Eco Island Ferry

Comparative LCA of island ferry with carbon fibre composite based and steel based structures

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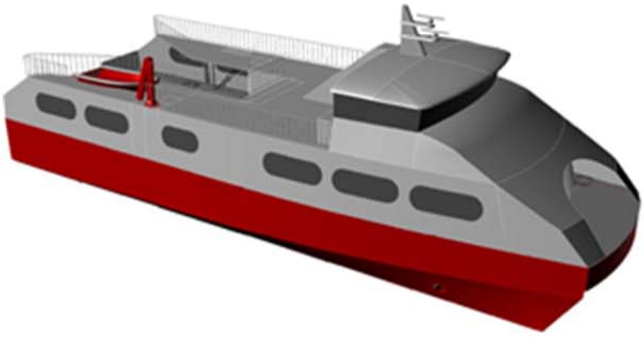

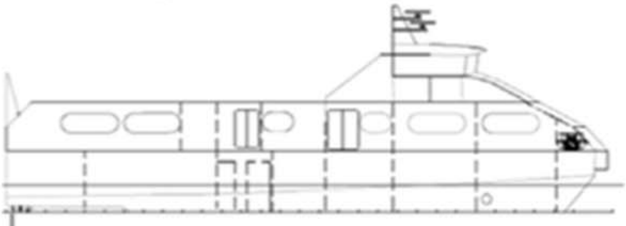

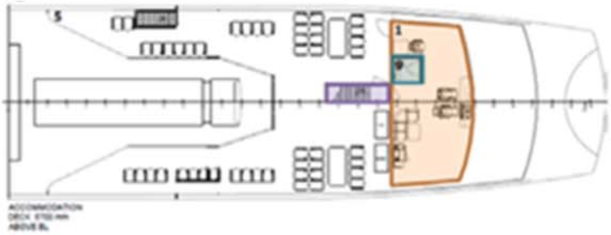

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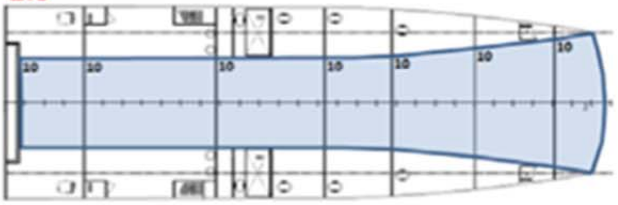

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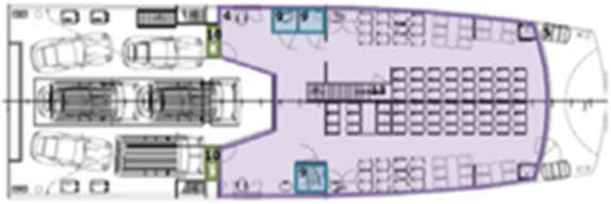

Preface

This report is part of the "Øko-Ø-færge" (Eco Island Ferry) project. The project group consists of naval architects from Sweden and Denmark, university and shipyard representatives as well as specialists from research institutes. The project includes a full fire safety assessment according to SOLAS chapter II-2 Regulation 17 along with a life cycle costing (LCC) and a life cycle assessment (LCA) for the new ecological and economical island ferry. The current report is the LCA-part of the Eco Island Ferry project.

The report is carried out by Jannick H Schmidt and Jenna Watson.

Acknowledgements: The realisation of the current detailed LCA of the operations of two ferry alternatives was possible thanks to the engagement and support from a number of people within and outside the "Øko-Ø-færge" (Eco Island Ferry) project consortium. Special thanks go to:

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- Bjarne Moellgaard manager of Hov-Tunø Ferry, Odder Municipal, Odder
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Aalborg, April 15th 2013

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1. Introduction

This report is a comparative life cycle assessment of a conventional steel ferry and a carbon fibre reinforced polymer (FRP) composite ferry.

Following a kick-off meeting for the EU project MARKIS in 2010 with the title “Light Weight Marine structures”, an industrial group in North Jutland, Denmark and SP Technical Research Institute of Sweden started discussing displacement ferries with a reduced environmental footprint. This led to the creation of a Swedish-Danish consortium with the objective of starting construction of this type of ferry in the Swedish and Danish region. The project was named “Øko-Ø-færge” (Eco Island Ferry) and a project group was formed consisting of naval architects from Sweden and Denmark, university and shipyard representatives as well as specialists from research institutes. A project plan was prepared, which included a full fire safety assessment according to SOLAS chapter II-2 Regulation 17 along with a life cycle costing (LCC) and a life cycle assessment (LCA) for the new ecological and economical island ferry.

A preliminary study (Amen and Evegren 2012) was carried out by the SP Technical Research Institute of Sweden that reviewed national, European and international regulations, along with studies of the potential market and financing for lightweight island ferries in the region.

The project work is meant to illustrate the feasibility of a more ecological and economical alternative for island ferries. The project sets out to replace the old Tun Island Ferry (Tunøfærgen), which travels between Hov and the Tunö Island in Denmark. One of the requirements was that the new ship maintains the same capacity as the Tun Island Ferry, which holds 200 passengers and six cars (or four cars and a truck). By using carbon fibre reinforced polymer (FRP) composite as an alternative to steel, a weight reduction of up to 71% can be achieved, which could provide significant improvements to operational costs and environmental impacts.

As such, the objective of this report is to evaluate the environmental impacts of the current Tun Island Ferry and the proposed alternative Eco Island Ferry according to ISO 14040 standards for life cycle assessment. The functional unit is defined as servicing the Tunø ferry route in one year. This includes:

- 700 voyages per year
- Each journey from Hov to Tunø is approximately 2 times 9.7 nautical miles or 18 km (out and return) = 19.4 nautical miles or 36 km (estimated in Google Earth)
- Each journey has a duration of 2 times 1 hour (out and return) = 2 hours (Soerensen 2012)
- The load capacity of the ferry is 200 passengers and 6 cars (or 4 cars and 1 truck) (Evegren and Rahm 2012, p 4)

This report studies the environmental performance of the two ferry alternatives, including the emissions related to the production of construction materials and engine size, energy savings related to change in the weight of the ferry, and the waste handling at the end-of-life of the ferry.

2. Goal and scope definition

2.1 ISO 14040/44 on LCA

The LCA is carried out in accordance with the ISO standards on LCA: ISO 14040 (2006) and ISO 14044 (2006). However, at one point the study is not in compliance with ISO 14044, see **section 2.2** below.

2.2 Critical review

A critical review has been carried out. It should be noticed, that according to ISO 14044 (2006, p 39): "*…a panel of interested parties shall conduct critical reviews on LCA studies where the results are intended to be used to support a comparative assertion intended to be disclosed to the public.*". Since the current study is used to support a comparative assertion that is disclosed to the public, and since the review is not carried out by a panel, the review cannot be characterised as being in accordance with the ISO standards on LCA.

The critical review is carried out by Henrik Wenzel. The review report is available in '**Appendix 5: Critical review report including author's response**'. Each of the comments raised in the review report has been addressed and this is also available in '**Appendix 5: Critical review report including author's response**'.

2.3 Functional unit and purpose of the study

Functional unit

The functional unit is defined as servicing the Tunø ferry route in one year. This includes:

- 700 voyages per year
- Each journey from Hov to Tunø is approximately 2 times 9.7 nautical miles or 18 km (out and return) = 19.4 nautical miles or 36 km (estimated in Google Earth, see **Figure 2.1**)
- Each journey has a duration of 2 times 1 hour (out and return) = 2 hours (Soerensen 2012)
- The load capacity of the ferry is 200 passengers and 6 cars (or 4 cars and 1 truck) (Evegren and Rahm 2012, p 4)

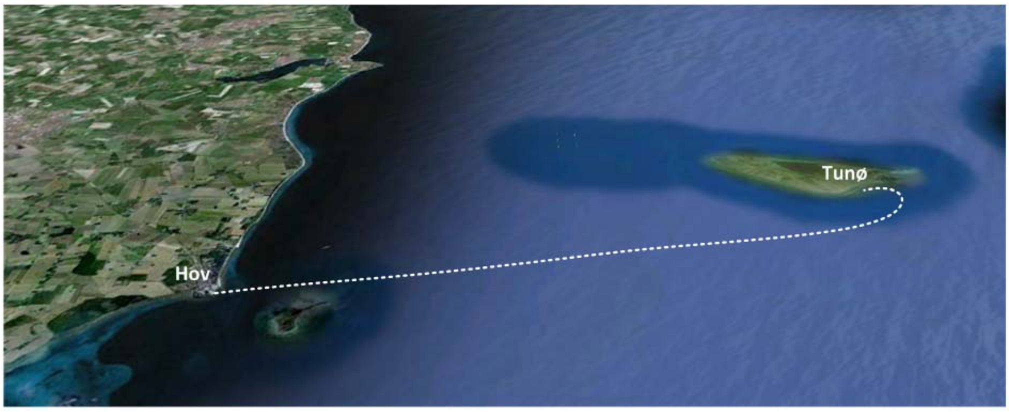

Figure 2.1: The Tun Island Ferry route from Hov to Tunø as seen from Google Earth.

Purpose and type of study

This purpose of this study is to compare the life cycle of ferry transport in a conventional steel ferry and an alternative composed of carbon fibre reinforced polymer (FRP) materials. The report will study the environmental performance of the reference ferry and the alternative, including the emissions related to the production of construction materials and engine size, energy savings related to change in the weight of the ferry, and the waste handling at the end-of-life of the ferry.

Another purpose of the study, in keeping with the purpose of the Eco Island Ferry Project, is to change the perspective among ship owners and authorities with competence building within industry and authorities, as well as inspiring ship owners and naval architects to consider modern materials for shipbuilding. (Riisgaard et al. 2011)

Description of the ferries and their components

The ferries studied in this report are the Tunøfærgen (or the Tun Island Ferry in English), which is a Ro-pax ferry class D from 1993. The Tun Island Ferry has a length of 30.5 meters, a width of 9.0 meters, depth of 3.20 meters and a draft of 2.10 meters. The Eco Island Ferry has roughly the same dimensions, with a length of 30.7 meters, a width of 10 meters, a depth of 3.2 meters and a draft of 1.40 meters. (Evegren and Rahm 2012). The payload capacity is equal to 200 passengers plus 3 crew members. An additional 6 cars can also be carried or 4 cars and 1 truck. The total payload capacity is 45.3 tonnes for the Eco Island Ferry and 56.1 tonnes for the Tun Island Ferry. This capacity is almost identical for the two ferries and is, together with the speed, the key design parameter for the Eco Island Ferry (Soerensen 2012). The two ferries are shown in **Figure 2.2** below.

