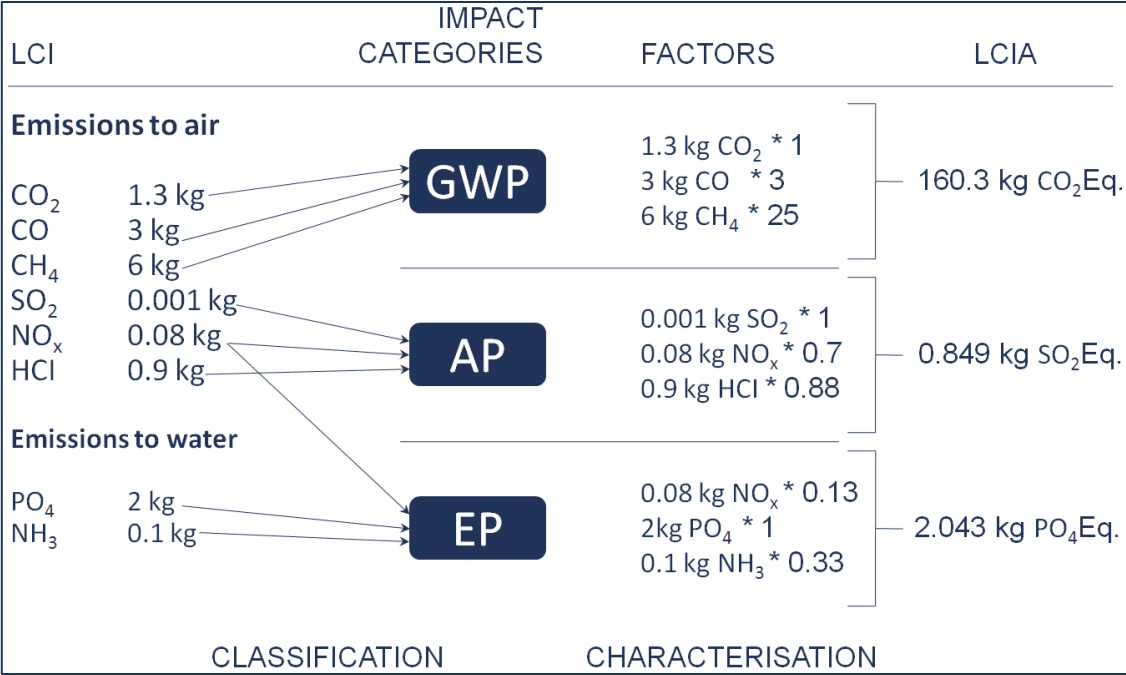
Figure 6 - An example of an environmental characterisation model

With regards to LNG as fuels, the most essential impact categories that reflect the impacts of fossil fuel are climate change, acidification and eutrophication, toxic effects on humans and ecosystems, and depletion of resources. As mentioned in the previous the scope of this thesis is limited to greenhouse gas emissions.

The biggest environmental concern associated with GHG emissions is climate change. Although climate change has a wide range of consequences, such as rising sea levels, extreme weather, changes to agriculture and human health issues, assessing these are not of particular interest to this analysis. A midpoint-interpretation of climate change is therefore sufficient.

Consequently this analysis will be a *Problem-Oriented* LCA (problem- and damage-oriented approaches are described in the project thesis, chapter 4.3.3 (Ryste 2011). *The CML 2001* assessment method is a problem-oriented model which is well-suited for the analysis. The method will be described in chapter 6.5.1.

As described in the previous the characterisation factor related to climate change is global warming potential. GWP will therefore be described in detail in the following.

3.3.2 Global Warming Potential

Global warming potential is a simplified index based on radiative properties, used to estimate the potential future impact on a climate system due to different gas emissions, also known as the carbon footprint.

The Climate Change report from IPCC describes the GWP thoroughly (IPCC 2007):

The global warming potential is a well-established and well-defined physical metric that compares the integrated radiative forcing of two greenhouse gases over some chosen time period resulting from pulse emissions of an equal mass. Radiative forcing itself is a fundamental physical parameter that quantifies a primary way in which human activity causes climate to change.

The IPCC has created a characterisation model for GWP for 20, 50 and 100 year perspectives. The numerical value of the GWP can change significantly with the choice of time horizon. The Kyoto Protocol is, for instance, based on the GWP with a 100 year time horizon.

The GWP is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas (IPCC 2001). The equation in Figure 7 below demonstrates this.

$$GWP(x) = \frac{\int_0^{TH} a_x \cdot [x(t)] \, dt}{\int_0^{TH} a_r \cdot [r(t)] \, dt}$$

Figure 7 - The Global Warming Potential Integral

The GWPs of various greenhouse gases can then be easily compared to determine which will cause the greatest integrated radiative forcing over the time horizon of interest. Table 1 below lists the global warming potentials of some of the common greenhouse gases (IPCC 2001).

Species	Chemical formula	GWP_{100}
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298
HFCs	-	124 – 14 800
Sulphur hexafluoride	SF_6	22 800
PFCs	-	7 390 – 12 200

Table 1 - Global Warming Potential for common Greenhouse Gases

4 The LNG Value Chain

Bunkering of LNG has already been identified as the process of most interest to the analysis in this thesis. Nevertheless other stages of the LNG chain should be documented, not least to create a holistic account and provide better understanding of the whole life cycle of LNG as a ship fuel.

In the preceding project thesis, five stages of the value chain were highlighted as areas of interest for the following analysis (Ryste 2011). This chapter will present these in more detail. The hotspot of the analysis, bunkering of LNG, will be presented in-depth in chapter 5, along with descriptions of the equipment used both on land at the terminal, and on board an LNG fuelled vessel, as well as all emissions associated with bunkering.

4.1 Transportation - LNG carriers

LNG has since 1964 been transported by LNG carriers in specially designed tanks with insulated walls, where LNG is kept in liquid form by the concept of auto refrigeration which was described in chapter 2.3. The resulting boil-off gas is vented out of the storage tank and used as fuel for propulsion, or to generate electricity on board the vessel.

LNG is a cryogenic fluid. All containment and transfer equipment for cryogenics must be made to withstand the low temperature, and should be insulated to keep the LNG refrigerated. Containment tanks must also be designed to take higher pressures so as to be able to contain the LNG without creating vapour (if the pressure is kept constant, the LNG will not boil, as explained prior).

4.1.1 Cryogenic Tanks

There are two main types of containment systems for LNG carriers: *Membrane* and *Self-supporting.* These are designed by the two main tank designers Gaztransport & Technigaz (GTT) and Moss Maritime, respectively. Membrane tanks from GTT are usually of prismatic shape, directly supported by the inner hull. Figure 8 illustrates the GTT system, showing that the whole tank is integrated inside the ship hull (GTT 2009).

Figure 8 - LNG carrier with prismatic membrane containment system

The Moss spherical self-supporting tank claims to be the safest and most reliable LNG containment system on the market. Moss LNG tanks do not form a part of the ship's hull strength and are not affected by possible damage to the ship's hull (Moss Maritime 2012). This eliminates the need for a full secondary barrier between the tank and hull, such as membrane tanks do. LNG carriers with the MOSS system are recognisable by the tanks protruding from the hull as Figure 9 (NWS 2011) below illustrates.
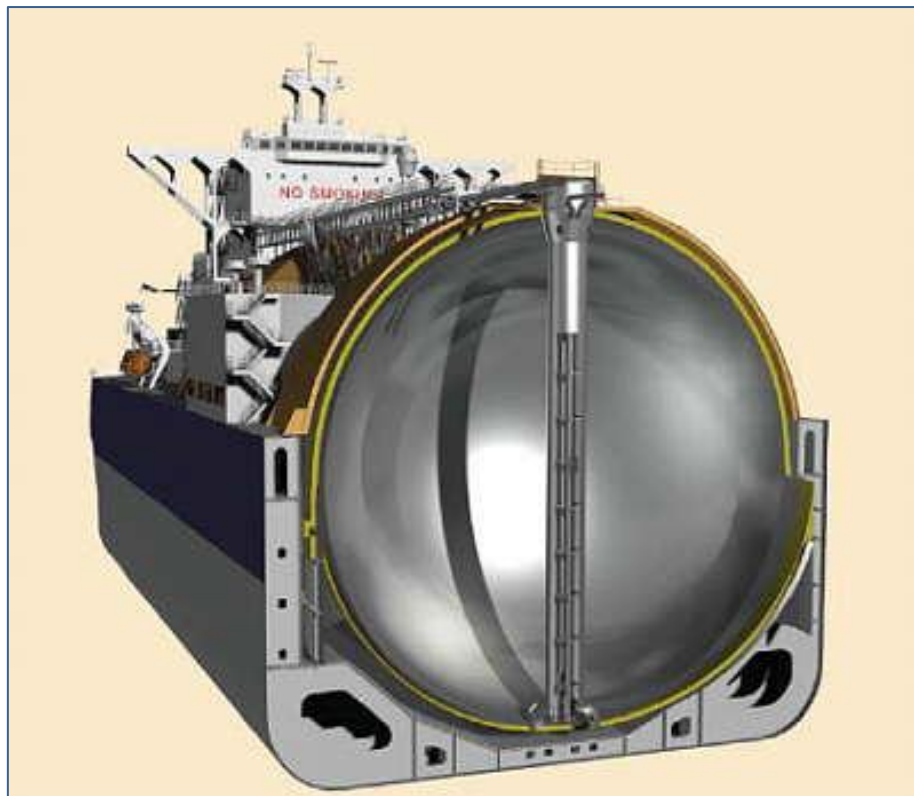
Figure 9 - LNG carrier with the self-supporting Moss containment system

Most LNG carriers have four to six tanks, placed along the centre line of the hull. The tanks are typically manufactured from aluminium or stainless steel, with tank volumes ranging from 147-270 000 [m^3]. The Moss spherical tank weighs approximately 800 [tonnes] (NWS 2011). Membrane tanks are insulated with polyurethane foam in two layers (GTT 2009), whilst Moss tanks are insulated with polyurethane purged with nitrogen in a single layer (NWS 2011).

4.1.2 Loading

The following description of the preparations for LNG loading is provided by (Liquefied Gas Carriers 2011).

Before loading, tanks are inerted with nitrogen or carbon dioxide to remove the tanks of oxygen. This is to avoid the risk of having an explosive atmosphere in the tanks. Inert gas must then be displaced to avoid formation of water condensate. This is done by blowing a small amount of warmed up LNG through the tanks, sending the inert gas to shore in pipelines where it is burnt to avoid venting of methane gas to the atmosphere.

Tanks must then be cooled down to create the appropriate conditions for cryogenic LNG. This is done by spraying small amounts of cold LNG onto the tank walls via spray nozzles placed on the top of each tank. This slowly cools down the tanks to at least -140°C, a process which takes up to 36 hours. Loading can then begin. Excess gas created during loading is sent to shore by high duty compressors, where it is re-liquefied or burnt at a flare stack.

Loading of LNG carriers has a sequence similar to LNG bunkering, which is described in detail in chapter 5.1.

4.1.3 Offloading

Presuming that most LNG is kept refrigerated throughout the voyage without significant temperature rise (by use of auto refrigeration), offloading at the LNG terminal will not be time-consuming. The LNG terminal will have an inerted receiving system with precooled hoses and storage tanks, ready for loading.

4.2 Storage on Land

At LNG terminals, LNG is stored in large cryogenic tanks under strict regulations of observation and maintenance. The tanks are equipped with excellent insulation to keep the LNG refrigerated. However, no insulation is perfect. Depending on the length of time the LNG is stored before use, some heat exchange may occur. Referring to chapter 2.3, heat exchange leads to the production of BOG.

The Norwegian Standard for Installation and equipment for liquefied natural gas (NS 2007) states that:

Provisions should be taken during design and operation to ensure that potential gas waste streams, wherever practically possible, are recovered and not routed to flare or vent during the normal operation of the plant.

There is however no standard practice that applies for all LNG facilities of how this boil-off is handled, but there are some known alternatives:

1. Use a pressurised vapour return line to send the boil-off back to the storage tank
2. Use a re-liquefaction plant to re-liquefy the gas before it is returned to the LNG tank
3. Use the boil-off to create electricity
4. Vent the BOG to the air

The choice of alternatives depends strongly on the amount of BOG created. If there is little BOG, the environmental gain of using either a re-liquefaction unit or an electricity generator will be lost in the production of these large units, as well as the units being highly cost-inefficient.

The only LNG storage tanks to produce enough BOG for this to be energy and cost-efficient, are at large LNG liquefaction plants and LNG export terminals (Wold 2012). At LNG terminals such as Ågotnes, LNG is constantly used, and the storage tanks are so small that they require continuous re-filling. The time in storage is therefore so short that little BOG is produced (the time the tank can hold LNG without venting BOG is called "holding time". By codes in US and Canada the holding time is five days (Ursan 2011)). Also, using boil-off to produce electricity is a fairly undeveloped idea in Norway, and these two alternatives are therefore unlikely to be used at Norwegian terminals.

Venting the boil-off to the air is the most unwanted alternative; however this is likely to be the standard procedure at some terminals. Using a vapour return line is the most cost-efficient and environmentally sound alternative.

4.3 On Board Ship

The final stage of the LNG value chain is the on board process and combustion in the engine, also called the *Use* stage of the entire life cycle. Once LNG has entered the fuel tank and engine room, *Gas Detection* and *Emergency Shut Down* systems make sure the LNG is monitored and safe at all times. Pipes are not required to be double-walled due to this extensive monitoring.

LNG is kept in the bunker tank until it is needed in the engine room. From the bunker tanks, the LNG is sent through a vaporiser and heated up before it is sent through to the engine. No pumps are needed to transfer LNG; this is done by differential pressure. Any boil-off that occurs during storage is sent directly to the engine (Strøm 2012).

The amount of emissions caused in the use stage depends largely on the type of engine used, the type of vessel and its operational profile. If one wishes to be very thorough in analysing this stage, the type of LNG fuel system, as well as the equipment used in the LNG engine, also matters. For example, insulation in the bunker tank can either be foam or vacuum, since vacuum is not a material, this choice directly affects the amount of emissions.

Two LNG fuel systems are shown below to demonstrate the alternatives. The first (Figure 10, (Harperscheidt 2011)) is a system using a vacuum insulated tank with vaporisers. The *Tank Vaporiser* extracts LNG from the tank and sends gas into the top of the tank to keep the pressure under control. The *LNG Vaporiser* converts the liquid to gas form before it is sent to the heater. Thus the gas is sent directly to the engine at the correct temperature and pressure. The system uses differential pressure to transfer the gas, eliminating the need for transfer pumps.
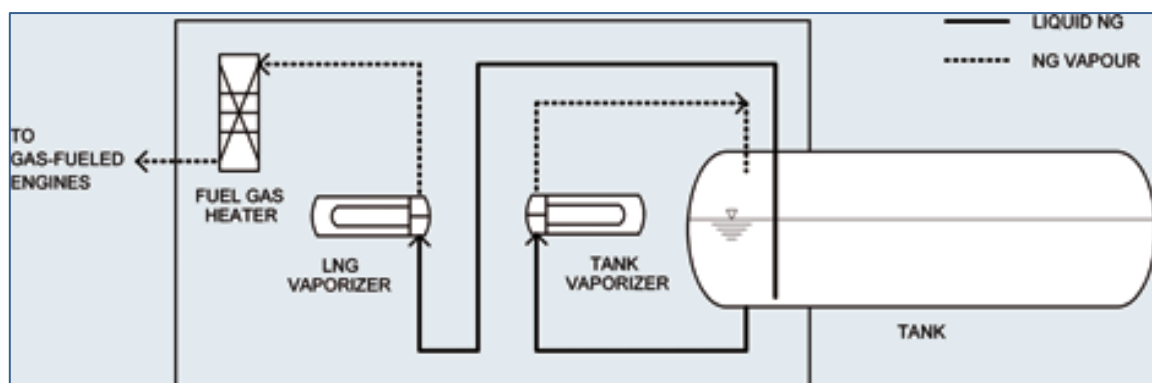
Figure 10 - Vacuum insulated tank with vaporisers

The second example (Figure 11, (Harperscheidt 2011)) is a fuel gas system with a compressor. This means that the tank is foam insulated rather than vacuum insulated, and therefore produces some amount of BOG. This can be sent directly to the engine as mentioned earlier, and the pressure in the tank is thereby controlled by venting. Because of this, the LNG must be sent through a compressor to increase its pressure, before it can enter the engine room.
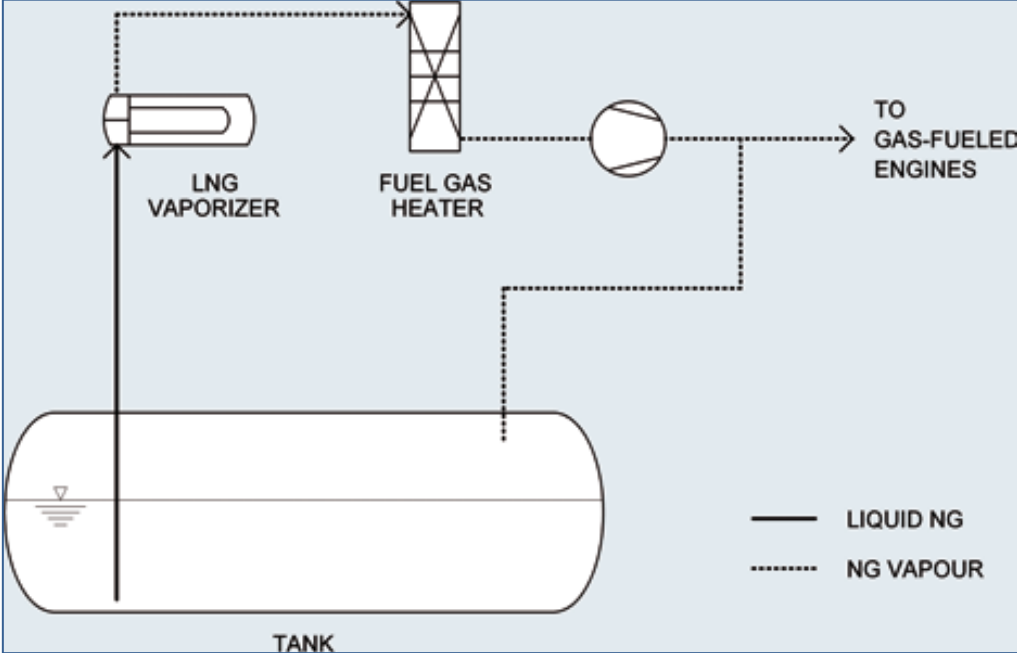
Figure 11 - Foam insulated tank with a compressor

A complete LNG system is illustrated in Figure 12. The two tanks each have a capacity of 250 [m^3], serving the two LNG engines on board this vessel, the *Island Crusader*. Typically, LNG fuelled offshore vessels are also equipped with diesel engines so they can operate both on LNG and on diesel. This is to ensure an operation is not affected by low LNG availability (due to few bunkering stations). In addition, diesel electric propulsion offers higher propeller efficiencies than with LNG at low engine loads (Æsøy, Einang et al. 2011). The *Island Crusader* has two auxiliary diesel engines included in its engine system for these purposes.
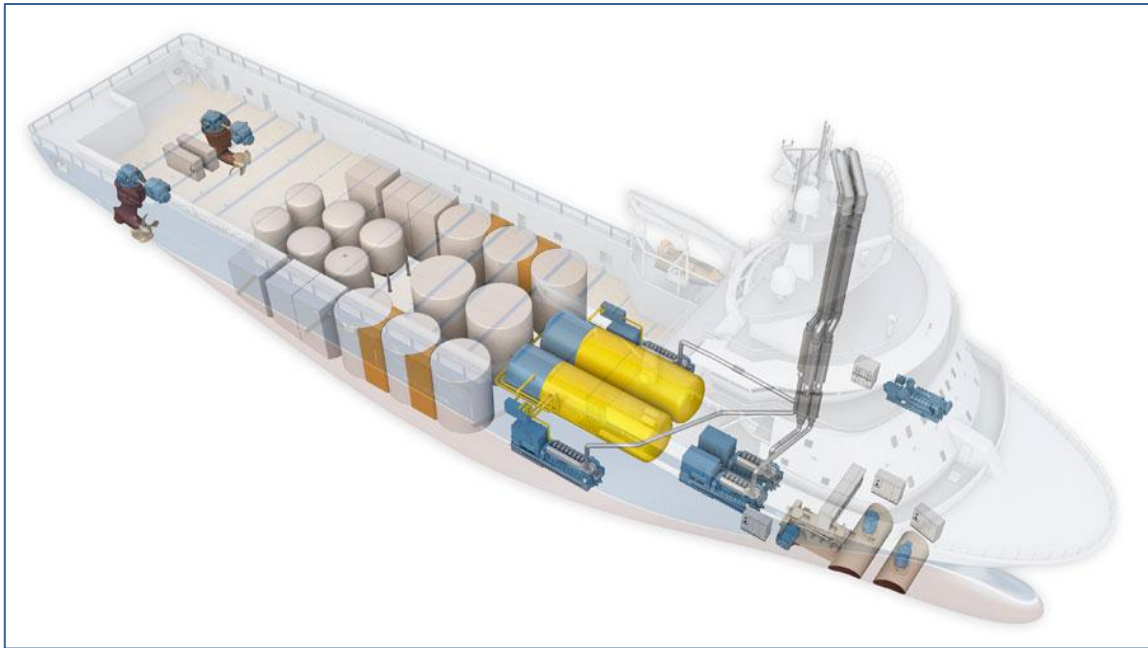
Figure 12 - Illustration of an LNG system. Illustration: Rolls Royce

Some vessels have a dual-fuel system, which allows the vessel to run on both diesel and LNG intermittently without the need of two separate engine systems. Figure 13 (Æsøy, Einang et al. 2011) is an example of a diesel-electric system for a dual-fuel engine on an offshore supply vessel fuelled by LNG and MDO.
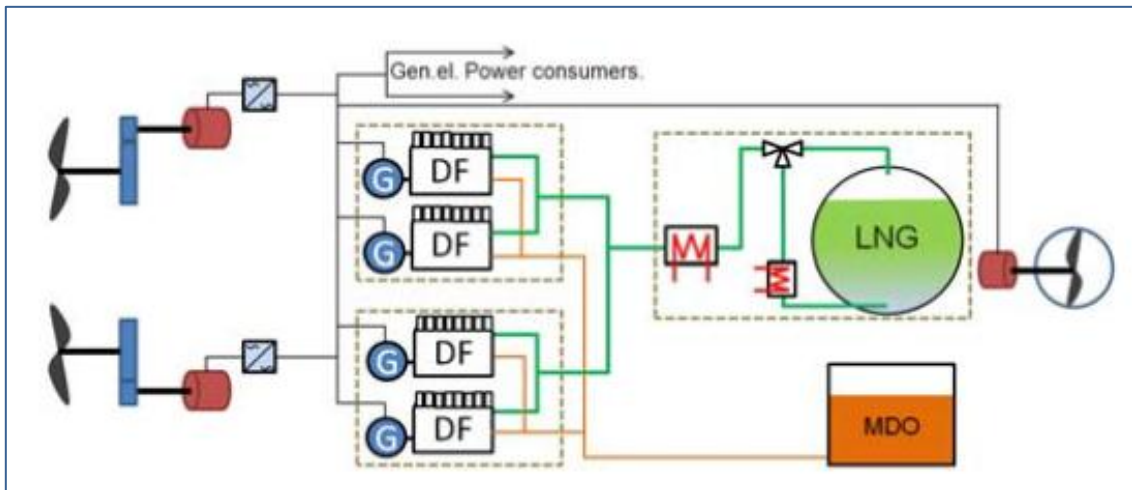
Figure 13 - Dual fuel propulsion on a Platform Supply Vessel

Two examples of engines used in such systems are the Rolls Royce Bergen B35:40 gas engine (Rolls Royce 2009), and the Wärtsilä 34DF dual-fuel engine (Wärtsilä 2012). Rolls Royce gas engines have a fuel oil consumption of 33 g/kWh less than a general diesel engine (Haack 2011). However, some engines have unfortunately proven to produce a methane slip. Some say most engines have been updated and no longer have this problem; however documentation to prove this has been hard to come by.

If this stage is to be analysed in detail, the greatest emission sources apart from the combustion, are due to energy used to vaporise and heat up the LNG, as well as potential compressors to pressurise the gas.

For more information about rules and regulations regarding gas fuelled engines, please refer to DNV's rules for classification (DNV 2011).

5   Bunkering

LNG can be transferred to LNG fuelled vessels using three main methods. The two most widely used are land-to-ship, known as *Intermediary Tank-to-Ship via Pipeline* (ITPS), and *Truck-to-Ship* (TTS). The third option is *Ship-to-Ship* (STS) bunkering which takes place between a bunker vessel and a receiving vessel, possible both in ports and at sea. However, for LNG bunkering, this is a concept under development and is currently being tested by the "Joint Industry Project" lead by the Swedish Marine Technology Forum (Swedish MT Forum, Linde Cryo AB et al. 2010). TTS bunkering is often used for small scale LNG vessels such as passenger ferries, and can be done at any port where a nitrogen battery and inert line for the inerting process is provided.

The most common bunkering process for a typical offshore supply vessel at this time is ITPS, and is the bunkering option chosen for the analysis in this thesis. For this bunkering option, LNG is provided via a pipeline from an intermediary storage tank at the terminal. Not all LNG terminals are suitable for ITPS bunkering, due to berth restrictions and pipeline distances, which affects LNG fuelling availability.

Using LNG as fuel in supply vessels is a fairly new development, and even though Norway is the most developed in Europe within LNG terminals (42 in total, (ÅF&SSPA 2011)), only five terminals offer bunkering services for vessels of medium/large scale (Strøm 2012). This bodes for some difficulties when trying to make LNG available to a broader selection of ships, and to gain market value for using LNG as a fuel.

5.1   The bunkering process

Bunkering from land is a fairly extensive procedure which starts before the receiving vessel arrives at the terminal. All on-land activities start while the ship is approaching the terminal and during docking. When the system has been precooled and the vessel has docked, the two bunkering facilities (both on shore and on board) must be connected safely and then rinsed and prepared for the transfer. The same rinsing procedures must also be done after bunkering is finished, and finally the bunkering systems can be disconnected and the vessel is ready to go.

All the processes involved in bunkering are listed below, along with a more detailed description in the following.

- Pre-cooling of system – 45 minutes
- Pre-cooling of cargo pumps – 16 minutes
- Connect hose-system - 5 minutes
- Prepare (rinse) system
    - Inerting (N_2) – 5 minutes
    - Purging (NG blows out N_2) – 2 minutes
- Open valves
- Transfer – 120 minutes
- Empty (rinse)system
    - Stripping – 4 minutes
    - Inerting (NG) – 5 minutes
    - Purging (N_2 blows out NG) – 4 minutes
- Close valves
- Disconnect

The following descriptions are based on standard procedures at the *CCB LNG Terminal* at *Ågotnes* outside Bergen. Details have been provided by Katrine Strøm at DNV (Strøm 2012).

Precooling of system

Between bunkering operations, the whole on-land LNG system returns to atmospheric conditions. To ensure that the LNG transferred to the receiving vessel is of the right temperature and pressure, the system must be cooled down prior to commencing transferral. If the pumps and hoses are not pre-cooled, the high temperature difference can lead to rapid phase transition and a high pressure build up in the piping system. This can lead to burst valves (Bjøndal 2012), and in the worst case scenario, to cavitation in the system (Strøm 2012). On-land pre-cooling takes approximately 45 minutes and is operated by pumps, requiring the use of an energy source.

Cooling is done by pumping LNG through the system in a loop. During this process, the LNG looping the system gets warmed up, contributing to a temperature rise in the storage tank. The LNG reacts to this temperature increase by creating boil-off gas (BOG) which leads to increased pressure in the tank. In some cases, this creates a substantial amount of BOG, and only by venting this BOG the LNG is restored to its normal conditions (the principle is called auto refrigeration, as described in chapter 2.3). A major concern here is that venting is done directly to air, as witnessed at the CCB terminal Ågotnes (Wold 2012). The standard procedure for BOG recovery is not known, but some options for BOG handling were discussed in chapter 4.2.

Pre-cooling of cargo pumps

When the receiving vessel has docked, the vessel's cargo pumps must also be cooled. This is the same process as described above, using LNG residues in the ships bunker tank. The whole operation takes approximately 16 minutes.

Grounding and connection

Before the bunkering preparations can begin, the on shore and on board systems must be securely connected, and the pipes and hoses grounded. This procedure takes approximately 5 minutes and is done manually.

Inerting of system

Bunkering of LNG in a safe manner according to the regulations requires some steps of preparation of the system. To ensure there is no risk of explosion, moisture and oxygen is removed from the pipes and hoses by injecting nitrogen gas (N_2) into the system. This ensures there is not an explosive atmosphere in the tanks and pipes. The process takes five minutes, and requires the use of an energy source.

Purging of system

After inerting, the system is contaminated with nitrogen. Some engines are sensitive to N_2 and so standard procedure is to rinse the system of any nitrogen residues at this point. The process is called purging, and takes approximately two minutes. At most terminals purging is done by injecting natural gas into the system to blow out the nitrogen. This is then vented directly to air through a gas mast, resulting in the direct emissions of natural gas and nitrogen (Strøm 2012). Although nitrogen does not pose a great threat to the environment, natural gas certainly does. The operation requires an energy source, as well as contributing to direct emissions.