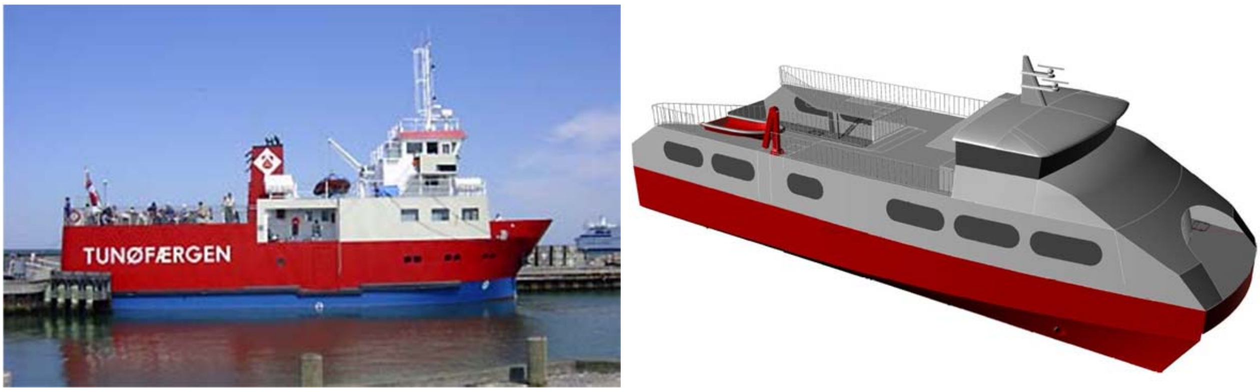

Figure 2.2: The Tun Island Ferry on the left and the Eco Island Ferry on the right. (Evegren and Rahm 2012)

The ferries carry out 700 return voyages per year. Each voyage is 2 x 1 hour at approximately 9.5 knots (Soerensen 2012). The route of the ship is between Hov and Tunø in Denmark and the approximate number of passengers using the ship per year is 50,000 (Amen and Evegren 2012). The distance is approximately 2 x 9.7 nautical miles = 19.4 nautical miles (out and return) (estimated in Google Earth). The Tun Island Ferry is built using steel and the Eco Island Ferry is designed using FRP composite materials. The weight specifications for the reference ferry and the Eco Island Ferry are shown in **Table 2.1** below and include the weight of crew members, passengers, luggage, cars, cargo etc., whereas **Table 2.2** provides the weight and material composition without these components and broken down by material type.

Table 2.1: Payload data for the two the ferry alternatives (Amen and Evegren 2012).

	Payload weight	
Material	**Eco Island Ferry (tonne)**	**Tun Island Ferry (tonne)**
Fuel	8.0	18.8
Stores	1.0	1.0
Passengers	15.0	15.0
Crew	0.2	0.2
Luggage	2.0	2.0
Cars	16.0	16.0
Deck Cargo	3.1	3.1
Total payload	**45.3**	**56.1**

Table 2.2: Lightweight data of the two ferry alternatives. Sources: Tun Island Ferry data (Moellgaard 2012); Eco Island Ferry data (Hjoernet 2012).

	Lightweight	
Material	**Eco Island Ferry (tonne)**	**Tun Island Ferry (tonne)**
Hull material, fibre reinforced polymer (FRP)	27.7	-
Hull material, aluminum	1.3	-
Hull material, steel and other materials	-	237
Insulation materials	11.2	7.0
Machinery and equipment	31.8	18.2
Total lightweight*	**72.0**	**262**

*The lightweight is a nautical term for the displacement of a ship without cargo, fuel, lubricating oil, ballast water, consumable stores as well as passengers, crew and their effects.

The design of the Eco Island Ferry is the same as the Tun Island Ferry, but all steel structures have been replaced by carbon FRP composite. It should be noted that the Eco Island Ferry is made up of a main deck and an upper deck on two pontoons. There is a wet deck between the two pontoons that consists of shallow void spaces. The levels of the ship are referred to as deck 1, deck 2, and deck 3, starting from the base of the pontoons. The wet deck is referred to as deck 1.5. (Evegren and Rahm 2012) The design of the ship is seen below in **Figure 2.3**.

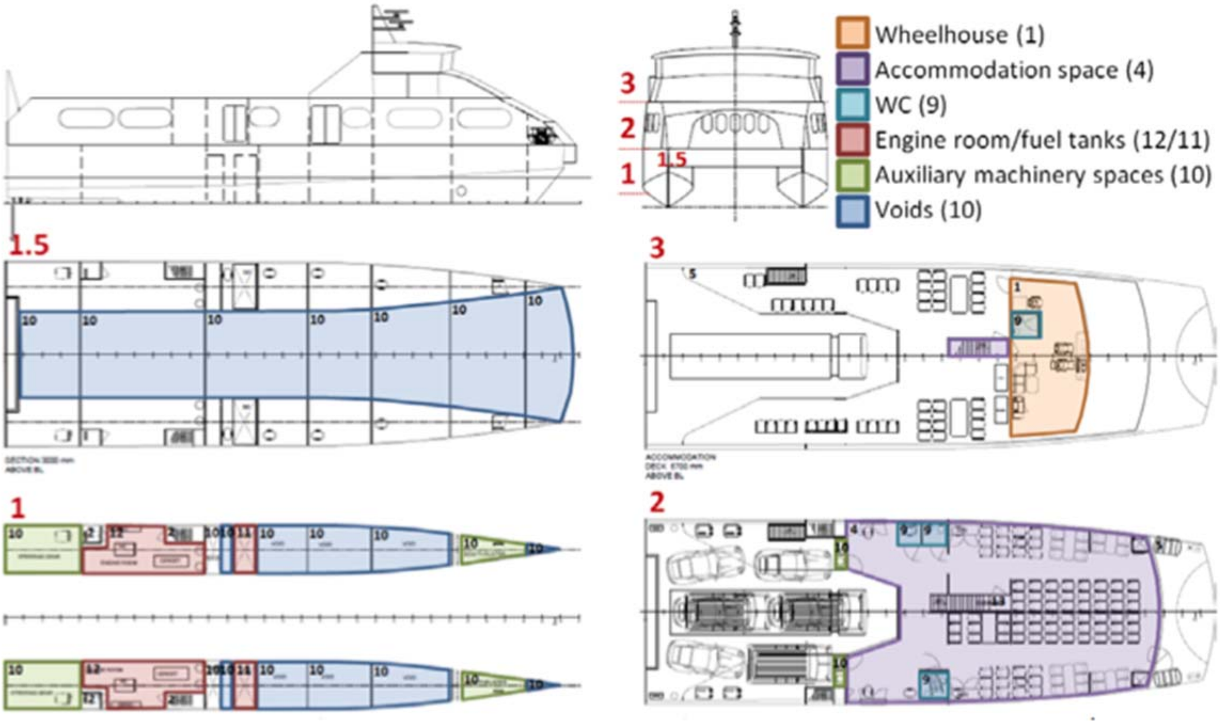

Figure 2.3: Overview of the ship (Evegren and Rahm 2012, p 9).

In the Eco Island Ferry the decks and bulkheads are made in carbon FRP composite, and in some cases thermal insulation is applied to protect structural performance in the case of fire. This thermal insulation is normally in the form of mineral wool. (Evegren and Rahm 2012) More detailed information regarding insulation is outlined in **chapter 4.6**.

Construction of steel ferries is usually carried out using sheet or plate steel for all-metal hulls. Since the material rusts due to contact with water, it is usually protected with a covering of paint on the entire hull and with the placement of zinc anodes. The application of zinc anodes takes place after sandblasting and before painting. Modern steel components are welded and/or bolted together.

FRP composite and construction of the materials of the base design

A fibre reinforced polymer (FRP) composite panel consists of a lightweight core that separates two rigid and strong fibre reinforced polymer laminates. The core usually consists of polyvinyl chloride (PVC) foam or balsa wood, while the face sheets are made of a carbon or glass fibre reinforced polymer. When these laminates are bonded to the core, the combination produces a lightweight, yet strong and rigid construction (Evegren and Rahm 2012). **Figure 2.4** illustrates the composition of a carbon FRP composite panel.

Figure 2.4: Illustration of a carbon FRP composite panel (top) and a close-up on the core and the fibre reinforced laminates (bottom). (Evegren and Rahm 2012, p 11)

A typical carbon FRP composite panel consists of a 50 mm PVC foam core (80 kg/m^3) sandwiched by two 1.5 mm carbon FRP laminates (approximately 2,100 kg/m^3). The total weight of said carbon FRP composite is ~10.5 kg/m^2. This composite panel could replace a 7 mm steel plate with a weight of 55 kg/m^2 (Evegren and Rahm 2012).

2.4 Life cycle inventory modelling approach

Consequential and attributional modelling

Generally there are two different approaches to modelling in life cycle inventory:

- consequential modelling
- attributional modelling

According to Sonnemann and Vigon (2011, p 132), attributional modelling is defined as: "*System modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule.*" In the current study attributional modelling is carried out by assuming that the products are produced using existing production capacity (current or historical market average), and multiple-output activities are dealt with by applying allocation factors based on economic value.

According to Sonnemann and Vigon (2011, p 133), consequential modelling is defined as a: "*System modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit.*" Hence, in consequential modelling it is generally a change in demand for the product under study that is modelled. A cause-effect relationship between a change in demand and the related changes in supply is intended to be established. This implies that the product is produced by new capacity (if the market trend is increasing). In addition, it is taken into account that the affected production capacity must be the actual affected, i.e. it is not constrained. Multiple-output activities are dealt with using substitution. The modelling principles are comprehensively described in Weidema et al. (2009) and Weidema (2003).

Applied modelling approach

The current study will apply the consequential modelling approach because this describes the consequences of a specific decision instead of following more normative (often mass flow analysis inspired) modelling rules.

2.5 System boundaries

The system boundaries represent a cradle-to-grave perspective for ferry operation. An overview of the life cycle stages are illustrated in **Figure 2.5**.

The Eco Island ferry is constructed by Danish Yachts in Denmark and the lifetime of the ship is assumed to be 40 years. It is assumed for the purposes of this study that the conventional steel ferry is constructed in Europe and the lifetime of the ship is 30 years. The assumed life times are similar to the life times assumed in a life cycle costing study of the two ferry alternatives; Lindquist (2012).

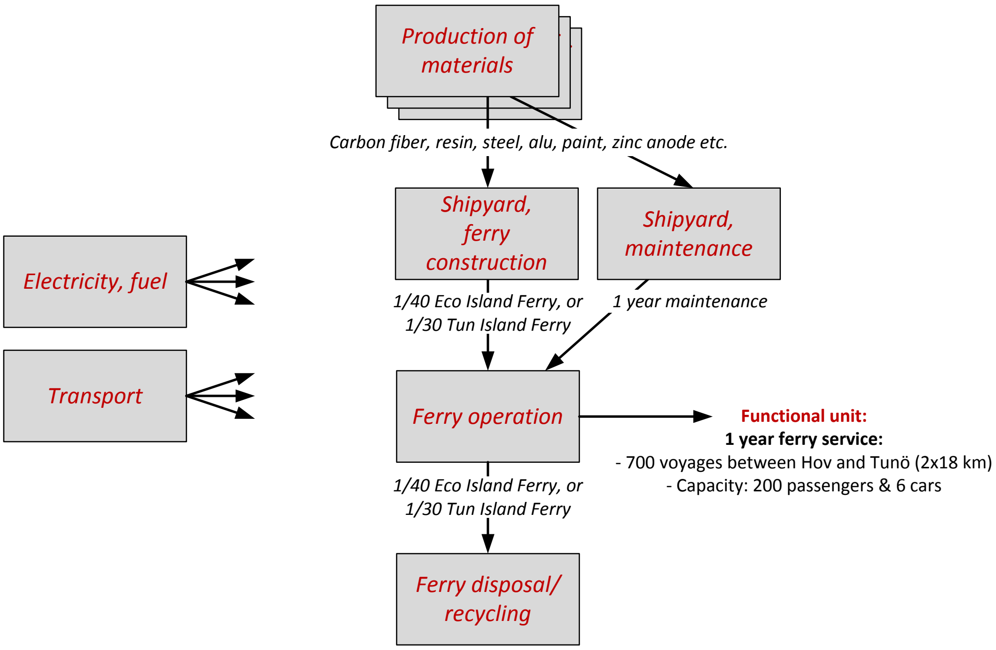

Figure 2.5: Overview of the life cycle stages of the two ferries under study.

The life cycle inventory in **chapter 3** to **7** is structured following the life cycle stages in **Figure 2.5**. The life cycle stages are summarised for the two ferry alternatives in **Table 2.3**.

Table 2.3: Brief description of the life cycle stages of the two ferry alternatives

Life cycle stage	Eco Island Ferry	Tun Island Ferry
Production of materials	Production of carbon fibre, resin, core (PVC foam), engine, and other components.	Production of basic steel including sheet and bar rolling, engine, and other components.
Shipyard, ferry construction	Assembly of the materials and components including resin hardening and painting.	Assembly of the materials and components including painting.
Shipyard, ferry maintenance	Painting and zinc anode for corrosion protection.	Painting and zinc anode for corrosion protection.
Ferry operation	Use of fuel oil, emissions associated with zinc anode.	Use of fuel oil, emissions associated with zinc anode.
Ferry disposal/recycling	Carbon fibre reinforced polymer (FRP) is shredded and incinerated. Metal is recycled.	Metal is recycled.

All life cycle stages involve transport and the input of electricity and other energy.

The major relevant parameters when comparing the two ferry alternatives are:

- the composite alternative has a lighter hull and superstructure which enables:
    - smaller engine and thereby less energy when the ferry is not sailing
    - the draft of hull is lesser and thereby less energy is required when sailing
- production and disposal of materials for ferries: different total weight of used materials and different environmental impact per kg of material

2.6 Description of the System

Production of Materials:

The materials produced in this life cycle stage for the Eco Island Ferry include carbon fibre, resin, the core (made of PVC foam), the engine and the other components of the ferry made from materials such as wood, plastic, ceramic and textiles. The production process for carbon FRP varies depending on the piece created, the outside gloss needed, and the number of pieces that are being produced. The quickest method involves the use of compression moulds, which is the method assumed here for the production of pieces for the Eco Island Ferry. The Tun Island Ferry materials include basic steel including sheet and bar rolling processes, the engine and other components from materials such as wood, plastic, ceramic and textiles. Materials are transported to the shipyard for ferry construction using ship and lorry.

See **section 4.4** for detailed information on the production process for steel.

Shipyard/Ferry Construction:

The Eco Island Ferry is constructed in shipyards in Denmark, while the Tun Island Ferry is constructed in Europe. The components are put together using various processes that include the welding, sawing, cutting and hammering of materials. This phase includes resin hardening as well as painting of the ferries themselves.

Shipyard/Maintenance:

During the operation stage of the ferry life cycle, maintenance is carried out on an annual basis. Maintenance includes painting of the ferry and re-application of zinc anodes for corrosion protection in the case of the Tun Island Ferry. See **section 5** for additional detailed information.

Ferry operation

As described in **section 2.3**, the ferries carry out 700 return voyages per year. Each voyage is 2 x 1 hour at approximately 9.5 knots (Soerensen 2012). The route of the ship is between Hov and Tunø in Denmark and the approximate number of passengers using the ship per year is 50,000 (Amen and Evegren 2012). The distance is approximately 2 x 9.7 nautical miles = 19.4 nautical miles (out and return) (estimated in Google Earth). This stage in the life cycle of the ferries includes both fuel oil and electricity use, in addition to emissions associated with zinc anode.

Ferry disposal/recycling

In this stage of the ferry life cycle, the carbon fibre material is shredded. All combustible parts are incinerated and the residual glass fibres are sent to landfill. Metal parts are recycled for both ferries. A sensitivity analysis will be carried out to apply a recycling scenario.

Cut-off criteria

All processes/activities in the affected product systems will be included. Inputs related to services etc. are modelled using hybrid input/output models. More information regarding this can be found in **section 3.5**.

2.7 Categories of activities and products and level of detail of data

A rough overview of the level of detail in the inventory of different activities is presented in **Table 2.4**, where it is indicated whether specific data have been inventoried or if generic data directly obtained from LCI databases have been used. It should be noticed that hybrid data are applied in the processes representing the main life cycle stages of the ferries and also one tier upstream in the product system. Since a tiered approach for hybridisation has been used, it was overly time consuming to go into further detail.

Table 2.4: Overview of the level of detail (specific/detailed versus generic) of the inventory of the transactions of different categories of products in different categories of activities.

activities **Products**	**Shipyard: Eco E Ferry / Steel**	**Operation: Eco E Ferry / Steel**	**Maintenance: Eco E Ferry / Steel**	**Disposal: Eco E Ferry / Steel**
Inputs per unit of output				
Carbon fiber	Specific	Specific		
Resin & core	Specific	Specific	Specific	
Steel	Specific	Specific	Specific	
Fuels, electricity, chemicals	Specific	Specific	Specific	Generic
Other products incl. services etc.	Generic	Generic	Generic	Generic
Emissions per unit of output				
Emissions	Specific	Specific	Specific	Generic

2.8 Data sources for background data

Data sources for ferry construction, operation, maintenance and disposal

Detailed data on the material and component composition, performance, construction etc. of the Eco Island Ferry are provided by:

- Hjortberg M (2012), Personal communication with Mats Hjortberg, owner of Coriolis. Gothenberg, Sweden
- Sørensen J O (2012), Personal communication with Mechanical Engineer Jens O Soerensen. Danish Yachts, Skagen, Denmark
- Hjoernet, N K (2012), Personal communication with Naval Architect Niels Kyhn Hjørnet. Yacht Design, Sæby, Denmark

Data on the material and component composition, performance, construction etc. of the Eco Island Ferry are provided by:

- Moellgaard B (2012), Personal communication with the manager of Hov-Tunø Ferry, Odder Municipal, Odder

Further, more general information on the ferry alternatives are obtained from:

- Lindquist Å (2012), Life Cycle Cost Analysis - Eco-Island ferry. SP Technical Research Institute of Sweden.
- Amen M P and Evegren F (2012), Preliminary study of the Øko-Ø-færge project, SP Technical Research Institute of Sweden
- Evegren F and Rahm M (2012), Preliminary Analysis report – Eco-Island-Ferry (Reference BRd6035). SP – Technical Research Institute of Sweden

Data sources for background data: Ecoinvent and DK and EU27 hybrid IO-database

Generally, the ecoinvent database v2.2 (ecoinvent 2010) is used for the upstream product system relating to the production of materials, energy, capital goods as well as treatment/recycling of waste/scrap. The ecoinvent database is the most comprehensive transparent LCA database on the market. The database is fully linked (no black box processes) in the LCA software (SimaPro), and the full documentation of all data in ecoinvent are publically available at http://ecoinvent.org/.

The ecoinvent database v2.2 is not linked using consequential modelling (see **section 2.4**). Therefore, all significant ecoinvent activities are checked for allocation issues or constrained inputs and adjusted accordingly.

The ecoinvent database does include inputs of services, such as wholesale, business travelling, accounting, legal services etc. In order to obtain a cut-off criterion close to 0%, service inputs are generally based on the FORWAST hybrid IO-database (Schmidt 2010c, Schmidt 2010d, and Schmidt et al. 2010). The database is publically available in the demo version of the LCA software SimaPro: http://www.pre-sustainability.com/simapro-lca-software

FORWAST is a hybrid input-output model. The original FORWAST database includes the following emissions and resource inputs: Emissions to air: ammonia, carbon dioxide, carbon monoxide, methane, nitrogen dioxide, nitrous oxide, NMVOC, sulphur dioxide. Resources: carbon dioxide in air, coal, oil (crude), gas (natural gas), iron, aluminium, copper, nickel, zinc, lead, sand and clay, other minerals (extracted for use), other minerals (related to unused extraction).

The FORWAST database applied in this study is an updated version compared to the original one available in SimaPro and described in the FORWAST reports. Compared to the original version, the updated version distinguishes production outside Denmark between Europe and rest of the world (RoW), and the following emissions have been added to the inventory in the database:

- Particulates, to air
- Nitrate, to water
- Phosphate, to water

The updates of the original FORWAST model are described in Mikkelsen et al. (2011).

2.9 Life cycle impact assessment (LCIA) method

The method used for LCIA is the Stepwise 2006 method, version 1.3. The method is described and documented in Annex II in Weidema et al. (2008) and in Weidema (2009). This method is developed by choosing the best principles from the Danish EDIP 2003 method (Hauschild and Potting 2005) and from the Impact 2002+ method (Jolliet et al. 2003).

The indicators in the Stepwise method are explained in **Appendix 4: Explanation of indicators in the Stepwise LCIA** method**.**

Generally, inputs and outputs of biogenic CO_2 are considered as having no effect on global warming. The only exception is CO_2 emissions related to indirect land use changes. However, this contribution is generally insignificant for the types of products included in the current study. This is because these products are not related to inputs of biogenic materials, which are related to the occupation of land.

3. Life cycle inventory: electricity, transport and fuels

This chapter documents the life cycle inventory data that surround the detailed inventoried product system. This includes inventory data for electricity, district heating, transport, diesel incl. combustion, lubricants, services and capital goods.

3.1 Electricity

Electricity is used in most activities of the inventoried product systems. Generally, electricity at medium voltage is used in all activities. This includes production, high voltage grid and medium voltage grid. Grid losses are considered.

The methodology for the inventory of electricity is described in Schmidt et al. (2011). This is an electricity life cycle inventory project, which allows for application of different modelling assumptions:

1. Consequential future (based on data for 2008-2020)
2. Consequential historical (based on data for 2000-2008)
3. Consequential coal (100% coal)
4. Attributional (applied average data for year2008)

In the modelling of electricity, the consequential (future) scenario is used. In the consequential (future) scenario, the affected suppliers are identified as the proportion of the growth for each supplier during the period 2008-2020. The electricity generation in 2020 is identified by use of energy plans. The methodology for inventorying electricity is further described in Schmidt et al. (2011), which can be freely accessed here: http://www.lca-net.com/projects/electricity_in_lca/

In the current study, country/region specific inventory data are relevant for the following countries/regions and are obtained from the following data sources:

- Denmark: Merciai et al. (2011a)
- Europe: Merciai et al. (2011b)
- World: Merciai et al. (2011c)
- Sweden: Dalgaard and Schmidt (2012, p 11)
- China: Merciai et al. (2011d)

It should be noted that the electricity inventories are linked to the ecoinvent database. This enables for the identification of capital goods for electricity generation and transmission through the use of the ecoinvent data for capital goods.