Transfer

The system has now been cautiously prepared, and the filling process can commence. The process simply requires a pump to send the LNG through the system. The time to complete this operation of course depends on how much LNG is to be transferred. As a reference value, the MS *Viking Energy* has an Aga Cryo LNG tank with an operational capacity of 220 [m^3] (Eidesvik Shipping AS 2007). The typical transfer rate during ITPS bunkering is 100 [m^3/h]. In comparison, TTS bunkering has a transfer rate of [50 m^3/h], and a large LNG carrier has a transfer rate up to 1000 [m^3/h] during loading. For the example above, the filling process will take approximately 130 minutes, but the average filling process takes 120 minutes (Strøm 2012). An LNG fuel tank shall not be filled with more than 95 % of the tank's volume.
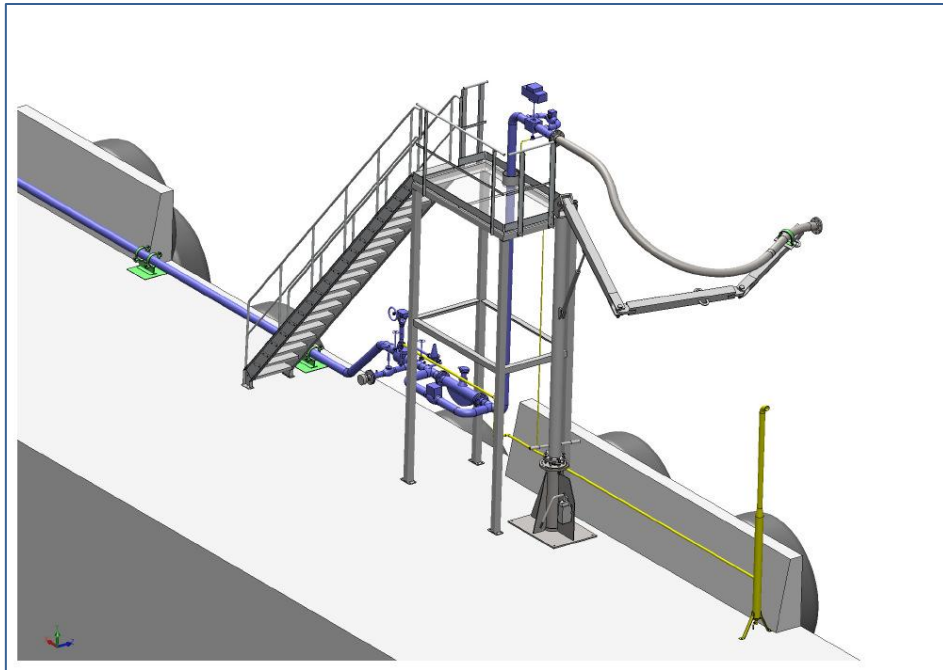
Figure 14 – LNG bunkering unit

Figure 14 (Gassteknikk Ltd. 2012) depicts an automatic transfer unit equipped with a remotely controlled bunker-hose arm. The purple pipes are the LNG terminal pipes from the storage tank. Mounted to the arm is the flexible bunkering hose.

Differential Pressure between the land system and on board system can, in theory, push the LNG through the system without the need of pumps. The ability to do this throughout the whole filling process depends largely on the magnitude of differential pressure and the time available. If pressure build-up is low, the transfer rate also decreases. Most bunkering operations are on a time schedule, and without the pumps to adjust and control the transfer rate, this method is seldom used. Moreover, some on board tanks are "low pressure tanks" which do not create the differential pressure required to do this, the same goes for excessively long pipes.

During filling the pressure in the receiving tank will be continuously increasing, and a pressure build up can occur. To control this, the process called *Sequential Filling* is used, by which cold LNG is sprayed into the tank at the top, whilst also being pumped into the tank at the bottom. This causes condensation in the tank which thereby reduces the pressure. This is also known as vapour collapse, and the system is depicted in Figure 15 (Ursan 2011). There is therefore no production of BOG during filling.
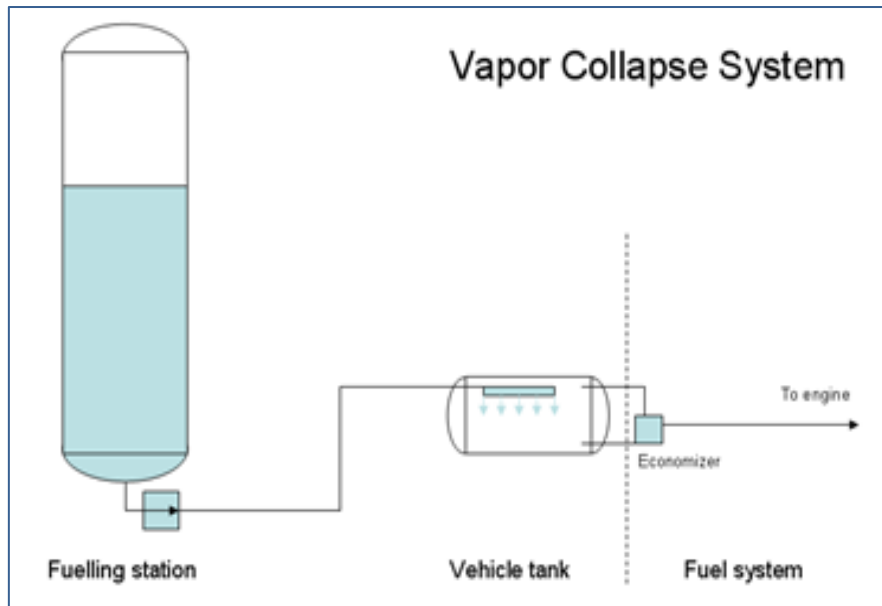
Figure 15 - Vapour return system for sequential filling

However, in some cases where sequential filling is not used, or it does not control the pressure correctly, some vapour will be produced, which can potentially lead to methane emissions. To avoid this, the vapour can be processed in two ways:

1. Many LNG terminals use a vapour return system, which securely re-routes the vapour back to the storage tank through a vapour return line. Due to increased pressure in the return line, the vapour is restored to its liquid state before entering the tank. Figure 16 (Ursan 2011) depicts a vapour return system. No venting is necessary, but this does however require an energy source such as a pump.
2. If a vapour return system is not available, an alternative is to vent vapour directly to the air. However this can have a substantial negative impact on the environment due to the high methane content, and should be avoided at all costs.
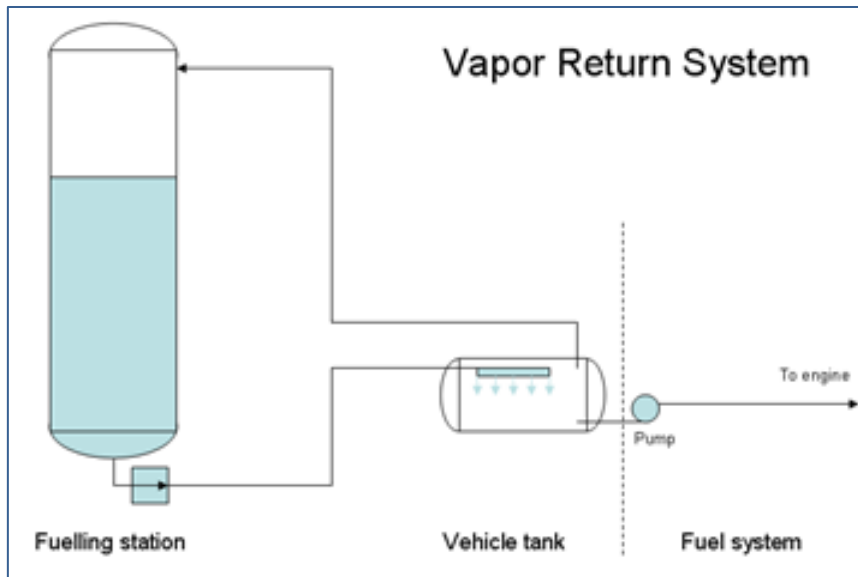
Figure 16 - Vapour return system for vapour recovery during fuelling

Stripping of the system

When the tank is fully bunkered, the pipes and hoses need to be emptied for LNG before they are restored to stand-still mode. Stripping allows the remaining LNG to be sent back to the storage or bunker tank by use of the pressure difference; When the valves on each side of the transfer line are closed, a pressure build up occurs due to rapid phase transition and heating (LNG expands approximately 600 volume units from liquid phase to gas phase) (Strøm 2012). This forces the LNG back to the respective tanks, without the need of external pressure. The procedure takes approximately four minutes, and does not contribute to any emissions.

Inerting of system

To ensure all residual of LNG is removed from the system, the pipes and hoses are once again inerted. This time warm natural gas is injected through the system (Strøm 2012) to restore the system to its atmospheric temperature (opposite of the inerting that happens prior to filling). As before, the process takes five minutes and requires an energy source.

Purging of system

As with the inerting process, purging after filling is also opposite to prior. Now, nitrogen is injected into the system to blow out the remains of natural gas. As before, this is vented directly to air, posing an environmental impact. The process takes approximately four minutes and requires an energy source. To avoid confusion, the inerting and purging process that takes place before bunkering will be referred to as "preparation" whilst what takes place after bunkering is referred to as "rinsing".

Disconnect hoses

Now that the system has been completely rinsed, and the LNG fuelled ship is fully tanked, the transfer hoses can be disconnected safely. The whole bunkering process all together takes an average of three hours.

In literature, the term bunker tank is commonly referred to as the tank supplying the bunker (LNG), and storage tank refers to the tank receiving the LNG. In this paper, the term bunker tank refers to the tank receiving LNG on board the LNG fuelled vessel, whilst storage tank refers to the on-land tank providing the LNG for the transfer operation. Take care not to get these two confused.

5.2 The main sources of emissions

In order to correctly implement the product system for the bunkering process in the LCA software, GaBi, and ensure good results, all the sources of emissions should be determined and evaluated. Relative to the whole LNG value chain, the bunkering process contributes only a small amount to the environmental impact of LNG's life cycle. Therefore some of the sources of emissions in this stage can and should be left out.

As a result, the system boundaries of the product system will be clearly defined, and the goal of this chapter is to come to a final conclusion about the product system to be analysed.

Emissions are the total amount of environmental stressors emitted: Direct and indirect emissions. The direct emissions in this case are those in the exhaust gas when burning natural gas and any gas leaks and venting that may occur in the product system. Indirect emissions are such as those coming from processing, production and transport (Ryste 2011).

5.2.1 Direct Emissions

There are three processes in which direct emissions occur in the bunkering stage. These are all during venting of gas to the atmosphere:

- During pre-cooling of the system, BOG is vented to the air (see chapter 5.1)
- During preparation of the system, inerting and purging leads to venting of natural gas and nitrogen
- As does rinsing the system after bunkering is finished

5.2.2 Manufacturing

Manufacturing of the equipment used in the bunkering process also contributes to life cycle emissions. This thesis will focus on analysing only the special cryogenic equipment associated with the terminal and bunkering. Other manufacturing elements that potentially could be included are pumps, valves, machines and electrical equipment used in the process. These have however been deemed too specific for this purpose and will not be included in the analysis. The equipment included is:

- LNG storage tank at the LNG terminal
- Piping from the storage tank to the bunkering facility at the dock
- Bunkering hose
- LNG fuel tank on board the ship

Many bunkering facilities use a vapour return system, which requires a vapour return line in addition to the bunkering hose. However vapour is not a cryogenic and does therefore not have the same requirements for containment, and is therefore not included.

Cryogenic fluids require equipment manufactured with double-piping/-walls and insulation, and must withstand cryogenic temperatures. This is the main difference between a normal fuel tank/pipe and bunker hose, and cryogenic tanks and hoses. This indicates that manufacturing of this equipment requires almost double the amount of steel, harder steels as well as a good insulating material over normal fuel tank/pipe and bunkering equipment.

Additionally, LNG takes up roughly twice the volume of fuel oil for the same energy content due to its low density (Harperscheidt 2011). This means that the fuel tank either has to be bigger or the vessels have to bunker more frequently. Since LNG bunkering has poor availability, this problem is compensated for by using bigger bunker tanks, often double the size of a diesel fuel tank. Since more steel is needed, the emissions during production will be higher.

5.2.2.1 LNG Storage tank

Information about LNG bunkering terminal storage tanks is deficient, however Figure 17 (from a video of LNG bunkering at Ågotnes posted on the DNV blog "LNG – Energy of the Future" (Blikom 2011)) shows a cylindrical storage tank. It has a capacity of 500 [m^3], and is estimated to be approximately 15 [m] long.

Figure 17 - Cylindrical LNG storage tank

This tank looks similar to the cylindrical IMO type C tank as described by (Harperscheidt 2011), shown in Figure 17. The inner tank is usually made of *Austenitic Stainless Steel* because of its excellent low-temperature characteristics and stable quality (Osaka Gas 2012). Outer tanks do not have the same requirements to withstand cryogenic temperatures, so *Carbon Alloys* are used (see chapter 6.3.1). Some LNG tanks also have a concrete outer wall to increase insulation effectiveness. However tanks of the dimension as shown above are too small to require this.

Cryogenic equipment often requires insulation to keep the LNG refrigerated. There are many types of insulation available, such as perlite, polyurethane foam, spray foam and gels. A newer development that is becoming increasingly popular is vacuum insulation (PHPK Technologies 2008). The annular space between the inner and outer pipe is vacuumed and sealed to create a static vacuum which will last throughout the products lifetime. This vacuum nearly eliminates the convective heat transfer into the LNG containment system and makes this system thermally efficient (Bonn 2004).

5.2.2.2 LNG piping

As with most equipment handling cryogenic liquids, the LNG piping also requires double piping and insulation.

As with the storage tanks, austenitic stainless steel is used for LNG piping, along with carbon alloys for outer piping. Depending on the length of the pipes, bent piping may be required to absorb thermal contraction (Osaka Gas 2012). Figure 18 below depicts stainless steel bent LNG piping.
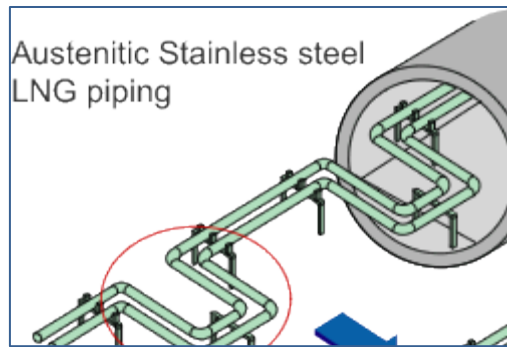
Figure 18 - An example of Austenitic Stainless Steel LNG piping

For piping, the choice of whether to use vacuum (VIP) or mechanical insulation (MIP) depends on the length of the pipe. For pipes longer than 200 [m] it is economical to use VIP, but for those shorter, MIP is preferred (Bonn 2004). The pipes at Ågotnes are approximately 300[m] long, it is assumed VIP is used.

5.2.2.3 Bunker hose

An LNG bunker hoses main requirement is flexibility. It is therefore a single-piped hose without insulation. To strengthen the hose it contains an outer layer of steel braid. Flexibility requirements put greater demands on the material used, the manufacturing method and maintenance due to requirements of enhanced resistance to fatigue and tension loads, as well as the ability to bend. Even so, the common material for bunker hoses is, as for tanks and pipes, austenitic stainless steel.

Figure 19 - Bunker hose (Fuelling of MS *Tresfjord* in Trondheim)

Figure 19 shows a bunker hose of this type, here used during TTS bunkering of MS *Tresfjord* at Trondheim harbour, *Pir 1*.

Since the bunker hose lacks insulation, the cryogenic fluid freezes the equipment during bunkering and the hose eventually looks like Figure 20 below. This may affect the temperature of the LNG entering the bunker tank.

Figure 20 - Frozen bunker hose without insulation

5.2.2.4 Fuel Tank

There are three main types of self-supporting fuel tanks as defined in the IMO IGC Code[1]

- Type A – designed as a ship structure
- Type B – prismatic or spherical design
- Type C – designed as a cylindrical pressure vessel

Type C tank is the only one that can control the pressure in the tank itself, without the requirement of pressure maintenance as the other two. Also, type A and B do not have secondary barriers to the surroundings. Therefore the type C is the widely preferred tank (IMO 1996). Figure 21 shows a cylindrical IMO type C fuel tank (Harperscheidt 2011).

---

[1] International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk

Figure 21 - Cylindrical IMO Type C LNG fuel tank

As mentioned earlier, cryogenic equipment is usually made of austenitic stainless steel and carbon alloys, this also holds for bunker tanks.

LNG fuel tanks are roughly double the size of a regular diesel tank since LNG takes up roughly twice the volume of fuel oil for the same energy content. This puts restrictions and additional requirements to the placement of the fuel tank on board the ship. One alternative currently being evaluated is placing the bunker tanks below the accommodation unit if the vessel (Blikom 2011).

Many fuel tanks are vacuum insulated, however this is limited to cylindrical shapes and does not allow for in-tank inspections or mounting of in-tank equipment since there is no manhole. Therefore vacuum insulation is normally only used in small tanks. Tanks that exceed 500 [m^2], or that are of bi-lobe or conical shape, require other insulation such as foam or special insulation panels (Harperscheidt 2011). Supply vessel fuel tanks seldom exceed 500 [m^2], and therefore vacuum insulation is opted for in this analysis.

5.2.3 Energy use
A most interesting part of this analysis is the energy use throughout the bunkering process. LNG bunkering requires substantially more preparation and maintenance of the system than for other fuels. Almost all these activities require power, which leads to the question whether the energy use is substantially higher than for diesel bunkering. In addition, the filling process takes longer with LNG due to the need to fill double the amount of fuel (refer to chapter 5.2.2). This can potentially increase life cycle emissions a great deal.

Stages where a power source is needed are:

- Pre-cooling of the system
- Preparation
    - Inerting
    - Purging
- Filling sequence
- Rinsing
    - Inerting
    - Purging
- Storage

Most of these energy consumers are cryogenic pumps, as described in the following.

5.2.3.1 Pumps

To pump the LNG around the on-land system and on board the LNG vessel, two separate pumping systems are used: one connected to the on-land LNG terminal, and one at the LNG filling station connected to the vessel. It is assumed that the on-land pump is used in all cooling, inerting and purging processes, whilst the transfer-pump is solely used for the actual filling. ACD, a world leading supplier of cryogenic pumps, provides useful information about their pumps online.

Two of their pumps have therefore been chosen to represent the pumps used at Ågotnes. The two chosen are presented in Figure 22 and 23, and described below, (ACD 2012).

- AC-32: A seal-less pump for LNG filling and fuel loading with a maximum rating of 19 [kW]
- AC/TC.30: A close-coupled centrifugal pump for liquid storage transfer with a maximum rating of 75 [kW].
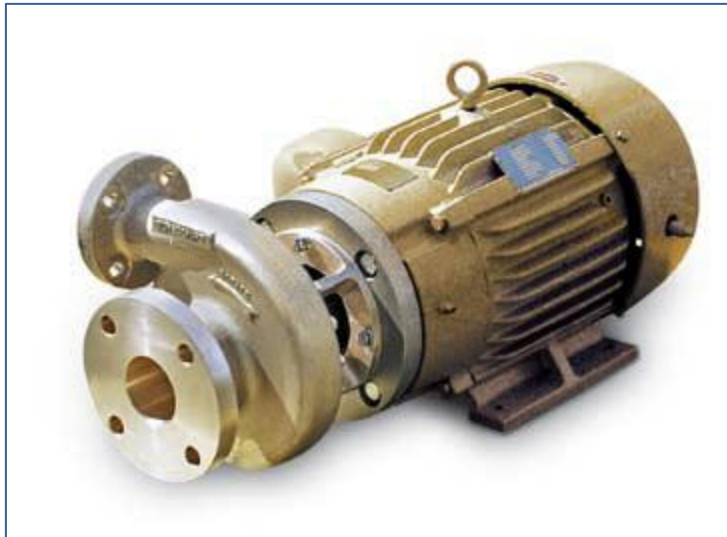
Figure 22 - ACD model AC-32 LNG pump

Figure 23 - ACD model AC/TC 30 LNG pump

6 The analysis

6.1 Goal and scope of the analysis

Before a GaBi analysis of the LCI can begin the goal and scope of the analysis shall be clearly stated and should be consistent with the intended application.

6.1.1 Goal

In the preceding chapters it has become clear that the process of most interest in the context of this analysis is the process of LNG bunkering. Research of countless life cycle studies has found that no analyses exist of this stage. It is therefore intriguing and poses a suitable hotspot for the screening analysis. Three areas draw attention to this hotspot:

1. Cryogenic fluids place strict requirements on the equipment, such as material strength and resistance to withstand cryogenic temperatures. Does manufacturing of this special equipment and the amounts of steel needed contribute substantially to the total environmental impact?
2. Bunkering of LNG is an extensive process requiring many steps of preparation and maintenance both before and after fuelling. This implies high energy use at the LNG terminal, how much does this affect the emissions?
3. Preparations at the terminal contribute to direct emissions of ventilated LNG. How does this affect the global warming potential?

The goal of the analysis is therefore to answer these three questions and supply sound results that can be added to life cycle studies where this step has been left out.

The results of the analysis have potential to highlight the problem areas regarding emissions. This can bring attention to the areas in the life cycle in need of emission reduction solutions. These will be discussed and possible solutions or suggestions to the problem will be evaluated.

6.1.2 Scope

The scope of the analysis has been simplified to a screening analysis as explained in chapter 3.2. The assessment is limited to a midpoint-evaluation of greenhouse gas emissions which will be interpreted in a problem-oriented perspective. The CML 2001 method will be used to evaluate the global warming potential of the resulting emissions.

Although LNG has been used in ferries since 2000, it is not yet widely used in offshore supply vessels. To create momentum around LNG as a fuel, more ocean-faring vessels need to switch to LNG. The analysis is therefore aimed at OSVs. Eidesvik and their ships MS *Viking Energy* and MS *Viking Queen* will be used as references.

The scope of the model to be implemented in GaBi is described in the following chapter.

6.2 The Product System

Now that all the operations and processes of LNG bunkering have been meticulously described and defined, it is time to set the system boundaries for the product system to be implemented in GaBi.

6.2.1 System Boundaries

Considering each system's relative contribution to the environmental impact it has been concluded that the on-land systems are of the most interest to the analysis. The on-board systems (bunker tank and cargo pumps) are of much smaller dimensions, thus contribute less to the overall emissions. Additionally, environmental analyses of LNG combustion are likely to include these steps, meaning they are better documented than the systems at the terminal.

The GaBi analysis therefore focuses on the manufacturing of the on-land terminal facilities, the direct emissions related to the bunkering process and the energy use throughout the system. The treatment of BOG at the LNG terminal during stand-still periods has also been left out of the analysis, as well as the energy associated with normal operation of the terminal. This is mainly due to the low availability of data at such a high level of detail.

Regarding the use of insulation in cryogenic equipment it has been decided that due to the increasing use of vacuum insulation, this will be used in the GaBi analysis. The only insulation flow available in GaBi is glass fibre composites, which does not meet the requirements of cryo-insulation. Since a user-defined flow for insulation would be difficult to implement, this is left out. Vacuum insulation also reduces manufacturing emissions since the production of an actual insulation material is taken out of the balance.

Depending on the extent of data included in the predefined flows in GaBi, some other processes will naturally be left out of the product system. For example, not all flows include data about extraction of resources for the production of steel, or the processes related to nitrogen production. This will be discussed further in the next chapter.

Figure 24 below depicts the complete product system that will be implemented in GaBi. The red arrows represent direct emissions of gases. The blocked blue arrows represent material flows and finally the through-blue arrows represent the energy use throughout the bunkering procedure.
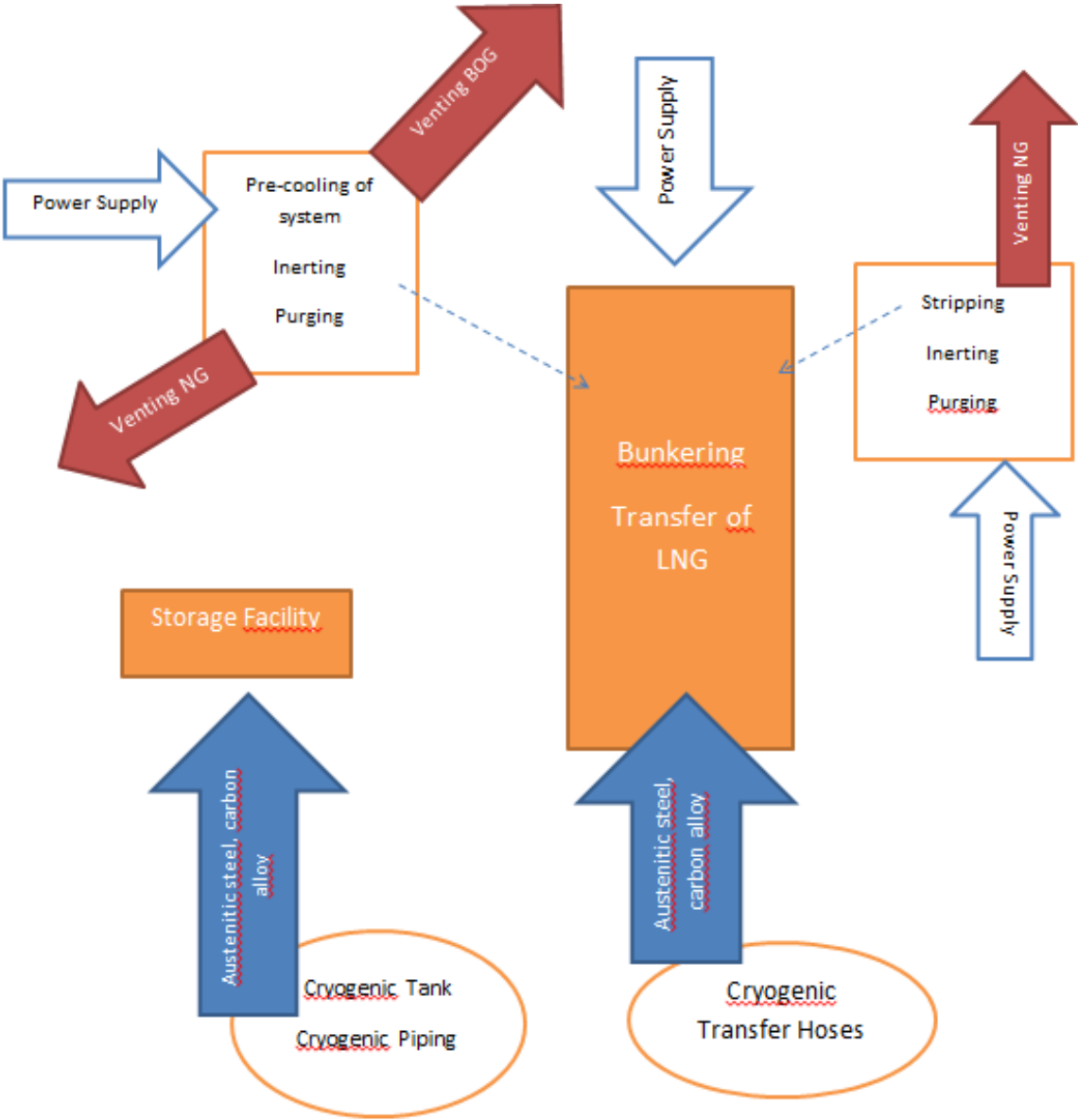

Figure 24 - The Product System for LNG Bunkering

6.3   Data collection

Before implementation in GaBi some datasets need to be established. It should be mentioned that data at this extreme level of detail is very to challenging obtain. Although the goal was to collect as much data as possible from the industry, this has been a difficult and tedious task. The data that could not be gathered by has therefore been subject to assumptions. These assumptions are based on advice and suggestions from professionals, as well as information found during research at the library and on the internet. Some data is based on ISO standards.

Data quality can cause uncertainties, which may lead to misleading results. However, as the objectives of this thesis state, the goal is to make a model that can be used by others and potentially developed further. This is to ensure a user-friendly design so that data can easily be replaced in the GaBi-model should more detailed or reliable data be gathered.

The following will describe where data has been collected and how amounts and sizes have been calculated. The resulting datasets are subsequently listed. The units used to present the datasets are due to the way in which they have been calculated. In some cases, GaBi will require a different unit is used to insert the values. Unit conversions are dealt with in chapter 6.4, where the GaBi implementation is described.

6.3.1   Cryogenic Equipment – Materials

The equipment to be implemented in GaBi is all the critical, cryogenic equipment:

- Piping at the LNG terminal (inner and outer pipes)
- Storage tank at the terminal (inner and outer tank)
- Flexible bunker hose (single piped with braid)

According to Annex A of the ISO 21020 standard for cryogenic vessels, inner jackets of all vessels, valves and flexible hoses are typically made of Austenitic stainless steel (ISO 2004). This is a chromium- and nickel-based steel alloy with excellent corrosion resistance and high tensile and creep strength, which makes it ideal for cryogenic temperatures. The outer jackets of vessels and pipes are commonly made of low carbon alloy steels, with manganese being the most common alloy element. See *Appendix II* for a summary of ISO 21010 Annex A.

6.3.2 Cryogenic Equipment – Manufacturing

Manufacturing emissions should be included to make the analysis more comprehensive, and GaBi does this effortlessly. The difficult part, however, is gathering information about the size of the equipment and the amounts of steel required to manufacture them.

When attending an excursion to oversee TTS-bunkering of LNG (in cooperation with an LNG course by Gassteknikk in Trondheim (Gassteknikk Ltd. 2012)) the diameters and lengths of a typical bunker hose and LNG piping was collected. The dimensions of the storage tank have been calculated based on the tank at CCB Ågotnes which has a capacity of 500 $[m^3]$.

Steel plate thickness has been estimated based on information found during research (AK Steel 2007). All equipment has been assumed to be of cylindrical shape. Table 2 lists the resulting values representing the size of the cryogenic equipment. The rightmost column "Size $[m^3]$" refers to the magnitude of steel the equipment is composed of.

Equipment		Diameter [m]	Length [m]	Thickness [m]	Size [m³]
Cryogenic piping	Inner pipe	0,13	300	0,003	0,19
	Outer pipe	0,2	300	0,006	0,57
Cryogenic Storage Tank	Inner tank	7,98	10	0,006	0,75
	Outer wall	8,25	10	0,006	0,78
Cryogenic Transfer Hose	Single piped	0,13	10	0,003	0,006

Table 2 - Calculations representing the size of cryogenic equipment

6.3.3 Energy use and direct emissions

The pumps used both during preparation and LNG transfer, were described in chapter 5.2.3.1. There the power of the pump used during pre-cooling, inerting and purging was stated at 75 [kW]. During filling the pump used has a power of 19 [kW]. Together with the time used for each process (as listed in chapter 5.1), the energy use [kWh] is calculated, as Table 3 depicts.