The applied electricity mixes in the three countries/regions are shown in **Table 3.1**.

Table 3.1: GHG-emissions related to electricity production and distribution (Merciai et al. 2011a,b,c,d; Dalgaard and Schmidt 2012).

Energy source	Elec DK	Elec EU	Elec SE	Elec CN	GLO
Coal	-	-	-	53%	31%
Oil	-	-	-	-	-
Natural gas	20%	13%	-	8%	21%
Biomass	40%	12%	27%	1%	4%
Nuclear	-	-	-	13%	13%
Hydro	-	7%	12%	15%	15%
Wind	40%	58%	61%	9%	13%
Geothermal	-	1%	-	-	1%
Solar	-	9%	-	-	2%
Total	**100%**	**100%**	**100%**	**100%**	**100%**

3.2 District heating

LCA data on district heating in Denmark are based on Schmidt (2012, p 91-92). The data are shown in **Table 3.2**.

Table 3.2: LCI-data for district heating in Denmark. Data are obtained from Schmidt (2012, p 91-92).

Exchanges	Unit	District heating, combined heat and power (CHP)	LCI data
Reference flow			
District heating	MJ	0.59	Reference flow
Energy inputs			
Wood pellets burned in power plant	MJ	1	LCI-Data are fully documented in Schmidt et al. (2011).
Co-product: Electricity DK	MJ	-0.28	See **section 3.1**.
Transport			
Transport, lorry 16-32 t	tkm	0.0106	Amount calculated based on calorific value of wood pellets at 18.8 MJ/kg and assumed distance at 200 km for all material inputs. LCI data: Transport, lorry 16-32t, EURO5/RER (ecoinvent 2010).

3.3 Transport

Inventory data for transport are obtained from ecoinvent (2010). The following transport activities are included in the inventory. The reference flow is shown, and ecoinvent activities that are used are specified in brackets:

- Road transport/lorry, tkm (Transport, lorry 16-32t, EURO3/RER)
- Ship transport, tkm (Transport, barge/RER)

3.4 Marine diesel incl. combustion

Emission data for the major emissions (CO_2, SO_2, $PM_{2.5}$, NO_x, CO, NMVOC and CH_4) from combustion of marine diesel in Danish national sea for high speed 4 stroke ship engines are obtained from Nielsen et al. (2012). This reference is the Danish national emission inventory submitted under the Kyoto Protocol in 2012.

Emission data for 18 other emissions (e.g. heavy metals and specific NMVOCs) are obtained from ecoinvent (2010): 'Operation, barge/RER'. Also the LCI data for upstream production of diesel are obtained from this data set. The reference flow of the ecoinvent activity is tkm. The activity only includes input of diesel and the associated combustion emissions. The reference flow is changed to litres based on the input of diesel to the activity (0.00939 kg/tkm) and the density of diesel, which is 870 kg/m^3 (Andersen et al. 1981, p 119, 218).

The major emissions that are obtained from Nielsen et al. (2012), are compared with the figures in the ecoinvent data set, see **Table 3.3**. It appears from the comparison, that the differences are relatively small.

Table 3.3: Emission factors for diesel combustion in Denmark; national sea (Nielsen et al. 2012; emission factor for CO_2 is obtained from p 840&842 and other emissions are from p 1008-1013). The applied emissions from Nielsen et al. (2012) are compared with the ecoinvent (2010) data set for diesel combustion emissions.

Emissions	**Applied emission factors (g/kg fuel)**	**For comparison: Emission factors in ecoinvent (2010) data set: 'Operation, barge/RER' (g/kg fuel)**
Engine specific emissions		
NO_x (engine specific emission; high speed 4 stroke engine, year 2000)	55.0	50.0
CO (engine specific emission; high speed 4 stroke engine, year 2000)	8.00	2.7
NMVOC (engine specific emission; high speed 4 stroke engine, year 2000)	2.43	1.0
CH_4 (engine specific emission; high speed 4 stroke engine, year 2000)	0.08	0.024
Fuel specific emissions		
CO2 (Gas/diesel oil)	3160	3152
SO_2 (national sea, year 2009)	2.0	0.60
$PM_{2.5}$ (national sea, year 2009)	0.9	0.92

3.5 Lubricants

The use of lubricants is modelled as diesel including production and combustion. It has been assumed that all lubricants are fully combusted.

3.6 Services

The use of services is estimated based on generic Danish and European average figures for manufacturing of 'other transport equipment' (NACE industry classification which includes building and repairing of ships and boats). The data are obtained from a Danish and EU27 input-output (IO) database (Schmidt 2010a, Schmidt 2010b, and Schmidt et al. 2010). This database is publically available in SimaPro 7.3 (it can be freely accessed in the demo version):
http://www.pre-sustainability.com/simapro-lca-software

The way services are included in the inventory can be characterised as a tiered hybrid approach[1], where the gaps in the ordinary process-based (detailed modelled LCA activities and activities from the ecoinvent database) are filled using input-output data. The gaps in the process-based activities are filled by adding IO-data to all activities representing the life cycle stages in the product system for the ferries as well as to the

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[1] For further information see Weidema et al. (2009).

inputs to the activities, i.e. hybridisation has been done in two tiers. Ideally, all process-based activities including the whole ecoinvent database should be supplemented by IO-data, but this would require significant amounts of work well beyond the scope of an individual LCA study.

An LCA activity for services is established per unit of total supplied ships in monetary unit. Hence, 1 EUR of the reference flow of the activity accounts for the services that relates to the production or maintenance of 1 EUR ship. Each activity in the EU27 IO-database has inputs of 132 products. The life cycle emissions related to 21 of these products are defined as the emissions related to services. The 21 products are:

- Agricultural services n.e.c.
- Recycling services
- Trade and repair of motor vehicles and service stations
- Wholesale trade
- Retail trade and repair services
- Hotels and restaurants
- Post and telecommunication
- Financial intermediation
- Insurance and pension funding
- Services auxiliary to financial intermediation
- Real estate services
- Renting of machinery and equipment etc.
- Computer and related services
- Research and development
- Business services n.e.c.
- Public service and security
- Education services
- Health and social work
- Membership organisations
- Recreational and cultural services
- Services n.e.c.

Service inputs in other industries than the shipyard industry are determined in the same way as for shipyards as described above.

3.7 Capital goods, shipyard

A shipyard uses buildings, machinery, vehicles etc. This is regarded as the shipyard capital goods. Generally, capital goods for all other relevant industries are inventoried and included in ecoinvent, but shipyards are not included. Therefore, the uses of buildings, machinery, vehicles etc. in the shipyard industry per monetary unit of supplied ship are determined in the same way as the service inputs as described in **section 3.6**. Each activity in the EU27 IO-database has inputs of 132 products. The life cycle emissions related to 10 of these products are defined as the emissions related to capital goods. The 16 products are:

- Sand, gravel and stone from quarry
- Clay and soil from quarry
- Concrete, asphalt and other mineral products
- Bricks
- Motor vehicles and trailers
- Buildings, residential
- Buildings, non-residential
- Infrastructure, excluding buildings

There are a number of additional inputs to shipyards, which could also be considered as capital goods. But since these additional inputs of products are also present in the supplied ships, they are not considered as capital goods. These are:

- Fabricated metal products, except machinery
- Machinery and equipment n.e.c.
- Office machinery and computers
- Electrical machinery n.e.c.
- Radio, television and communication equipment
- Instruments, medical, precision, optical, clocks
- Transport equipment n.e.c.
- Furniture and other manufactured goods n.e.c.

4. Life cycle inventory: shipyard, ferry construction

The material inputs to the construction of the Eco Island Ferry are generally based on a detailed inventory of the material composition provided by Hjoernet (2012). This is presented in **Appendix 1: Detailed Components Lists**. For the use of carbon fibre and resin there is a general material loss at 15% at Danish Yachts (Soerensen 2012). Carbon fibre is lost because mats are cut to fit the structure, and resin is lost as excess resin in pipes etc. Electricity in the Eco Island Ferry shipyard is used for heating the hall for post curing of the paint. Electricity data are provided by Soerensen (2012).

Less detailed data are available for the Tun Island Ferry, where only data on the total lightweight and the weight of the engine were provided from Moellgaard (2012). The reason for the limited access to data for the Tun Island Ferry is that this ferry is relatively old and because there is no direct contact with the providing shipyard. For the Tun Island Ferry, it has been assumed that the use of machinery and equipment is the same as for the Eco Island Ferry, with the following exceptions:

- The weight of the diesel engine for the Tun Island Ferry is 10,000 kg instead of 3,000 kg, which is the weight for the Eco Island Ferry.
- The Tun Island Ferry has a ballast system, which the Eco Island Ferry does not have. The weight of the ballast system is estimated as 800 kg steel and 200 kg engine (pumps).
- The Tun Island Ferry has an oil-based heating system and not a ventilation/air-conditioning system as the Eco Island Ferry. However, the weight and material composition of the two systems is assumed to be equal.
- Whenever, changes are introduced for the Tun Island this is counter balanced in the material input of steel in order to maintain the total lightweight.
- It is assumed that the steel in the structure is distributed as 50% steel sheet and 50% steel section bars.
- Insulation use in the Tun Island Ferry is assumed to be 60% of that used in the Eco Island Ferry. This assumption is made because the Eco Island Ferry requires more insulation to meet fire safety regulations. The assumption is made in collaboration with Hjortberg (2012).

The weight and material composition of the two ferry alternatives can be seen in **Table 4.1**. However, it should be noted that **Table 4.1** also includes material inputs that become waste at the shipyard, e.g. at Danish Yachts the loss of all ingoing carbon fibre and resin is around 15% (Soerensen 2012). No data on the material loss at the shipyard that produces the Tun Island Ferry are available. Therefore, it has roughly been assumed that 5% of the input of steel sheet and section bars are lost and subsequently sent to recycling.

According to Lindquist (2012, p 9), the production costs of the Eco Island and the Tun Island Ferries are 5.2 and 4.6 million EUR respectively. These prices are used as reference flows for including services and capital goods at the shipyards.

The details of the life cycle inventory of each material are presented in the subsequent sections. In **Table 4.1** reference is made to these descriptions. Notice that specific reference is made to all inputs of process LCI data, while the inputs of services are not explicitly mentioned in **Table 4.1**. The services are included by adding one additional row for each material/energy input and material for treatment in **Table 4.1**, which accounting for the services related to the manufacturing and disposal of each product input. It is relatively easy to identify which input-output data represent each product input because the input-output used here follows international industry/product classifications that cover the entire economy, i.e. all industries/products. Transport of the materials used in the ferry construction stage is included in the service inputs to the shipyard.