Process	[kW]	Time [h]	[kWh]
Pre-cooling	75	0,75	56,25
Inerting of system (N2)	75	0,08	6,25
Purging (NG)	75	0,03	2,50
Filling (transfer)	19	2,00	38
Inerting of system (NG)	75	0,08	6,25
Purging (N2)	75	0,07	5,00

Table 3 - Calculations of energy use from cryogenic pumps

The direct emissions of natural gas and nitrogen gas associated with the product system occur during pre-cooling, inerting and purging of the system. The transfer rate of the system can be used as a basis for calculation of the amounts of NG and N_2 used for these activities.

The pumps have a transfer rate of 100 [m^3/h]. However it is unlikely the pumps are used at full utility during these processes, so a rate of 50 [m^3/h] is chosen for these purposes. The resulting amounts are shown in Table 4.

Process	Substance	Time [h]	Amount [m^3]
Pre-cooling	LNG	0,75	37,50
Inerting (N_2)	Nitrogen	0,08	4,17
Purging (NG)	Natural Gas	0,03	1,67
Inerting (NG)	Natural Gas	0,08	4,17
Purging (N_2)	Nitrogen	0,07	3,33

Table 4 - Calculations of gas amounts (cool, inert and purge)

6.4 GaBi Implementation

The starting point to an analysis in GaBi is creating a *Plan*. Each plan represents a life cycle or process stage of the product system to be analysed, and is defined as the working space. The bunkering system as described in the previous is divided into 5 plans which all will be nested onto a main plan before balancing the system:

- Storage Facility – Manufacturing of on-land equipment (Piping and storage tank)
- Bunker Facility – Manufacturing of transfer-equipment (Bunker hose)
- Preparation for bunkering – Inert and Purge (Nitrogen and Natural Gas)
- Rinsing after bunkering – Inert and Purge (Natural Gas and Nitrogen)
- Bunkering of LNG – The main plan on which the "use phase" of the product system is implemented, and onto which the other plans will be nested.

The *Balance* is GaBi's name for the LCI results, which is carried out once all plans are nested and processes connected. This will be described in greater detail later on. In each plan there are three main elements: *Processes*, *Process Instances* and *Flows*. A process is often a user-defined element which describes a single unit process such as "Inerting system with N_2", defined by its unique input and output flows. A process instance is connected to the process by means of a material flow, and may be referred to as the source. For example "Nitrogen" is a process instance that will be connected to "Inerting system with N_2" and represents the production of nitrogen. Flows are the actual materials and gases that flow through the system, from one process instance to one or more processes. They represent the input and output of each process, and are the basis for the emissions in each product system.

Throughout the implementation of the specific product system, it is essential to use as many predefined flows and process instances as possible. This ensures a standard quality of the inputs and outputs, and reduces uncertainty. The two databases predominantly used by GaBi Educational are *Ecoinvent* (EI 99) and the GaBi's own *GaBi database*. The data within each of these databases is individually collected and updated. The sources, data quality and level of detail by which the data is collected, will therefore differ between the two. For this reason it is recommended to use the GaBi database wherever this is possible (Skaar 2012), since it is the more comprehensive database within the software. It is also favourable to use the same database throughout the analysis to ensure a uniform data set and quality.

Where predefined processes are lacking, these can easily be created specifically for the system. Since the system being analysed in this thesis is very unique, there are not many predefined processes that coincide with the unit processes of LNG bunkering. This means that most of the processes are created by the user, and defined by the flows from the GaBi database. The main flows in this particular system are power, natural gas, nitrogen, LNG and BOG, as well as the material inputs for the cryogenic manufacturing processes, mainly steel. These flows are standard and are therefore likely to be found in the database.

Creating a user-defined flow, however, is not recommended since one would have to implement the exact composition of the flow in the correct physical state, a meticulous process which is difficult to carry out correctly (Skaar 2012).

6.4.1 Implementation of the storage and bunker facilities

When a plan for each of the facilities is made, process elements are created manually for each unit process such as "Production Storage Tank". It is possible to add a substantial amount of information about each process, but the results are only affected by the input and output flows implemented in them so this has not been prioritised here. An example of such a plan is shown in Figure 25.
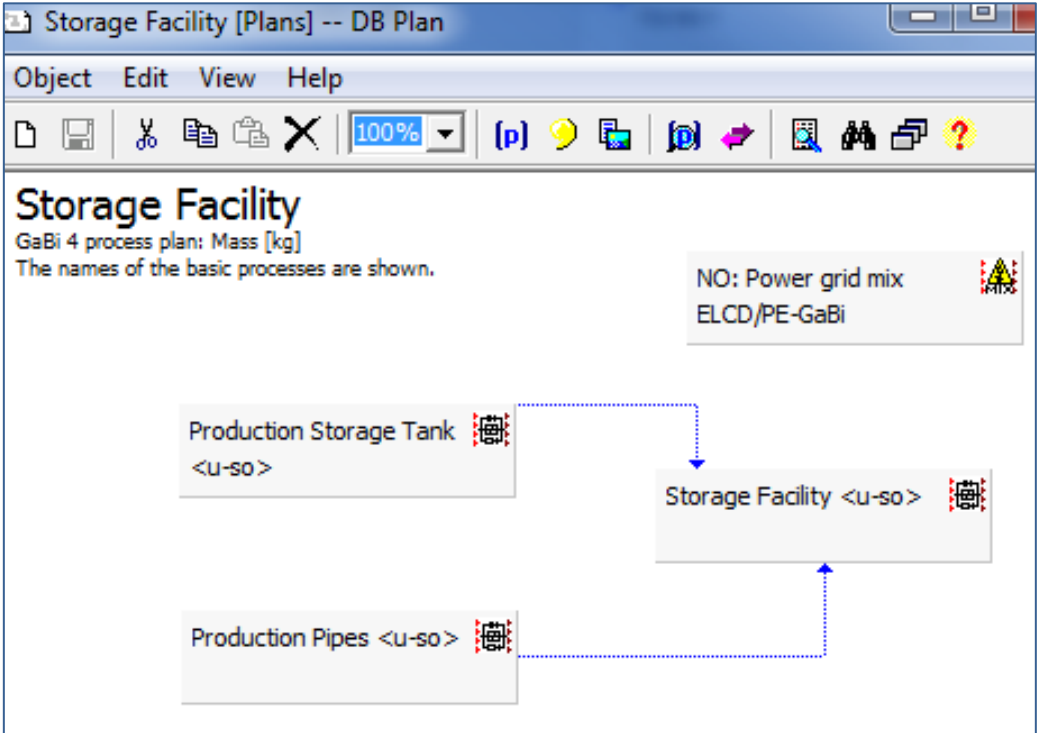
Figure 25 - GaBi: Storage Facility Plan

Within each process, the associated flows of steel are chosen. GaBi requires that flows of metal parts are implemented using the unit [kg]. The values related to the cryogenic equipment are therefore converted from amounts of steel [m^3] to mass of finished product. This is done by using the values in Table 2 along with the density of the steels. The resulting input and output values are shown in Table 5 below.

These are implemented as the output flows. It is safe to say that some amount of the steel used to produce the metals parts go to scrap. However it is difficult to estimate the percentage of this scrap, and it is therefore uncertain the input of steel used to manufacture the cryogenic equipment. An assumption of 10 % has been added to the input flow to each of the unit processes.

This also requires that the amount of scrap is specified in GaBi as an output, which is done by implementing the pre-defined flow "Steel scrap" (for waste recovery). This automatically is included in the balance.

Equipment		Material	Density [kg/m³]	Input [kg]	Output [kg]
Cryogenic piping	**Inner pipe**	Austenitic Stainless	8 030	1 658,7	1 492,8
	Outer pipe	Low Carbon Alloy	7 850	5 006,3	4 505,7
Cryogenic Storage Tank	**Inner tank**	Austenitic Stainless	8 030	6 711,9	6 040,7
	Outer wall	Low Carbon Alloy	7 850	6 783,4	6 105,1
Cryogenic Transfer Hose	**Single piped**	Austenitic Stainless	8 030	55,3	49,8

Table 5 - GaBi input and output values for cryogenic equipment

The output of each of these unit processes is the terminal pipes, storage tank and bunker hose respectively. These are not flows that can be found in the GaBi database. User-defined flows must therefore be created; since they are simply metal parts, the flow-definition does not require detailed datasets. The flows "Cryogenic Pipes", "Cryogenic Tank" and "Bunker Hose" are therefore created, defined as "Metal Parts" in the *Flow-Hierarchy*. For each user-defined flow, the reference quantity must also be defined. Since these flows are defined as metal parts, the reference quantity is automatically set to mass [kg]. They can also be cross-referenced to other quantities, for example "number of pieces". This is done in the implementation where, for instance, 1 kg of bunker hose is cross-referenced to 1/49,8 [piece of hose].

The flows represent the output connection to the next step, only dependant on the amount of steel each part consists of. An example of the input and output implementation is shown in Figure 26.
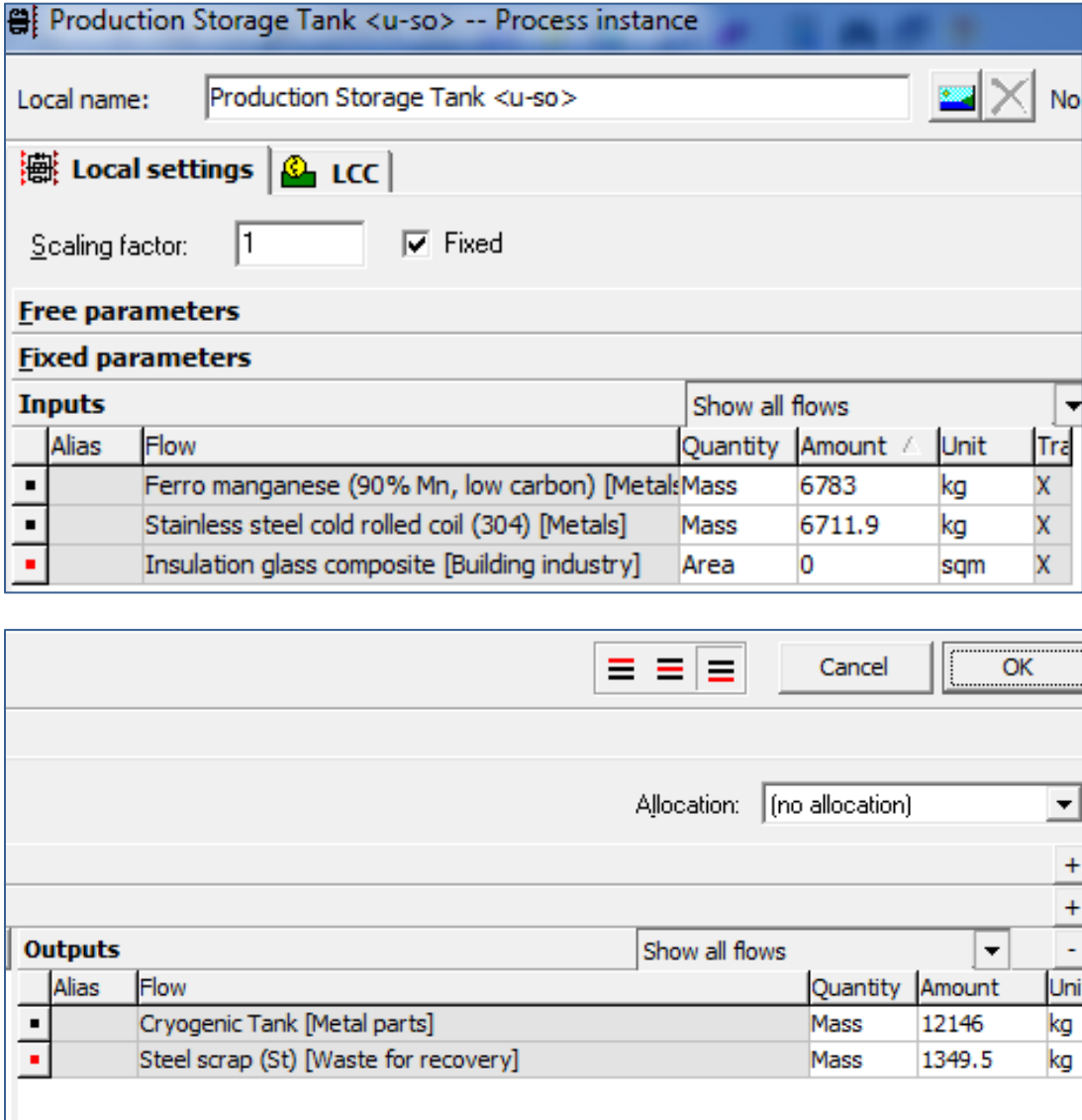
Figure 26 - GaBi: Data implementation for Storage tank

As you can see the output is a cryogenic tank weighing 12 146 [kg], the combined weight of the inner and outer tank. This is an assumption made for simplicity's sake; of course the actual tank will weigh a little more than the inner and outer tank only, since more equipment is connected to the tank, such as valves, bolts, paint, and not least the insulation used. The elements included here do, however, represent the largest contributors to the emissions, which in a project with this scope is detail enough.

Now the plans can be nested onto the "Bunkering of LNG" plan, and the processes connected. The process instance of each material used must be added to the plan in order for the emissions connected to these to be included in the analysis.

As described in chapter 6.3.1 the two main steels used for production of the cryogenic equipment included in this analysis is austenitic stainless steel and low carbon alloy steel.

There are two types of austenitic steel in GaBi, type 304 and 306. Type 304 is the most common of austenitic grades (SPP 2011) and is the material of choice in cryogenic systems (Marquardt, Le et al. 2000). Of the austenitic type 304 steels in GaBi the "Stainless steel cold-rolled coil" (Europe) is chosen for the analysis. It contains 18 % chromium and 10 % nickel, which coincides with the ISO 21010 regulations. The process instance includes a dataset based on average values of cradle-to-gate data, collected from different European steel producers, including power grid mix. Stainless steels are manufactured from mixtures of steel scraps, and the mining process is therefore not included in the dataset.

Of the carbon steels in the GaBi database only one is specified to be low-carbon, namely the "Ferro Manganese" from South Africa, containing 90 % manganese. The process instance includes data from the ore mining process, ore beneficiation, power grid mix and the thermal energy used to produce the finished carbon steel.

With this information, material flows are connected to the unit processes "Production Storage Tank", "Production Pipes" and "Production Bunker Facility" as depicted in Figure 27 below. Please see the *Appendix III* for details regarding the calculations and methods used in this chapter.
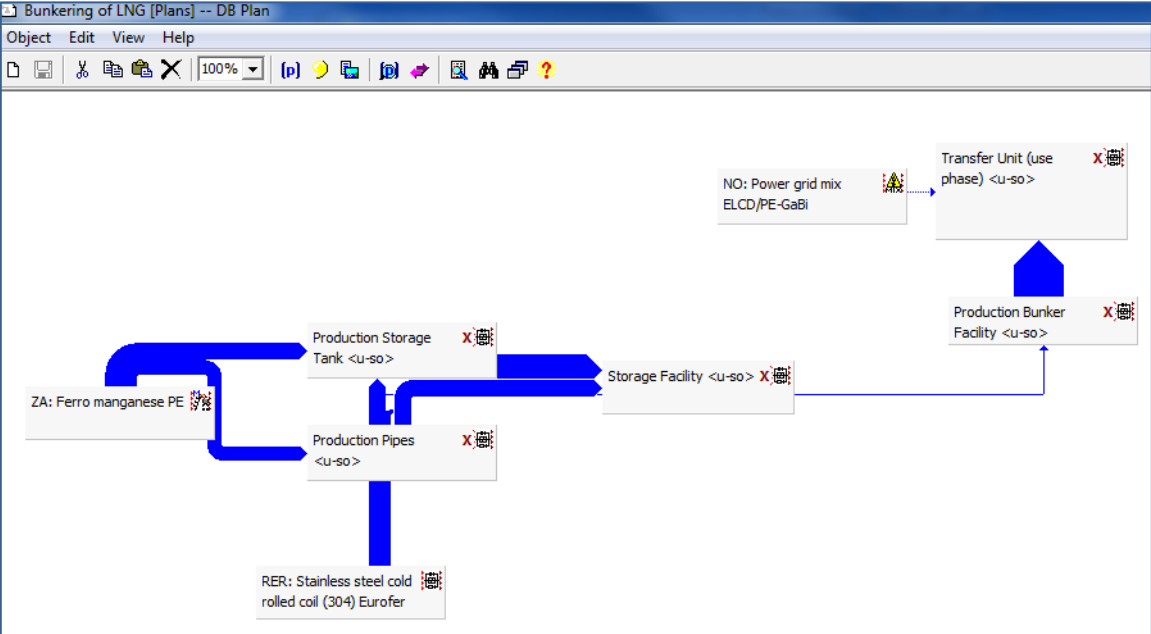

Figure 27 - GaBi: Storage and Bunker facility Plan

6.4.2 Implementation of preparation and rinsing processes

Plans and processes for these two stages are implemented the same way as described in the previous. The amount of nitrogen and natural gas used in each of the unit processes is given in Table 4 but GaBi requires that these are implemented in [kg] as opposed to [m^3]. The density of natural gas (0,8 [kg/m^3]) and nitrogen (1,165 [kg/m^3]) are used to convert the values. Table 6 lists the resulting input and output flows implemented in GaBi.

Process	Substance	Amount [m^3]	Amount [kg]
Pre-cooling	LNG	37,5	16 891,9
Inerting (N2)	Nitrogen	4,2	4,9
Purging (NG)	Natural Gas	1,7	1,3
Inerting (NG)	Natural Gas	4,2	3,3
Purging (N2)	Nitrogen	3,3	3,9

Table 6 - GaBi input values for cooling, inerting and purging (NG and N$_2$)

The process of stripping the system, as described in chapter 5.1 does not require any energy, and does not contribute to any emissions. For this reason it has been left out of the GaBi analysis.

The plans are now nested on to the main plan where the process instance for natural gas and nitrogen are added. The chosen instance for natural gas is a "European gas mix (EU-27)" from the GaBi database which includes comprehensive datasets for the whole supply chain of natural gas: exploration, onshore and offshore production, processing (liquefaction and re-gasification) as well as pipeline for regional distribution and LNG tanker for long distance transport. As for nitrogen, an EU-27 instance is again used. The dataset is based on the LINDE process of cryogenic air separation, and also includes the power grid mix average for nitrogen production.

In order to create a clear picture of what happens in the system each process should have an output-flow describing the "service" the process supplies the system with, which can be connected to the next stage of the life cycle. These outputs do not have materialistic flows, nor do they contribute to emissions, thus they do not exist as predefined flows in GaBi. However, simple flows can be created, and new output flows are defined: "system inerted", "system purged" and "system rinsed". The reference quantity of each flow is set as "Number of pieces" which is a standard unit of measure in GaBi. When the system is inerted, one "piece" of "system inerted" is connected to the next phase; "Purge system". All services of this kind will in the following be referred to as "service flows".

A power grid mix representing the Norwegian grid is connected to each unit process that requires power. The values in Table 3 are implemented in [kWh] and GaBi automatically converts this to [MJ] as this is the preferred unit.

All the input and output flows are implemented in the scale of one bunkering operation. This does not, however, coincide with the scale of equipment manufacturing – if these have the same scale GaBi understands this as: one whole storage and bunker facility is made each time a ship bunkers (or the system is only cooled, prepared and rinsed one time throughout the lifetime of the facility) – and must be scaled accordingly. This is done when the main plan is complete and ready to balance. The product system should be scaled to coincide with the functional unit, for example bunkering of one m^3 of LNG, however this is up to the user.

In this analysis the model is scaled to represent the lifetime of the whole facility. This is done by leaving the cryogenic equipment scaled to one, whilst the processes that happen every time a vessel comes to re-fuel, such as pre-cooling and rinsing the system, are scaled up accordingly. An LNG tank system with a total capacity of 500 [m^3] will provide enough fuel for two to three weeks operating time, this according to an article about the Island Crusader in (Maritimt Magasin 2012). This suggests that each LNG fuelled ship needs to re-fuel approximately 26 times each year (provided they have tanks this big). With five LNG fuelled ships in operation today, 130 fuelling operations occur each year.

Statistics regarding where the different vessels choose to re-fuel is lacking. There are five LNG terminals along the coast of Norway suitable for mid to large scale vessels, it can be estimated that these are used equally. The resulting frequency is thus 26 bunkering operations each year at each LNG terminal. The life expectancy of a storage facility is set to 20 years (this is the average value for the life expectancies of 10-25 years as stated by the two sources (Lee, Park et al. 2012) and (CIT 2012)). The resulting scaling factor is therefore calculated to 520 for the whole life time of a terminal. This is easily implemented in GaBi by inserting the value in the "scale" box.

With only five vessels fuelled by LNG, the frequency of bunkering operations at any terminal in Norway is rather low. The frequency is expected to increase within the near future, however it is not possible to take this into account since the rate at which the frequency will increase cannot be calculated at this stage.

6.4.3 Pre-cooling

The process of precooling the system is added at this point (it is too simple to require its own plan). Although it is expected that the only emissions related to pre-cooling is due to energy use, it is stated in chapter 5.1 that at some LNG terminals the LNG used to pre-cool the on-land system is vented to air. Although this is not assumed regular practice, it is interesting in this perspective to look at the worst case scenario of all the emissions. For this reason, it is included in the analysis. The input is shown in Table 6 and is connected to the natural gas process instance. The output is in theory BOG but this is not a predefined flow in GaBi. Since it would require extremely precise data and in-depth knowledge of how GaBi works, it is too risky to create a new flow. Natural gas is therefore used as the output.

Another output flow is the cooling service which has been implemented with the reference quantity of number of pieces in consistency with the other "service flows".

6.4.4 Use phase

Every system analysis should have a use phase in the life cycle. The previous plans represent the production of the facility and processes that occur on the facility prior to and after a bunkering procedure is done. Although the combustion of LNG in the LNG-fuelled ship is the use phase of the total life cycle of LNG (from extraction to combustion), this product system analyses the life cycle of the LNG bunker terminal, hence the actual filling of LNG from land to the receiving ship is the use phase of this particular system. This is implemented in the main plan and consists of no other elements than the power used to pump the LNG through the system. The amount of energy used is shown in Table 3 and a power grid process instance is added to supply the energy.

6.4.5 The GaBi model

The whole system as implemented in GaBi is shown in Figure 28 below. All material flows are coloured blue whilst the direct emission gases are coloured red. The model has been scaled to the lifetime of the terminal, i.e. the functional unit is *One LNG Terminal*. A larger scale figure is provided in *Appendix IV.*
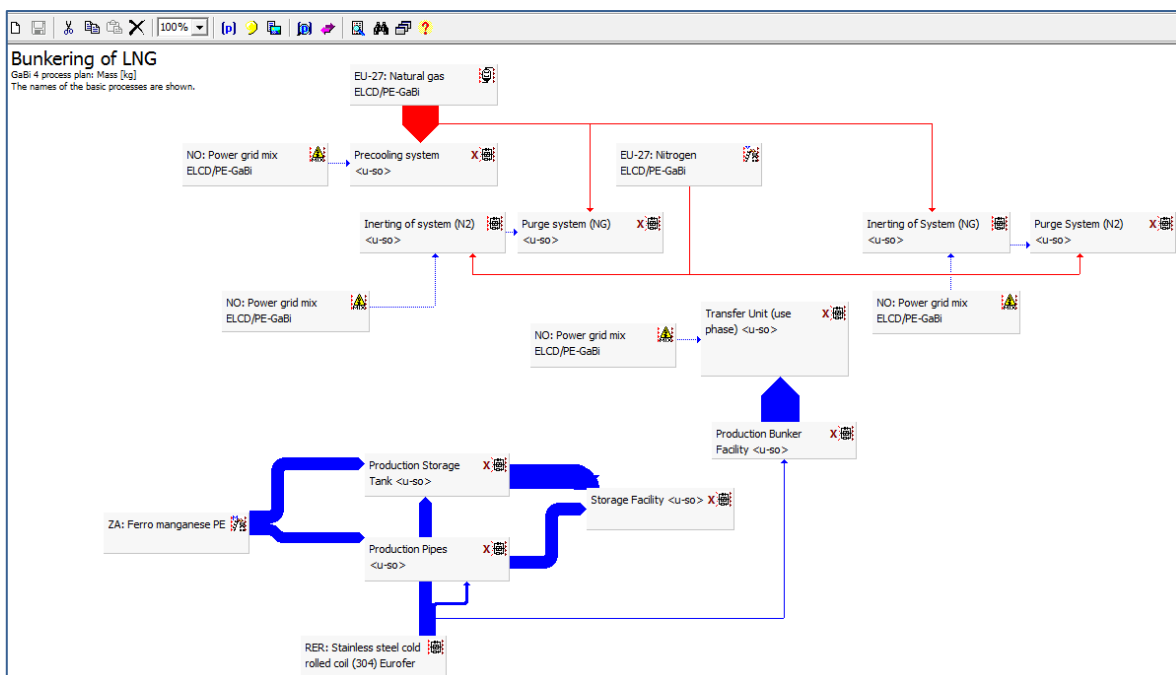

Figure 28 - GaBi: Complete *Bunkering of LNG* Plan

When model implementation is complete, the environmental impacts of the system is analysed by creating a GaBi balance. This is a file containing all the calculated results for the modelled system, and also includes all LCI and LCIA results. The following chapter will describe the results for the Bunkering model.

6.5 Impact Assessment

The preliminary balance is called the *Life Cycle Inventory* and shows a complete list of all input and output flows related to the model "Bunkering of LNG". It shows that the total flow of inputs is 2 050 [tonnes] and the output flows amount to 1 577 [tonnes]. It can also be deducted that the largest contributor to the mass flows is the process Ferro manganese with a total of 1 300 [tonnes], closely followed by Austenitic stainless steel with 899 [tonnes].

This however does not give a satisfactory picture of the environmental impacts, therefore the following will describe the results in an LCIA perspective. All balance views and diagrams are filed in *Appendix V*, as well as exported balance results in the attached zip-file.

6.5.1 CML 2001

GaBi Educational operates with several impact assessment methods:

- TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts)
- I02+ v2.1
- EI 99 (Eco-Indicator 99) using DALY results
- EDIP 1997 and 2003 (Environmental Development of Industrial Products)
- CML 96, and finally
- CML 2001

The CML method was created by the Institute of Environmental Sciences (CML) at the University of Leiden, Netherlands and is continuously managed and updated (CML 2001 being the newest version). It is an impact assessment method which restricts quantitative modelling to early stages in the cause-effect chain to limit uncertainties (GaBi Software 2012), also known as a problem-oriented method. It is a reliable method, well-known in the LCA industry, and well-suited for this analysis.

CML 2001 impact categories included in GaBi are, among others, acidification potential, eutrophication potential, human toxicity potential, ozone layer depletion and of course global warming potential. The CML 2001 was updated in December 2007 and November 2009, which are both included in GaBi. Being the most up to date, the 2009 method will be used for this analysis.

The balance mode also offers additional analyses such as Data Quality and "Weak-point Analysis" which highlights the biggest contributors to environmental impacts.

6.5.2 Global Warming Potential

The CML 2001, November 2009 edition assesses the Global Warming Potential in a 100 years perspective. CML uses IPCC equivalency factors so that the impact category indicator result is expressed in kg CO_2-equivalents.

For this model, the balance shows a total impact of 1 947 [kg CO_2-Equiv] from the input flows. The output flows, naturally, contribute far greater to the emissions, with a total impact of 81 750 [kg CO_2-Equiv]. The total global warming potential in the bunkering process is 83 698 [kg CO_2-Equiv].

INPUTS	NG	N_2	Power	Austenitic steel	Ferro manganese	TOTAL
Material resources	1.40	0.01	0.23	1 864.91	80.46	1947.01
OUTPUTS	NG	N_2	Power	Austenitic steel	Ferro manganese	TOTAL
Inorganic emissions to air	4 856.93	0.73	3.20	35 971.97	33 365.71	74 198.54
Organic emissions to air (group VOC)	2 917.51	0.04	0.04	1 888.32	2 745.93	7 551.83
TOTAL	7 775.83	0.79	3.47	39 725.21	36 192.09	83 697.39

Table 7 - GaBi Balance - Global Warming Potential

Table 7 above shows the GWP results for each valuable process. Valuable processes are those process instances in the model that produce emissions related to the analysis. The only flow categories listed above are Material Resources, Inorganic Emissions to air and Organic Emissions to air, which makes sense since only these types of flows contribute to the GWP. Specifically the environmental impacts stem from:

- Material resources: CO_2
- Inorganic Emissions to Air: CO_2, CO_2(biotic) and N_2O
- Organic Emissions to Air: CH_4

Austenitic steel is the greatest contributor to global warming potential, closely followed by ferro manganese. Natural Gas also does a solid effort. Direct emissions, energy use and materials are the three main flows contributing to emissions; Table 8 lists the total results. Energy use has a surprisingly low GWP, in fact only 0,36 ‰ of the total impact.

	GWP [kg CO_2-Equiv]
Direct Emissions	7 777
Energy Use	3
Manufacturing	75 917

Table 8 - GaBi Balance - GWP grouped by source of emission

Changing the balance view to *Relative Contribution* indicates that 90,8 % of the GWP stems from CO_2 emissions, whilst only 9,12 % are from CH_4. This implies that LNG leaks at the terminal may not pose such a big environmental threat as one may assume.

A *Weak Point Analysis* shows that the weak points of the model, i.e. those that pose the biggest environmental threats, are

- Valuable processes: Austenitic stainless steel, ferro manganese
- Emissions: CO_2

6.5.3 Sensitivity check

The reliability of the final results can be assessed by determining how they are affected by uncertainties in data and allocation methods (ISO 2006).

Some datasets implemented in the model are based on assumptions, such as the storage tank dimensions and LNG amounts used for pre-cooling. These are simply based on estimations and create direct uncertainties in the input data. Other datasets such as pump power consumption is based on a specific pump's datasheet. The pump chosen for this, however, was solely based on the availability of the datasheet, since information directly from the industry was difficult to obtain. If the pump chosen is not representative of the pumps used at Ågotnes, this also can create some uncertainties in the data.