Table 4.1: LCI-data for the production of the Eco Island Ferry and the Tun Island Ferry. Notice that the inputs of services related to each material, energy and material for treatment are not shown here – this is described in **section 3.6**

Exchanges	Unit	Eco Island Ferry	Tun Island Ferry	LCI data
Reference flow				
Ferry	Pieces	1	1	Reference flow
Material inputs				
Carbon fibre	tonne	10.031	-	See **section 4.1**. Notice that this includes 15% loss at the shipyard. Hence 8.527 tonne remains in the ship and 1.505 tonne is loss.
Resin (vinylester)	tonne	13.121	-	Epoxy resin, liquid, at plant/RER (ecoinvent 2010). Notice that this includes 15% loss at the shipyard. Hence 11.153 t remains in the ship and 1.968 is loss.
Core (PVC foam)	tonne	7.420	-	See **section 4.2**
E glass (fibreglass)	tonne	0.627	-	Glass fibre, at plant/RER (ecoinvent 2010)
Aluminium, sheet	tonne	1.325	-	See **section 4.3**
Steel, sheet	tonne	16.130	129.447	See **section 4.4**. For the Tun Island Ferry: There is an estimated 5% loss of the use of steel sheets for the structure. Hence 123.821 t remains in the ship and 5.626 t is loss.
Steel, section bar	tonne	-	112.517	See **section 4.4**. For the Tun Island Ferry: There is an estimated 5% loss of the use of steel section bars for the structure. Hence 106.891 t remains in the ship and 5.626 t is loss.
Engine	tonne	3.000	10.200	Gas motor 206kW/RER (ecoinvent 2010)
Electrical equipment	tonne	1.965	same as Eco	Electronics for control units/RER (ecoinvent 2010)
Cables	tonne	3.460	same as Eco	Cable, network cable, category 5, without plugs, at plant/GLO (ecoinvent 2010)
Transformers	tonne	0.300	same as Eco	Transformer, low voltage use, at plant/GLO (ecoinvent 2010)
Batteries	tonne	0.900	same as Eco	Battery, LiIo, rechargeable, prismatic, at plant/GLO
Insulation	tonne	11.161	6.697	See **section 4.6**
Textiles	tonne	2.000	same as Eco	See **section 4.7**
Wood products	tonne	0.650	same as Eco	See **section 4.8**
Plastics products	tonne	3.170	same as Eco	See **section 4.9**
Ceramic products	tonne	0.200	same as Eco	Sanitary ceramics, at regional storage/CH (ecoinvent 2010)
Paint – solids and curing agent	tonne	1.346	same as Eco	See **section 4.10**
Service inputs at shipyard	EUR	5,200,000	4,600,000	See **section 3.6**
Shipyard, capital goods	EUR	5,200,000	4,600,000	See **section 3.7**
Energy inputs				
Electricity, medium voltage, DK	kWh	5,200	-	See **section 3.1**
Transport				
Transport, lorry 16-32 t	tkm	0	0	Transport is generally included via the input of services to the shipyard. A large part hereof is related to wholesale, which uses significant amounts of transport services.
Material for treatment				
Carbon fibre to incineration	tonne	1.505	-	See **section 7.2**
Resin (vinylester) to incineration	tonne	1.968	-	See **section 7.2**
Steel recycling	tonne	-	11.252	See **section 7.2**

4.1 Carbon fibre

Carbon fibre is used for the production of the Eco Island ferry. Data for carbon fibre is not available in ecoinvent. A specific life cycle inventory based on literature data is carried out by Schmidt (2012) and **Table 4.2** is also based on Schmidt (2012).

Table 4.2: LCI-data for the production of carbon fibre. The LCI data (process data) are obtained from Griffing and Overcash (2010).

Inputs and outputs	Amount	Unit	LCI data
Output of products			
Carbon fibre	1.00	kg	Reference product
Material inputs			
Polyacrylonitrile (PAN precursor fibre)	1.82	kg	Polyacrylonitrile fibres (PAN), from acrylonitrile and methacrylate, prod. mix, PAN w/o additives EU-27 S; (ELCD 2008). Notice that an error in this data set has been identified and corrected: In the original data set the only CO2 emission is 'Carbon dioxide, land transformation'. This is corrected to 'Carbon dioxide'.
Nitrogen	10.0	kg	Nitrogen, liquid, at plant/RER (ecoinvent 2010)
Water	2.88	kg	Tap water, at user/RER (ecoinvent 2010)
Sizing solids	0.0100	kg	Epoxy resin, liquid, at plant/RER (ecoinvent 2010)
Sulphuric acid	0.0200	kg	Sulphuric acid, liquid, at plant/RER (ecoinvent 2010)
Energy Use			
Electricity, medium voltage, Europe	6.99	MJ	See **section 3.1**
Heating steam	3.10	MJ	Natural gas, burned in industrial furnace >100kW/RER (ecoinvent 2010)
Capital goods and services			
Capital goods	4E-10	P	Flat glass plant/RER/I U (ecoinvent 2010)
Process Emissions			
Sulfuric acid	0.0199	kg	Emission to water
Ethane	0.0000101	kg	Emission to air
Ammonia	0.00116	kg	Emission to air
Hydrogen cyanide	0.0157	Kg	Emission to air
Carbon monoxide	0.00324	Kg	Emission to air
Carbon dioxide	1.013	Kg	Emission to air

4.2 Core: PVC foam

Core material/sections for the Eco Island Ferry construction are made of pre-shaped PVC foam. The core sections are produced at DIAB International in Sweden. The following LCI data for the production of pre-shaped PVC foam sections is based on Sandström and Karlsson (2012).

Table 4.3: LCI-data for the production of shaped PVC foam produced at DIAB.

Inputs and outputs	Amount	Unit	LCI data
Output of products			
Shaped PVC foam	1.00	kg	Reference product
Material inputs			
Polyvinylchloride	1.11	kg	Polyvinylchloride, emulsion polymerised, at plant/RER (ecoinvent 2012)
Isocyanate	-	kg	Not included. Insignificant amount according to Sandström (2012)
Energy Use			
Electricity, medium voltage, Sweden	4.67	kWh	See **section 3.1**
Natural gas	32.6	MJ	Natural gas, burned in industrial furnace >100kW/RER (ecoinvent 2010)
Capital goods and services			
Capital goods	4E-10	P	Flat glass plant/RER/I U (ecoinvent 2010)
Materials for treatment			
Waste incineration, PVC	0.110	kg	See **Table 7.5**.

4.3 Aluminium sheet

Table 4.4: LCI data for aluminium sheet.

Inputs and outputs	Amount	Unit	LCI data
Output of products			
Aluminium sheet	1.00	kg	Reference product
Material inputs			
Primary aluminium	1.00	kg	Modified: 'Aluminium, primary, at plant/RER' (ecoinvent 2010). The electricity mix for aluminium production in ecoinvent is changed in order to reflect the marginal electricity mix for aluminium production. This is obtained from Schmidt and Thrane (2009, p 89). The mix is 62% coal, 9% natural gas, and 29% hydropower.
Aluminium sheet rolling	1.00	kg	Sheet rolling, aluminium/RER (ecoinvent 2010). In ecoinvent, this activity links to primary aluminium which is modified as described above. The sheet rolling data set includes transport of raw materials to the rolling activity.

4.4 Steel sheet and section bar

According to Suzuki et al. (2004, p 47) steel sheets for shipbuilding are hot rolled.

Table 4.5: LCI data for steel sheet.

Inputs and outputs	Amount	Unit:	LCI data
Output of products			
Steel sheet	1.00	kg	Reference product
Material inputs			
Primary steel, unalloyed	1.00	kg	Modified: 'Steel, converter, unalloyed, at plant/RER' (ecoinvent 2010). See text below the table.
Steel sheet rolling (hot rolling)	1.00	kg	Modified: 'Hot rolling, steel/RER' (ecoinvent 2010). In ecoinvent, this activity links to primary steel which is modified as described below the table. The hot rolling data set includes transport of raw materials to the rolling activity.

According to Schmidt (2005) primary steel is produced using the so-called basic oxygen furnace (BOF) technology. In this process, there is input of steel scrap, which is added for temperature control as well as feedstock. Since the activity has inputs of iron ore/pig iron as well as steel scrap, the activity is a mixture of recycling and primary production. A change in demand for steel will not affect the quantity of steel scrap collected for recycling. Therefore, the activity is modified to exclude the recycling part. Steel recycling uses the so-called electric arc furnace (EAF) technology. The mixed primary / recycling activity 'Steel, converter, unalloyed, at plant/RER' is modified to representing primary production only by reducing the product output by the same quantity as the steel scrap input and by adding a negative input of the same quantity steel produced by the EAF technology; ecoinvent activity: Steel, electric, un- and low-alloyed, at plant/RER. The modification is also described in Schmidt (2012, p 72).

Table 4.6: LCI data for steel section bar.

Inputs and outputs	Amount	Unit	LCI data
Output of products			
Steel section bar	1.00	kg	Reference product
Material inputs			
Primary steel, unalloyed	1.00	kg	Modified 'Steel, converter, unalloyed, at plant/RER' (ecoinvent 2010). See above below the table.
Steel sheet rolling	1.00	kg	Modified: 'Section bar rolling, steel/RER' (ecoinvent 2010). In ecoinvent, this activity links to primary steel which is modified as described above the table. The section bar rolling data set includes transport of raw materials to the rolling activity.

4.5 Engine

The LCI data for the engine are based on the data set 'Gas motor 206kW/RER/I' from ecoinvent (2010). This data set is modified as described in **Table 4.7**.

Table 4.7: Modification of the original ecoinvent data set 'Gas motor 206kW/RER/I'. Notice that only the modified inputs and outputs of the data set are shown here.

Inputs and outputs	Original ecoinvent	Modified	Unit	LCI data
Output of products				
Engine	1 p	1400 kg	changed	Reference flow
Material inputs				
Cast iron, at plant/RER	1000	1000	kg	Modified: 'Cast iron, at plant/RER' (ecoinvent 2010). The original cast iron data set represents a mix of recycled and virgin iron. The input of steel scrap to the process is displaced with pig iron so that the data set now represents 100% virgin cast iron.
Chromium steel 18/8, at plant/RER	100	100	kg	Modified: 'Chromium steel 18/8, at plant/RER' (ecoinvent 2010). The original data set represents a mix of recycled and virgin iron. The input of recycled (electric arc furnace) chromium steel is displaced with blast furnace chromium steel so that the data set now represents 100% virgin steel. Further the input of hot rolling to the activity is modified as described in **Table 4.5**.
Steel, low-alloyed, at plant/RER	200	200	kg	Modified: 'Steel, low-alloyed, at plant/RER' (ecoinvent 2010). The original data set represents a mix of recycled and virgin iron. Therefore the input is displaced with modified data as described in **section 4.4** so that the data set now represents 100% virgin steel.
Reinforcing steel, at plant/RER	100	100	kg	Modified: 'Reinforcing steel, at plant/RER' (ecoinvent 2010). The original data set represents a mix of recycled and virgin iron. The input of recycled (electric arc furnace) steel is displaced with blast furnace steel so that the data set now represents 100% virgin steel. Further the input of hot rolling to the activity is modified as described in **Table 4.5**.

4.6 Insulation

Data on different insulation materials used in the Eco Island Ferry are obtained from Hjoernet (2012). The data are provided as the weight of different product numbers of insulation materials from ISOVER. Further, Danish Yachts have provided product specifications for each insulation material. Based on this, the material composition of the insulation material is estimated. The material composition is divided into the material categories below:

- Rockwool (a very small share of the insulation material is laminate: <0.7%. This is modelled as Rockwool)
- Polystyrene
- Fibre glass cloth

The amount of insulation material in the two ferry alternatives is not the same. The Tun Island Ferry requires 60% of the total amount of insulation used in the Eco Island Ferry. This is because the Eco Island Ferry requires additional insulation to meet fire safety standards. The assumption is made in collaboration with Hjortberg (2012).

Table 4.8: LCI data for insulation material in the two ferry alternatives.

Inputs and outputs	Insulation	Unit	LCI data
Output of products			
Insulation	1	kg	Reference flow
Material inputs			
Rockwool	0.0304	kg	Rock wool, at plant/CH (ecoinvent 2010)
Polystyrene	0.959	kg	Polystyrene foam slab, at plant/RER (ecoinvent 2010)
Fibre glass cloth	0.0108	kg	Glass fibre, at plant/RER (ecoinvent 2010)

4.7 Textiles

The LCI modelling of textiles is based on the data set from ecoinvent: Textile, woven cotton, at plant/GLO (ecoinvent 2010). The production of textiles is associated with relatively high electricity consumption. Therefore, the electricity mix used in the ecoinvent activity is displaced with the global electricity data as described in **section 3.1**. The modification is introduced in the following two upstream activities of the textile activity (because these are the activities where electricity is used):

- Yarn production, cotton fibres/GLO (ecoinvent 2010)
- Weeving, cotton/GLO (ecoinvent 2010)

4.8 Wood products

The LCI modelling of wood is based on the data set from ecoinvent: ‘Laminated timber element, transversally pre-stressed, for outdoor use, at plant/RER’ (ecoinvent 2010). This activity of ecoinvent data sets for wood. These data sets are allocated between roundwood and wood residues based on economic value. This is not in line with the applied consequential modelling assumption in the current project. However, wood products only account for 0.25% (Tun Island Ferry) and 0.90% (Eco Island Ferry) of the total lightweight of the ferries. Hence, this uncertainty in the modelling of wood is regarded as insignificant.

The unit of the reference flow of the wood activity in ecoinvent is volume (m^3). This is converted to kg by use of an estimated density at 900 kg/m^3.

4.9 Plastics products

Plastics products are assumed to be based on polyethylene (PE), which is the most common plastic type on the market. The following data set for polyethylene from ecoinvent is used: ‘Polyethylene, HDPE, granulate, at plant/RER’ (ecoinvent 2010). This data set accounts for the production of basic plastics. The following data set from ecoinvent is used for representing the processing into plastics products: ‘Extrusion, plastic pipes/RER’ (ecoinvent 2010).

4.10 Paint

The majority of the paint used for both of the ferries in the ferry construction stage is amine cured epoxy resin. The ratio between the paint (resin and pigment) and the curing agent is based on a detailed inventory of paint used for the Eco Island Ferry, see **Appendix 2: Paint and** zinc anode calculations. The same paint is assumed for the two ferry alternatives. All paints are modelled as paint with white pigment (titanium dioxide). The ratio between resin and pigment is obtained from the ecoinvent data set: ‘Alkyd paint, white, 60% in solvent, at plant/RER’ (ecoinvent 2010). Further, capital goods and electricity are also obtained from this data set. The NMVOC emissions from paint application are calculated based on the amounts (litre), densities and VOC-content of the different paints, see **Appendix 2: Paint and** zinc anode calculations.

Table 4.9: LCI data for paint, including NMVOC emissions from application.

Inputs and outputs	Amount	Unit	LCI data
Output of products			
Paint	1	kg	Reference flow
Material inputs			
Epoxy resin	0.407	kg	Alkyd resin, long oil, 70% in white spirit, at plant/RER (ecoinvent 2010)
Pigment	0.421	kg	Titanium dioxide, production mix, at plant/RER (ecoinvent 2010)
Amine curing agent	0.172	kg	Trimethylamine, at plant/RER (ecoinvent 2010)
Energy inputs			
Electricity, medium voltage, Europe	0.0428	kWh	See **section 3.1**
Capital goods and services			
Capital goods	4.00E-10	p	Chemical plant, organics/RER/I (ecoinvent 2010)
Emissions			
NMVOC	0.221	kg	Quantity of VOC from paint; see **Appendix 2: Paint and** zinc anode calculations

5. Life cycle inventory: shipyard, maintenance

Maintenance of the ferry includes painting for general surface protection and anti-corrosion, use of zinc anodes for anti-corrosion and general maintenance in shipyard. Specific data on the use of paint are obtained from the Tun Island Ferry (Moellgaard 2012) and a similar use has been assumed for the Eco Island Ferry. This is an overestimation of the paint use for the Eco Island Ferry because there is almost no need for anti-corrosion applications.

Specific data on the annual use of zinc anodes are obtained from the Eco Island Ferry (Hjortberg 2012) and the Tun Island Ferry (Moellgaard 2012). In collaboration with Hjoernet (2012), it has been assumed that 50% of the initial weight of the zinc in the zinc anodes is emitted to seawater during operation. This emission is included in the operation stage in **chapter 1**. The remaining weight of the zinc after use is assumed to be recycled. The total weight of the steel in the zinc anode is assumed to be recycled after use.

According to Lindquist (2012, p 11), the maintenance costs of the Eco Island and the Tun Island Ferries are 35,000 and 71,000 EUR respectively. These prices are used as reference flows for including services and capital goods at the shipyards.

In **Table 5.1**, notice that specific reference is made to all inputs of process LCI data, while the inputs of services are not explicitly mentioned. The services are included by adding one additional row for each material input and material for treatment in the table accounting for the services related to the manufacturing and disposal of each product input. It is relatively easy to identify which input-output data that represent each product input because the used input-output follows international industry/product classifications that cover the entire economy, i.e. all industries/products. Transport of the materials used in the maintenance stage is included in the service inputs to the shipyard.

Table 5.1: LCI-data for the maintenance of the Eco Island Ferry and the Tun Island Ferry. Notice that the inputs of services related to each material, energy and material for treatment are not shown here – this is described in **section 3.5**.

Exchanges	Unit	Eco Island Ferry	Tun Island Ferry	LCI data
Reference flow				
Ferry maintenance	year	1	1	Reference flow
Material inputs				
Zinc anode – zinc	kg	18.3	107	Modified: Zinc, primary, at regional storage/RER (ecoinvent 2010). The electricity mix for zinc production in ecoinvent is changed in order to reflect the marginal global electricity mix (see **section 3.1**)
Zinc anode - steel	kg	1.69	9.80	See **Table 4.5**
Paint	kg	505	505	See **Table 5.2**
Service inputs at shipyard	EUR	35,000	71,000	See **section 3.5**
Shipyard, capital goods	EUR	35,000	71,000	See **section 3.7**
Transport				
Transport, lorry 16-32 t	tkm	0	0	Transport is generally included via the input of services to the shipyard. A large part hereof is related to wholesale, which uses significant amounts of transport services.
Materials for treatment				
Recycling of zinc in spent zinc anode	kg	9.16	53.3	See **section 7.1**
Recycling of steel in spent zinc anode	kg	1.69	9.80	See **section 7.1**

The majority of the paint used for both of the ferries in the ferry maintenance stage is amine cured epoxy resin. The ratio between the paint (resin and pigment) and the curing agent is based on a detailed inventory of paint used for the Tun Island Ferry, see **Appendix 2: Paint and zinc anode calculations**. The same paint is assumed for the two ferry alternatives. All paints are modelled as paint with white pigment (titanium dioxide). The ratio between resin and pigment is obtained from the ecoinvent data set: 'Alkyd paint, white, 60% in solvent, at plant/RER' (ecoinvent 2010). Further, capital goods and electricity are also obtained from this data set. The NMVOC emissions from paint application are calculated based on the amounts (litre), densities and VOC-content of the different paints, see **Appendix 2: Paint and zinc anode calculations**.

Table 5.2: LCI data for paint, including NMVOC emissions from application.

Inputs and outputs	Amount	Unit	LCI data
Output of products			
Paint	1	kg	Reference flow
Material inputs			
Epoxy resin	0.422	kg	Alkyd resin, long oil, 70% in white spirit, at plant/RER (ecoinvent 2010)
Pigment	0.437	kg	Titanium dioxide, production mix, at plant/RER (ecoinvent 2010)
Amine curing agent	0.141	kg	Trimethylamine, at plant/RER (ecoinvent 2010)
Energy inputs			
Electricity, medium voltage, Europe	0.0428	kWh	See **section 3.1**
Transport			
Transport, lorry 16-32 t	0.200	tkm	Transport, lorry 16-32t, EURO5/RER (ecoinvent 2010). Assumed distance at 200 km for all material inputs.
Emissions			
NMVOC	0.176	kg	Quantity of VOC from paint; see **Appendix 2: Paint and zinc anode calculations**

6. Life cycle inventory: Ferry operation

The ferry operation stage includes the use and combustion of diesel and lubricants, electricity and emissions of zinc from the zinc anode. Services related to tickets sale, marketing, webpage etc. are not included for this stage. Data on the annual use of diesel are provided by Sørensen (2012), see **Table 6.2**. According to Hjortberg (2012), the use of lubricants can be estimated as 1.6 kg per tonne diesel for new engines and 3.2 kg per tonne diesel for older engines. The average at 2.4 kg per tonne diesel is applied.

The total use of zinc anodes is described in **section 5**. It has been assumed that 50% of the weight of the original zinc in the zinc anode is emitted to sea water.

A potential significant emission from the operation stage of ships is the emission of anti-fouling agents to sea water, e.g. tributyl tin oxide or copper (Thrane 2004). The Eco and Tun Island Ferries use nanotechnology anti-fouling coatings. According to Szewczyk (2010), there are generally no hazardous emissions associated with nanotechnology anti-fouling agents. Therefore, no of such emissions are included in the study.

Table 6.1: LCI-data for the maintenance of the Eco Island Ferry and the Tun Island Ferry. Notice that the inputs of services related to the production of lubricants, diesel and electricity are not shown here – this is described in **section 3.5**.

Exchanges	Unit	Eco Island Ferry	Tun Island Ferry	LCI data
Reference flow				
Ferry operation	year	1	1	Reference flow
Material inputs				
Lubricants	litre	178	357	See **section 3.5**
Energy inputs				
Diesel incl. combustion	litre	74,340	148,792	See **section 3.4**
Electricity, medium voltage, DK	kWh	73,600	65,472	See **section 3.1**
Transport				
Transport, lorry 16-32 t	tkm	12,966	25,952	Transport, lorry 16-32t, EURO5/RER U. Assumed distance at 200 km for all material inputs. The mass of diesel is calculated using the density at 0.87 kg/litre (Andersen et al. 1981).
Emissions to water				
Zinc	kg	9.16	53.3	emission to water

Diesel and fuel oil consumption data is provided by Soerensen (2012) and is presented below in **Table 6.2**.