Uncertainties can be omitted only if datasets are available directly from the source.

When implementing process instances in GaBi there are often many choices and it can be difficult to assess which instance is the correct choice for the specific model. For instance, there are eight different process instances for natural gas in GaBi. Three of these are "EU-27 Natural gas", "EU-15 Natural gas Mix" and "NO Natural gas Mix". The extent of datasets included and the allocation methods used for each instance is not always documented or obvious, making it difficult to choose the most suitable instance. Uncertainties arise due to allocation and data variations. Expert guidance would be needed to ensure the correct choices are made, this was unfortunately not available during the course of this thesis.

Process instance choices can also affect the consistency of the results. For example, if a European process instance is chosen for one unit process and a Norwegian instance is chosen for a similar unit, this can lead to allocation inconsistencies within in the model. Such issues will not become apparent at any stage in the balance, and can cause uncertainties in the results.

7 Comparison

In a comparative study, the equivalence of the systems being compared shall be evaluated before interpreting the results. Consequently, the scope of the study shall be defined in such a way that the systems can be compared (ISO 2006). They must have the equivalent functional units and system boundaries, and the same assessment method must be used to interpret the results. Since the scope of this thesis focuses on LNG, there was not enough time available to perform similar analyses for other fuels.

Comparisons can be based on similar life cycle studies; however the bunkering process is too specific to have been given attention in any of the environmental studies found. This chapter will therefore be based on aspects of the bunkering process by which comparisons could be made, along with characteristics that distinguish bunkering processes of different fuels or create emission differences.

An aspect that can create differences in GHG emissions when bunkering LNG vs. traditional fuels is BOG production. BOG is created when LNG is stored over a period of time. There are no standard guidelines of how to handle this BOG, causing speculations whether this is vented directly to air. For diesel, the low vapour pressure limits requirements to vapour recovery and therefore also direct air emissions.

At CCB's terminals the MGO tanks are 1000-9000 [m^3] whilst the LNG tank is only 500 [m^3] (CCB 2012). Along with the fact that LNG takes up double the volume for the same energy output as diesel fuels, there is far less fuel energy of LNG compared to MGO available at the terminal. If LNG is to serve the same amount of vessels, expansion of the terminal is necessary. Manufacturing of new LNG tanks and more transport of LNG will contribute to emissions.

At Ågotnes CCB terminal the LNG transfer rate is approximately 100 [m^3/h], whilst the rate for MGO and SDM (special distillate Marine) is 140-200 [m^3/h] (CCB 2012). This indicates that the total estimated time to transfer 1 [m^3] of fuel is much higher for LNG than MGO. Although the energy use has been found to have a negligible effect in GWP, this is something to consider when comparing the bunkering processes for different fuels.

8 Conclusion

Bunkering of LNG was chosen as the hotspot due to being an undiscovered aspect of the LNG value chain. Although this lead to difficulties in completing a comparison, the analysis hopefully creates a solid basis for comparison should similar analyses of other fuels become available. The GaBi model is easy to use so that new values can be added if data of better quality can be gathered. The work presented in this report addresses issues that until now have been a missing link in environmental studies of LNG.

Manufacturing of cryogenic equipment is the largest contributor, with a total GWP of 75 917 [kg CO_2-Equivalent], representing 90,7 % of the emissions. This is clearly the area with the biggest potential to reduce the GWP. However, it is unlikely the material technology will advance enough to become more environmentally friendly in the near future. That said it may be possible to decrease emissions by searching for solutions to change the manufacturing process, or perhaps build more compact terminals to save steel.

Direct emissions are the only areas that can noticeably reduce GWP. They only account for 9,3 % of the total impact with a GWP of 7 777 [kg CO_2-Equivalent]. Still, all direct emissions can in fact be omitted. Options for LNG and BOG recovery are plentiful, the easiest being a vapour return line.

The emissions related to energy use only contribute to 0,36 ‰ of the total GWP impact. This is to be considered negligible when compared to the other contributors. The extended time it takes to bunker LNG should therefore not be a concern when comparing fuels.

BOG production can become substantial if LNG is stored over longer periods of time. To ensure this is not vented directly to air, regulations for BOG recovery should come into force, for example using BOG to produce electricity. This will not only eliminate direct emissions but also reduce energy consumption due to the terminal generating its own energy.

If LNG is to become the fuel of the future, fuelling availability must increase. Options for ship-to-ship bunkering are under development, which means ships can fuel both at shore and at sea. A major disadvantage with LNG at the moment is that fuelling can only take place at specified terminals. Diesel-fuelled ships that fuel portside can load and offload simultaneously, which LNG-fuelled cannot. STS bunkering will solve this problem, providing increased fuelling efficiency and availability for LNG.

9   Further work

To produce a more reliable inventory result, there are some issues that should be investigated further. Firstly, more precise data should be collected, preferably directly from an LNG terminal. Also, the only process instance available for low carbon steel (Ferro Manganese) originated from South Africa. Production countries can be revised to create more sound results. Lastly, more equipment such as valves and pumps ought to be included in the model to get a more thorough assessment of the emissions related to manufacturing.

End of life treatment and recycling was not included in the analysis. Since the balance was based on the entire lifetime of the facility, it is assumed some percentage of the materials will be recycled at the end of life. Implementing this will ensure a more complete analysis.

Where the LNG and natural gas comes from is important and can alter the environmental effect. Presumably most LNG used in Norway comes from Norwegian producers, however this should be considered if this report is to be used in other environmental studies. The LNG implemented in GaBi was based on an average value of all LNG-producers in the EU-countries.

Transportation of LNG is an additional hotspot that was considered for this analysis. There is a debate regarding the environmental impact of large LNG carriers. The general view is that LNG transport has a low GWP compared to other transoceanic cargo ships due to using excess BOG as fuel. Others now argue that the energy use is so enormous (possibly as much as 7 times the normal) that the GWP benefit is challenged. A detailed LCA of this stage can produce some interesting results.

LNG leaks and BOG production and emissions are all contributors to the overall emissions that should be investigated further. There is for instance no documentation of leakages. When observing a TTS bunkering procedure in Trondheim, LNG leaked out during filling simply because the connection was not tight enough. The crew did not seem to care about this because "it happens all the time". If this is the standard attitude leaks might pose a bigger threat than thought.

10 References

AK Steel. (2007). "304L Stainless Steel " Product Data Sheet
    Retrieved 19th April 2012, from www.aksteel.com.
Bjøndal, L. H. (2012). Risk Analysis; Bunkering of LNG. Master
    Thesis, NTNU.
Blikom, L. P. (2011). "LNG Bunkering operation caught on tape " DNV
    Blog: LNG - Energy of the Future.
    http://blogs.dnv.com/lng/2011/10/lng-bunkering-operation-
    caught-on-tape/ Desember 2011.
Blikom, L. P. (2011). "LNG fuel tanks located underneath
    accomodation unit " http://blogs.dnv.com/lng/2011/10/lng-fuel-
    tanks-located-underneath-accommodation-unit/ 5th Desember 2011.
Bonn, J. (2004). "Vacuum insulated pipe seeks increased use with
    LNG." Pipeline & Gas Journal.
CCB. (2012). "Bunkring."   Retrieved 25th April 2012, from
    http://www.coastcenterbase.no/index.php?mapping=53.
CIT. (2012). "Storage Tank Inspection "   Retrieved 8th May, 2012,
    from http://www.cituk-
    online.com/acatalog/Storage_Tank_Inspection.html.
Curt, B. (2004). "Marine Transportation of LNG" Intertanko
    Conference
DNV (2011). Rules for classification of Ships, High speed light
    craft and naval surface craft. Gas Fuelled Engine
    Installations.
Eidesvik Shipping AS. (2007). "Viking Queen Datasheet "   Retrieved
    25th April, 2012, from http://www.eidesvik.no/viking-
    queen/category128.html.
GaBi Software. (2012). "CML 2001 Method." Life Cycle Impact
    Assessment methods Retrieved 2nd February 2012, from
    http://www.gabi-software.com/support.
Gassteknikk Ltd. (2012). Compendium for Gas bunkering safety
    training course. Gasskurs kat A, B & C. Torghatten Nord AS.
    Trondheim, Norway
GTT. (2009). "LNG Carrier containment systems." Retrieved 12th
    February 2012, from http://www.gtt.fr/index.php.
Haack, T. (2011). Natural Gas as fuel in shipping - Experiences and
    perspectives, Rolls Royce.
Harperscheidt, J. (2011). "Bunkering, infrastructure, storage, and
    processing of LNG " Ship & Offshore(No.1).
Haugstad, T. (2012). Gassdrevne skip. Teknisk Ukeblad. Online
    Edition.
Hochschorner, E. and G. Finnveden (2003). "LCA Methodology -
    Evaluation of Two Simplified Life Cycle Assessment Methods "
    The International Journal of LifeCycle Assessment **8** (3): 119-
    128.
Hur, T., J. Lee, et al. (2004). "Simplified LCA and matrix methods
    in identifying the environmental aspects of a product system "
    Journal of Environmental Managament **75**: 229-237.
IMO (1996). IMO IGC Code Chapter 4 - Cargo Containment.
    International Maritime Organisation, DNV "Vega" Database.
IMO (2009). Second IMO GHG Study 2009, International Maritime
    Organization.
IMO. (2011). "Air Pollution and Greenhouse Gas Emissions." GHG
    Emissions, Retrieved 12th March 2012, from

http://www.imo.org/OurWork/Environment/PollutionPrevention/AirPollution/Pages/GHG-Emissions.aspx.

IPCC (2001). IPCC Third Assessment Report: Climate Change 2001. Radiative Forcing of Climate Change - Global Warming Potential

IPCC (2007). IPCC Fourth Assessment Report: Climate Change 2007. Direct Global Warming Potentials. S. Solomon and D. Qin. Cambridge, United Kingdom, Intergovernmental Panel on Climate Change.

ISO (2004). Cryogenic vessels- Gas/materials compatibility. Annex A, International Organisation for Standardisation. **ISO 21010.**

ISO (2006). Environmental Management - Life cycle Assessment - Requirements and guidelines. Life Cycle Interpretation - Evaluation, International Organisation for Standardisation. **ISO 14044.**

Lee, S., J. S. Park, et al. (2012). Service Life prediction of 9% Ni Steel LNG Storage Tank Using Fatigue Analysis. 12th Topical Conference on Gas Utilization

Linde. (2012). "Liquefaction of Natural Gas."   Retrieved 13th May 2012, from http://www.linde-engineering.com/en/process_plants/liquefied_natural_gas/index.html.

Liquefied Gas Carriers. (2011). "Preparation for loading LNG cargo." Retrieved 16th February 2012, from http://www.liquefiedgascarrier.com/preparation-for-loading-LNG.html.

Maritimt Magasin (2012). "Island Crusader er levert og døpt".

Marquardt, E. D., J. P. Le, et al. (2000). Cryogenic Material Properties Database. 11th International Cryocooler Conference Boulder, Colorado, USA.

MGI. (2012). "Products - LNG Fuel."   Retrieved 17th April, 2012, from http://www.mg-ins.no/index.cfm?id=337902.

Moss Maritime. (2012). "Moss Maritime General Brochure " Moss LNG Carriers Retrieved 12th February 2012, from http://www.mossww.com/pdfs/Moss%20Maritime%20General%20Brochure.pdf.

NaturalGas. (2010). "Focus on LNG " Retrieved 24th April 2012 from http://www.naturalgas.org/index.asp.

NS (2007). Installation and equipment for liquefied natural gas Design of onshore installations, Norwegian Standard. **NS 1473:2007.**

NWS. (2011). "Ship Technical Informations." Moss Rosenberg Retrieved 14th February 2012, from http://www.nwsssc.com.au/fleet_moss-rosenberg.aspx.

Osaka Gas. (2012). "Development of Invar Alloy LNG Piping." Gas Material, Processing and Power Technologies Retrieved 18th May 2012, from http://www.osakagas.co.jp/rd/sheet/001e.html.

PHPK Technologies. (2008). "Vacuum Insulated Piping for LNG Service."   Retrieved 18th April 2012, from http://www.phpk.com/pdf/2008Brochure.pdf.

Pré Consultants (2010). Introduction to LCA with SimaPro 7. Impact Assessment.

Richardsen, P. W. (2010). "A major step towards the new environmental era for tanker shipping." LNG as fuel for ships Retrieved October 2011, from http://www.dnv.no/presse/pressemeldinger/2010/Amajorsteptowardsthenewenvironmentalerafortankershipping.asp.

Rolls Royce. (2009). "Bergen B35:40 Gas Engine " Retrieved 2nd February, 2012, from http://www.rolls-royce.com/marine/products/diesels_gas_turbines/gas_engines/b3540_gas.jsp.

Ryste, J. M. (2011). A literature study of the LCA methodology and application to LNG as ship fuel. Project Thesis, NTNU.

Skaar, C. (2012). Conversation regarding GaBi with Christofer Skaar, Researcher at the Department of Industrial Economics and Technology Management, NTNU.

Skipsrevyen. (2000). "Ship of the Year - M/F "Glutra"." from http://www.shipoftheyear.com/ship-of-the-year-2000/ship-of-the-year-2000-mf-%C2%ABglutra%C2%BB/.

SPP. (2011). "A Brief Overview of Stainless Steel." Type 304 Retrieved 25th April 2012 from http://www.sppusa.com/reference/white_paper/wp_ss.pdf.

Statistics Norway. (2011). "Natural gas, domestic use, 2011." Lower consumption of natural gas. Retrieved 13th May 2012, from http://www.ssb.no/naturgass/.

Strøm, K. L. (2012). Conversation with Katrine Lie Strøm (DNV) about the details regarding the bunkering process, as identified by DNV in cooperation with Gasnor.

Swedish MT Forum, Linde Cryo AB, et al. (2010). "LNG ship to ship bunkering procedure". Gothenburg, Sweden.

TNO (2011). Environmental and Economical aspects of using LNG as a fuel for shipping in The Netherlands. Netherlands, TNO - Netherlands Organisation for Applied Scientific Research.

Ursan, M. (2011). "What is Boil-off?", Westport Power Inc.

WG Environment (2004). Life Cycle Assessment EIGA - Environmental Newsletter Brussels, European Industrial Gases Association (EIGA).

Wold, M. (2012). Conversation with Martin Wold (DNV) regarding the procedures at Ågotnes LNG terminal.

Wärtsilä. (2012). "Wärtsilä 34 DF." Retrieved 2nd February, 2012, from http://www.wartsila.com/en/engines/medium-speed-engines/wartsila34DF.

Æsøy, V., P. M. Einang, et al. (2011). "LNG-fuelled Engines and Fuel Systems for Medium-Speed Engines in Maritime Applications". Trondheim, Norway, NTNU and MARINTEK.

ÅF&SSPA (2011). "North European LNG Infrastructure Project: A feasibility study for an LNG filling station infrastructure and test of recommendations". Draft Feasibility Report. Sweden.