Table 6.2: Diesel/fuel oil consumption per year for the two ferry alternatives (Soerensen 2012).

Diesel/fuel oil consumption	Eco Island Ferry	Tun Island ferry
Main engines at 9.5 knots	41.4 litre/hour	90 litre/hour
Generator per hour (air condition etc.)	11.7 litre/hour	10 litre/hour
Total per voyage (2 hours per out and return trip)	**106.2 litre**	**200 litre**
Total per year (700 voyages/year)	**74,340 litre**	**140,000 litre**
Consumption in harbor per year (air condition etc.)	0 litre	8,792 litre
Total consumption per year	**74,340 litre**	**148,792 litre**

7. Life cycle inventory: Ferry disposal/recycling

At end of life of the ferries, the total weight of all materials (see **Table 4.1**) is sent to waste treatment. In **Table 7.1** the treatment/recycling of each material/component of the ferries are estimated. It should be noticed that the actual disposal/recycling is not known, and actual data are very difficult to obtain. A sensitivity analysis on alternative end-of-life scenarios is carried out in **section 9.11**.

Paint: Not all paint remains paint. Some of it is emitted immediately after application as VOC emissions. The solids applied in the construction stage can be seen in **Appendix 2: Paint and zinc anode calculations**. Further, paint is applied as part of ferry maintenance. Hence, the annual solids applied in the maintenance stage are multiplied by the life time (years) of the ferries to account for all added paint throughout the ferries' life cycle. It is assumed that only half of this amount is still present at the end of life of the ferry, whereas the remaining is assumed to be disintegrated/eroded during operation. The solids applied in the maintenance stage can also be seen in **Appendix 2: Paint and zinc anode calculations**.

In this chapter the inputs of services to the waste disposal activities are not explicitly mentioned. For each disposal activity, the services are included as described in **section 3.6**. Transport of the materials to treatment/disposal is included in the services.

Table 7.1: Ferry disposal scenario. The LCI data relating to each of the three disposal options for each waste/scrap category are described in **sections 7.1**, **7.2** and **7.3**.

	Eco Island Ferry	Tun Island Ferry	Waste/scrap category	Share category	Treatment		
					Recycling	Incineration	Landfill
Reference flow	**unit: piece**	**unit: piece**					
Ferry	1	1					
Components in ferry	**unit: tonne**	**unit: tonne**					
Carbon fibre	8.538	-	carbon fibre	100%		100%	
Resin (vinylester)	11.164	-	resin	100%		100%	
Core (PVC foam)	7.431	-	PVC	100%		100%	
E glass (fibreglass)	0.627	-	inert	100%			100%
Aluminium, sheet	1.325	-	aluminium	100%	100%		
Steel, sheet	16.130	123.821	steel	100%	90%		10%
Steel, section bar	-	106.891	steel	100%	90%		10%
Engine	3.000	10.200	steel	100%	90%		10%
Electrical equipment	1.965	1.965	steel	55%	50%		50%
			copper	10%	50%		50%
			plastics	35%	50%	50%	
Cables	3.460	3.460	copper	50%	50%		50%
			PVC	50%	50%	50%	
Transformers	0.300	0.300	steel	70%	80%		20%
			copper	30%	80%		20%
Batteries	0.900	0.900	steel	40%	80%		20%
			copper	10%	80%		20%
			inert	50%			100%
Insulation	11.161	6.697	plastics	96%		100%	
			inert	4%			100%
Textiles	2.000	2.000	textile	100%		100%	
Wood products	0.650	0.650	wood	100%		100%	
Plastics products	3.170	3.170	plastics	100%	50%	50%	
Ceramic products	0.200	0.200	inert	100%			100%
Paint – solids and curing agent	(1.049+40*0.329)/2= 7.11	(1.049+30*0.329)/2= 5.46	inert	100%			100%

7.1 Recycling

In this section the LCI data for recycling of different relevant scrap/waste materials are described. Generally, recycling if the different materials are assumed to take place in Europe. When services are included (see **section 3.6**), this is done for European industries.

Table 7.2: LCI data for recycling of different waste fractions. The data are further described below the table. In addition to the data in the table, lorry transport of the scrap/waste to the recycling plant at estimated 200 km is included: Transport, lorry 16-32t, EURO5/RER (ecoinvent 2010).

Waste/scrap fraction to recycling	Material recovery rate	Data source for recycling activity	Data source for the displaced virgin material
Plastics, polyethylene (PE) to recycling	88%	Schmidt (2005, p 105), see detailed description in **Table 7.3**.	See **Table 7.3**
Iron and steel scrap to recycling	90%	Steel, electric, un- and low-alloyed, at plant/RER. Original ecoinvent activity modified, see text below table.	Primary steel (not rolled) as described in **section 4.4**
Aluminium scrap to recycling	97%	Aluminium, secondary, from old scrap, at plant/RER. Original ecoinvent activity modified, see text below table.	Primary aluminium (not rolled) as described in **section 4.3**
Copper scrap to recycling	76%	Copper, secondary, at refinery/RER. Original ecoinvent activity modified, see text below table.	Copper, primary, at refinery/GLO (ecoinvent 2010)
Zinc scrap to recycling	76%	Copper, secondary, at refinery/RER. Original ecoinvent activity modified, see text below table.	Modified: Zinc, primary, at regional storage/RER (ecoinvent 2010). The electricity mix for zinc production in ecoinvent is changed in order to reflect the marginal global electricity mix (see **section 3.1**)
Inert waste to recycling (used as filler material)	100%	Based on parts of ecoinvent activity: Gravel, crushed, at mine/CH. Only the parts of the activity that relates to the crushing is included.	Sand, at mine/CH (ecoinvent 2010)

Material recovery efficiency for plastic scrap is obtained from Schmidt (2012). A material recovery efficiency of 88% means that 1 kg plastics waste/scrap which is sent to recycling is reprocessed into 0.88 kg new plastics and 0.12 kg processing waste. The efficiencies of metals are given below;

- recovery of iron/steel scrap: efficiency is 90% (based on Classen et al. 2009)
- recovery efficiency of aluminium scrap is 97% (based on Classen et al. 2009)
- recovery efficiency of copper is 76% (based on Classen et al. 2009)
- recovery efficiency of zinc is assumed the same as for copper
- when inert material is used as filler material no loss is considered, i.e. the efficiency is 100% (based on Schmidt 2012)

The inventory data used for the modelling of recycling of plastics scrap in **Table 7.2** are described in detail in **Table 7.3** below. Schmidt (2012) assumes that 50% of all plastic waste that is collected for recycling, is recycled in Denmark and that the remaining is recycled in China. It is assumed that process waste in Denmark is incinerated, while it is assumed that in China it is sent to landfill.

Table 7.3: LCI data for recycling of 1 kg plastics scrap – the shown data are applicable to all included plastic types. Data are obtained from Schmidt (2012, p 90).

Recycling of plastics scrap	Amount	Description of LCI data
Reference flow		
Recycling of plastics scrap	1 kg	Reference flow
Substituted production		
Recovered material, plastics	-0.88 kg	Polyethylene, HDPE, granulate, at plant/RER (ecoinvent 2010)
Electricity inputs		
Electricity, medium voltage, DK	0.29 kWh	See **section 3.1**
Electricity, medium voltage, CN	0.29 kWh	See **section 3.1**
Process waste to treatment		
Plastics waste to incineration, DK	0.06 kg	See **section 0**
Plastics waste to landfill	0.06 kg	See **section 0**

The ecoinvent activities used for the modelling of the metal recycling activities in **Table 7.2** are modified. All the ecoinvent activities have the recovered material as the determining product output. This is changed to be the incoming scrap instead. In order to do so, the reference flows of the original ecoinvent activities are renamed to be ‘*Recycling of…*’ instead of ‘*Secondary…*’. Further the reference flows are calculated as one divided by the material recovery efficiencies as of **Table 7.2**.

7.2 Incineration

This section describes the LCI data used for the modelling of waste incineration of different relevant waste materials. Generally the data are based on data in the ecoinvent database. However, these data do not include energy recovery; therefore, the ecoinvent data sets are modified to account for that. This is based on information in Schmidt (2012), and it is further documented in each of the following LCI tables for incineration.

It is assumed that all incineration takes place in Denmark, and therefore the incineration activities are also modelled using electricity efficiencies etc. like those for Danish incineration plants.

No specific data on waste incineration of carbon fibre and resin have been identified. Hence the combustion emissions and calorific value have been estimated as being similar to that of polyethylene.

Table 7.4: LCI-data for waste incineration of carbon fibre, resin and plastics waste (non-PVC).

Exchanges	Amount	Unit	LCI data
Reference flow			
Waste incineration, plastics, non-PVC	1.00	kg	Reference product
Material inputs			
Waste incineration process, incl. material inputs, transport, capital goods etc.	1.00	kg	Disposal, polyethylene, 0.4% water, to municipal incineration/CH (ecoinvent 2010)
Energy Use			
Electricity, medium voltage, DK	-6.44	MJ	Amount calculated as calorific value of PE (40 MJ/kg) multiplied with electricity recovery in Danish waste incineration plants (Schmidt 2012, p 91-92). LCI data for electricity, see **section 3.1**.
District heating, DK	-26.0	MJ	Amount calculated as calorific value of PVC multiplied with heat recovery in Danish waste incineration plants (Schmidt 2012, p 91-92). LCI data for district heating, see **Table 3.2**.

Table 7.5: LCI-data for waste incineration of PVC in Denmark.

Inputs and outputs	Amount	Unit:	LCI data
Output of products			
Waste incineration, PVC	1.00	kg	Reference product
Material inputs			
Waste incineration process, incl. material inputs, transport, capital goods etc.	1.00	kg	Disposal, polyvinylchloride, 0.2% water, to municipal incineration/CH (ecoinvent 2010)
Energy Use			
Electricity, medium voltage, DK	-3.70	MJ	Amount calculated as calorific value of PVC (23 MJ/kg) multiplied with electricity recovery in Danish waste incineration plants (Schmidt 2012, p 91-92). LCI data for electricity, see **section 3.1**.
District heating, DK	-14.9	MJ	Amount calculated as calorific value of PVC multiplied with heat recovery in Danish waste incineration plants (Schmidt 2012, p 91-92). LCI data for district heating, see **Table 3.2**.

Table 7.6: LCI-data for waste incineration of textiles in Denmark.