Appendix

Appendix I – Problem Description

Faculty of Engineering Science and Technology

Department of Marine Technology

MASTER THESIS

for

M.Sc. student Julianne Mari Ryste

Department of Marine Technology

Spring 2012

Screening LCA of GHG emissions related to LNG as ship fuel

Miljøanalyse av klimagasser knyttet til LNG som drivstoff

Background

In view of the increasingly popular climate change debate worldwide, maritime transport is under pressure to create sustainable solutions for a cleaner future. One of these solutions is using Liquefied natural gas (LNG) as an alternative fuel in the shipping industry.

LNG is a clean fuel containing no sulphur; this eliminates the SO_X and particulate matter emissions. Additionally, the NO_X emissions are reduced by up to 90% due to reduced peak temperatures in the combustion process. Due to its low hydrogen-to-carbon ratio compared with oil-based fuels, results in lower specific CO_2 emissions [kg of CO_2/kg of fuel]. However life cycle assessments of GHG emissions throughout the LNG value chain requires more attention.

Life cycle analysis (LCA) is a renowned method to assess the environmental performance at all the stages of a product or system's lifetime. A life cycle begins with the extraction of raw materials to manufacturing and use of the product, through to repair and eventually disposal.

Objective and sub-objectives

A screening LCA is to be carried out for the GHG emissions related to LNG as ship fuel. Firstly, the LNG value chain should be established and the areas suitable for screening highlighted. Consider both contributions to the environmental impact as well as areas of the LNG life cycle receiving little attention thus far.

GaBi educational software will be used to analyse the hotspots of the LNG value chain. The model design should aim to be user-friendly so that it can easily be adopted and developed further.

The results of the GaBi analysis will be assessed in a problem-oriented manner, focusing on GHG emissions and their Global Warming Potential. The results will thereby be compared to other marine fuels such as MDO and HFO.

Lastly, some suggestions of improvements in the bunkering cycle will be made according to the results.

General

The thesis must be written like a research report, with an abstract, conclusions, contents list, reference list, etc.

During preparation of the thesis it is important that the candidate emphasizes easily understood and well written text. For ease of reading, the thesis should contain adequate references at appropriate places to related text, tables and figures. On evaluation, a lot of weight is put on thorough preparation of results, their clear presentation in the form of tables and/or graphs, and on comprehensive discussion.

The thesis is to be handed in electronically. Also a .pdf-version of the final thesis is to be submitted to the supervisor by email.

Starting date: 15th January 2012

Completion date: 10th June 2012

Handed in: 10th June 2012

Trondheim 10th June 2012.

Ingrid Bouwer Utne

Professor

Appendix II – Materials for Cryogenic Equipment

ISO 21010, Annex A – review of common materials used for cryogenic vessels and associated equipment.

Metallic materials commonly used for liquid oxygen service

Cryogenic vessels and associated equipment		Metallic materials commonly used				
		Low alloy steels	Nickel steels	Austenitic stainless steels	Copper and copper alloys	Aluminium and aluminium alloys
Large transportable vessels	Inner vessel		×	×		
	Outer jacket	×		×		
Small transportable vessels	Inner vessel		×	×		
	Outer jacket	×		×		
Static vessels	Inner vessel		×	×		
	Outer jacket	×				
Valves and protective devices				×	×	
Flexible hoses				×		
Vaporizers				×		×
Insulation systems						×

Appendix III – Manufacturing of Cryogenic Equipment: Details

Piping

The outer diameter and length was discussed with the crew on board the LNG ferry "MS Tresfjord" and the crew manning the LNG filling truck, during the LNG course by Gassteknikk. The inner diameter was estimated based on own assumptions, and the thickness of the steel pipes was discussed with colleagues.

Storage Tank

The CCB LNG terminal at Ågotnes has a storage tank that rooms 500 m^3 of LNG (CCB 2012). By using an estimation about the length of the tank I was able to calculate the diameter, and thereby also the amount of steel needed. Information from Marine Gas Insulation (MGI 2012) has been used previously, since it is safe to assume the LNG terminals in Norway use a Norwegian based insulation expert. It is here again used to estimate the amount of insulation used and the MGI spray foam product catalogue states that 250-300 mm of insulation is normally used in their tanks. For ease of implementation in GaBi, the amount is set at 270 mm. Thereby the diameter of the outer tank is 0,27 [m] bigger than the inner. The distance between the pipes can be assumed the same whatever type of insulation.

Density of materials

GaBi uses kg as the standard unit, so the density of each material was used to convert from [m^3] to [kg].

Gases	Density [kg/m^3]
Nitrogen	1,165
Natural Gas	0,8
LNG	450,45
Steel	
Austenitic steel	8 030
Low alloy steel	7 850

Appendix IV – GaBi Implementation – Product System
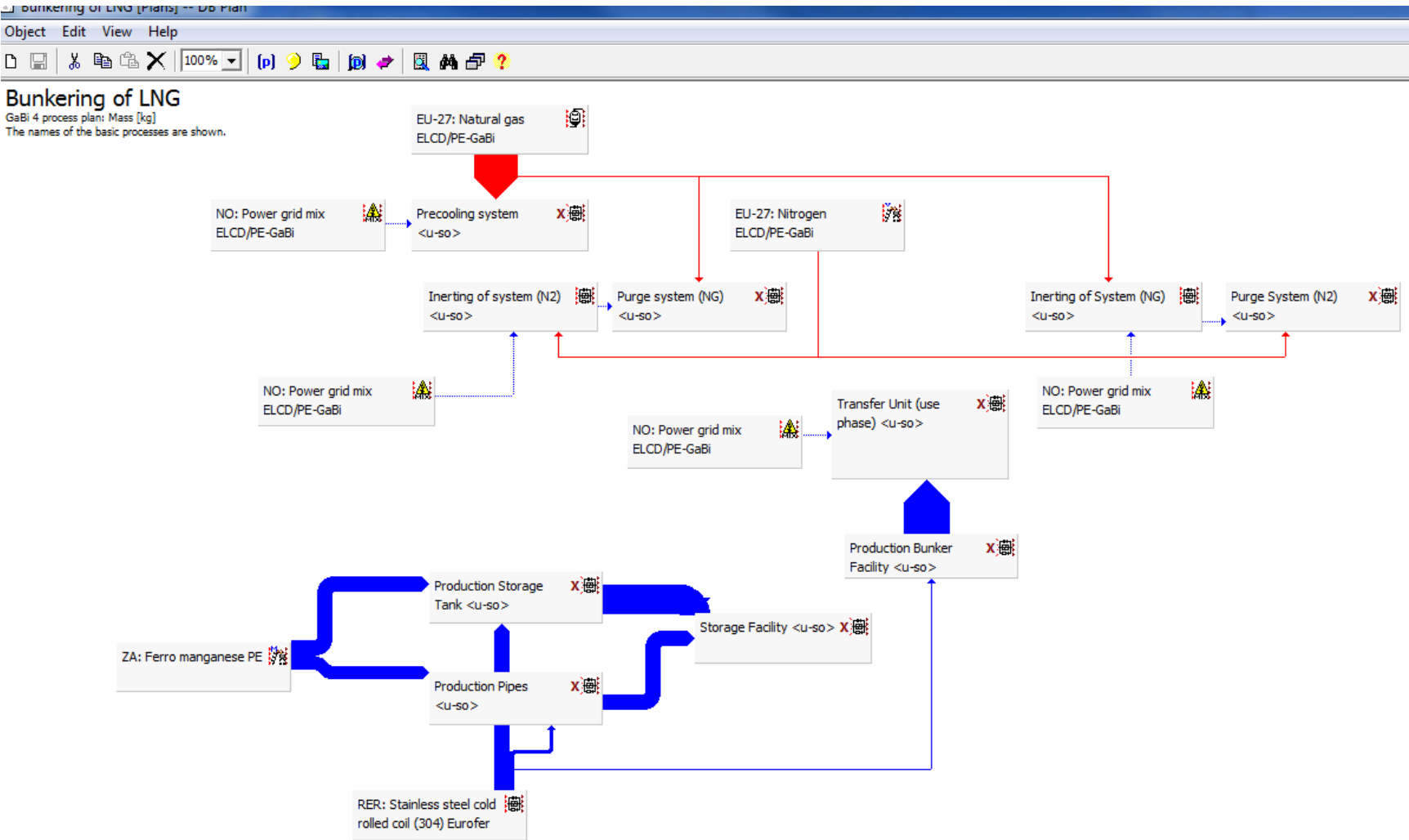
Appendix V – GaBi Result Figures

GaBi Balance – Life Cycle Inventory

Bunkering of LNG_2 -- Balance

Object   Edit   View   Tools   Help

Name   Bunkering of LNG_2

Quantity | Weighting | ☐ Quantity view   Unit

Mass [kg]   kg

LCA | LCC | LCWE

Inputs

	Bunkering of LNG
Flows	2.0505E006
Resources	2.0461E006
Valuable substances	83.943
Others	
Production residues in life cycle	4347.7
Emissions to fresh water	0.020159

Outputs

	Bunkering of LNG
Flows	1.5772E006
Resources	7.1123E005
Valuable substances	16905
Others	102.51
Production residues in life cycle	27866
Deposited goods	3.3189E005
Emissions to air	2.9674E005
Emissions to fresh water	1.9034E005
Emissions to sea water	2117.1
Emissions to industrial soil	3.1929

67

Global Warming Potential

Bunkering of LNG_2 -- Balance

Object   Edit   View   Tools   Help

Name: Bunkering of LNG_2   Rows: 2

Quantity | Weighting | ☐ Quantity view   Unit | Normalization   ☑ In/out aggregati

CML2001 - Nov. 09, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]   kg CO2-Equiv.   not filtered

LCA | LCC | LCWE

Inputs   ☐ Just elementary flows   ☑ separate IO tables

	Bunkering of LNG	EU-27: Natura	EU-27: Nitroge	NO: Power gri	NO: Power gri	NO: Power gri	NO: Power gri	RER: Stainless steel cold ro	ZA: Ferro mar
Flows	1947	1.3986	0.013942	0.1229	0.01289	0.013656	0.078373	1864.9	80.455
Resources	1947	1.3986	0.013942	0.1229	0.01289	0.013656	0.078373	1864.9	80.455
Energy resources									
Land use									
Material resources	1947	1.3986	0.013942	0.1229	0.01289	0.013656	0.078373	1864.9	80.455
Valuable substances									
Others									
Production residues in life cycle									
Emissions to fresh water									

Outputs

	Bunkering of LNG	EU-27: Natura	EU-27: Nitroge	NO: Power gri	NO: Power gri	NO: Power gri	NO: Power gri	RER: Stainless steel cold ro	ZA: Ferro mar
Resources									
Valuable substances									
Others									
Production residues in life cycle									
Deposited goods									
Emissions to air	81750	7774.4	0.77161	1.7453	0.18305	0.19392	1.113	37860	36112
Heavy metals to air									
Inorganic emissions to air	74199	4856.9	0.73465	1.7257	0.181	0.19175	1.1005	35972	33366
Organic emissions to air (group VOC)	7551.8	2917.5	0.036958	0.019587	0.0020544	0.0021764	0.012491	1888.3	2745.9
Other emissions to air									
Particles to air									
Radioactive emissions to air									
Emissions to fresh water									
Emissions to sea water									
Emissions to industrial soil									

Weak Point Analysis

GaBi Diagram – Global Warming Potential – Outputs
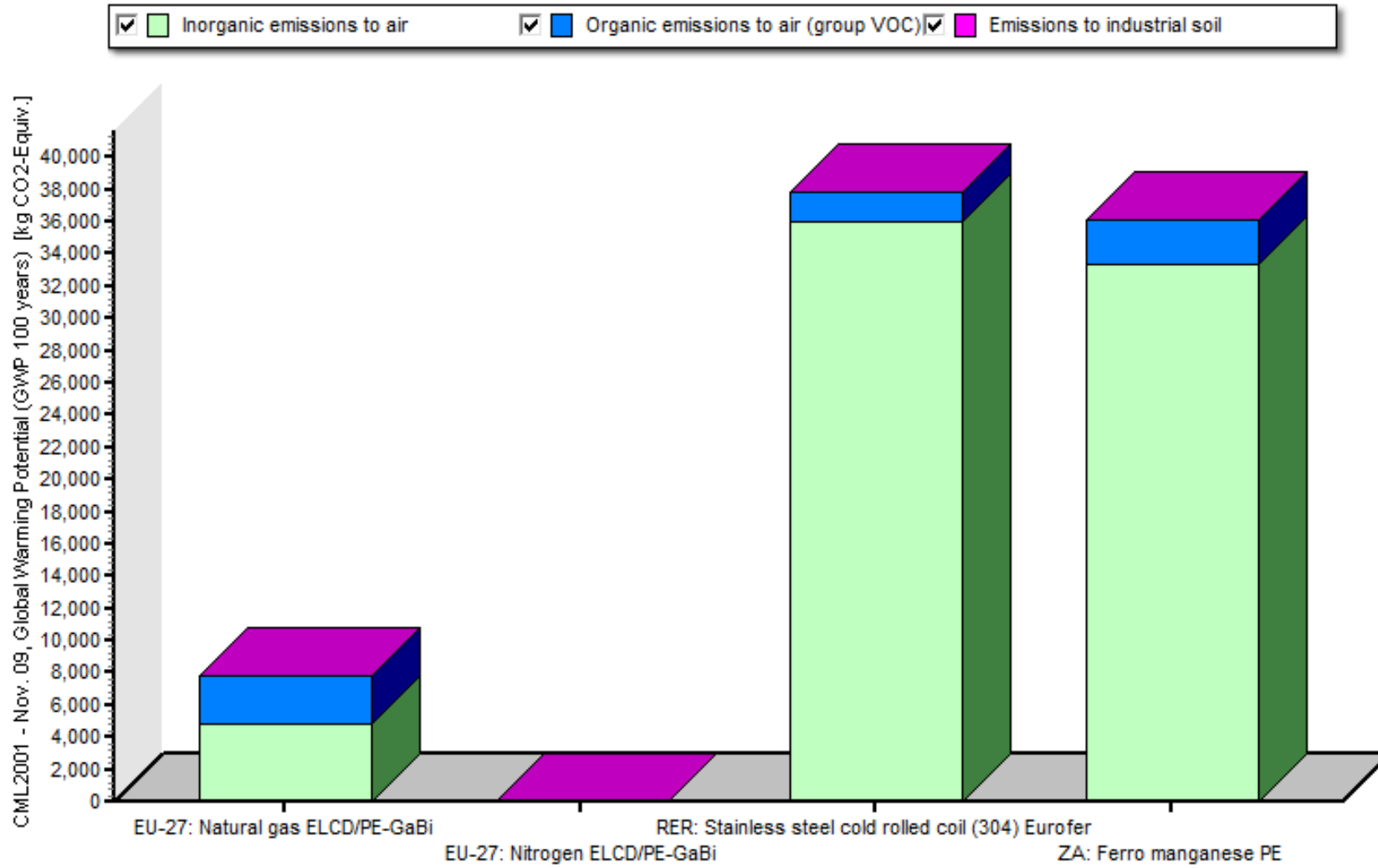
GaBi Diagram – Mass contribution – Inputs and Outputs (Relative Contribution)