Inputs and outputs	Amount	Unit:	LCI data
Output of products			
Waste incineration, textiles	1.00	kg	Reference product
Material inputs			
Waste incineration process, incl. material inputs, transport, capital goods etc.	1.00	kg	Disposal, polyvinylchloride, 0.2% water, to municipal incineration/CH (ecoinvent 2010)
Energy Use			
Electricity, medium voltage, DK	-3.06	MJ	Amount calculated as calorific value of textiles (19 MJ/kg obtained from the ecoinvent data set: 'Disposal, textiles, soiled, 25% water, to municipal incineration/CH') multiplied with electricity recovery in Danish waste incineration plants (Schmidt 2012, p 91-92). LCI data for electricity, see **section 3.1**.
District heating, DK	-12.3	MJ	Amount calculated as calorific value of PVC multiplied with heat recovery in Danish waste incineration plants (Schmidt 2012, p 91-92). LCI data for district heating, see **Table 3.2**.

Table 7.7: LCI-data for waste incineration of wood in Denmark.

Inputs and outputs	Amount	Unit:	LCI data
Output of products			
Waste incineration, wood	1.00	kg	Reference product
Material inputs			
Waste incineration process, incl. material inputs, transport, capital goods etc.	1.00	kg	Disposal, polyvinylchloride, 0.2% water, to municipal incineration/CH (ecoinvent 2010)
Energy Use			
Electricity, medium voltage, DK	-2.82	MJ	Amount calculated as calorific value of wood (17.5 MJ/kg obtained from the ecoinvent data set: 'Disposal, wood untreated, 20% water, to municipal incineration/CH') multiplied with electricity recovery in Danish waste incineration plants (Schmidt 2012, p 91-92). LCI data for electricity, see **section 3.1**.
District heating, DK	-11.4	MJ	Amount calculated as calorific value of PVC multiplied with heat recovery in Danish waste incineration plants (Schmidt 2012, p 91-92). LCI data for district heating, see **Table 3.2**.

7.3 Landfill

Landfill for the relevant waste materials is modelled using the LCI data specified below. Generally, landfilling of the different materials is assumed to take place in Europe. This is because it is typically a fraction of the components/materials that is sent to recycling, i.e. impurities, poor quality scrap etc., that ends up being landfilled – and recycling is generally assumed to take place in Europe. When services are included (see **section 3.6**), this is done for European industries.

Table 7.8: LCI-data for landfill for different waste materials.

Waste fraction for landfill	LCI data
Carbon fibre, Resin, Plastics	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH (ecoinvent 2010)
Steel waste	Disposal, steel, 0% water, to inert material landfill/CH (ecoinvent 2010)
Aluminium waste	Disposal, aluminium, 0% water, to sanitary landfill/CH (ecoinvent 2010)
Copper waste	Modelled as steel
Zinc waste	Modelled as steel
Wood	Disposal, wood untreated, 20% water, to sanitary landfill/CH (ecoinvent 2010)

8. Results: Life Cycle Impact Assessment

In this section the results of the LCA are presented.

8.1 Overall characterised and weighted results of the two ferry alternatives

The characterised results for the two ferry alternatives are shown in **Table 8.1** below.

Table 8.1: Characterised results for the two ferry alternatives. The results represent the functional unit: servicing the Tunø ferry route in one year.

Impact category	Unit	Eco Island Ferry	Tun Island Ferry
Global warming	kg CO_2-eq	295,154	546,305
Human toxicity, carcinogens	kg C_2H_3Cl-eq	1,036	3,421
Human toxicity, non-carc.	kg C_2H_3Cl-eq	3,243	10,499
Respiratory inorganics	kg $PM_{2.5}$-eq	613	1,193
Ionizing radiation	Bq C-14-eq	865,267	1,493,367
Ozone layer depletion	kg CFC-11-eq	0.034	0.064
Ecotoxicity, aquatic	kg TEG-eq w	17,909,827	83,764,965
Ecotoxicity, terrestrial	kg TEG-eq s	729,854	1,460,375
Nature occupation	m^2 agr.land	1,015	1,614
Acidification	m^2 UES	34,855	67,079
Eutrophication, aquatic	kg NO_3-eq	463	798
Eutrophication, terrestrial	m2 UES	127,967	251,180
Respiratory organics	pers*ppm*h	513	997
Photochemical ozone, vegetat.	m^2*ppm*hours	6,864,803	13,413,041
Non-renewable energy	MJ primary	4,331,095	7,953,873
Mineral extraction	MJ extra	555	1,367

The comparison of the two ferry alternatives in **Table 8.1** is presented in a chart below (**Figure 8.1**) showing the relative difference.

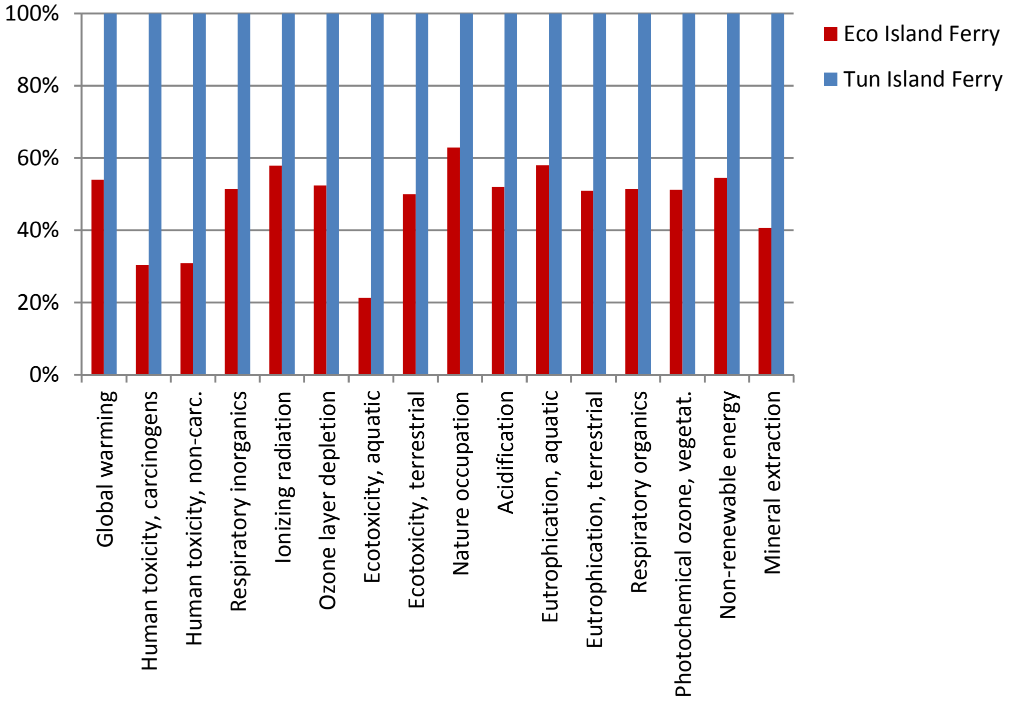

Figure 8.1: Comparison of the two ferry alternatives showing the relative difference.

It appears from the comparison of the overall characterised results that the Eco Island Ferry performs better than the Tun Island Ferry for all impact categories. Generally, the impacts related to the life cycle of the Eco Island Ferry are around the half of the impacts of the Tun Island Ferry. The explanation of the difference is related to the reduced fuel consumption in the Eco Island Ferry.

In order to focus on the most important environmental impacts in the further analysis of the results, the characterised results in **Table 8.1** are weighted. The characterised results are compiled into monetised environmental impacts using the Stepwise weighting methodology (Weidema 2009). By doing so, the relative significance of the different impact categories can be identified. The monetisation in Weidema (2009) is based on willingness to pay principles (which are also often used in cost-benefit analysis). Hence, the monetised impacts can be used as valuation of externalities in cost-benefit analysis. However, it should be noticed that timing of emissions is not discounted.

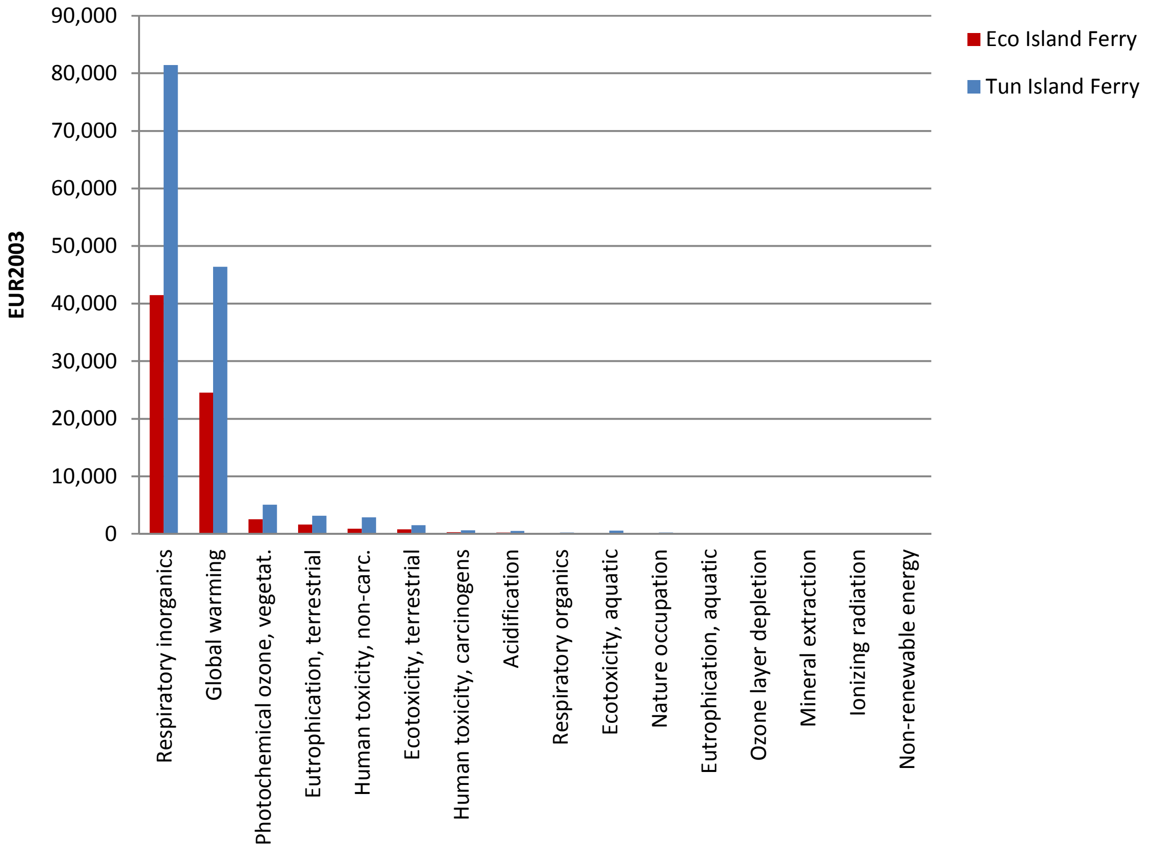

Figure 8.2: Weighting: Comparison of the two ferry alternatives showing the weighted results. The results are sorted after importance; the most significant contributions of the Eco Island Ferry are the left.

The weighting in **Figure 8.2** shows that the most significant impact categories are respiratory inorganics, global warming and photochemical ozone formation (impact on vegetation). Obviously, this ranking of the importance relies on the embedded methodology in the weighting method (Weidema 2009). Alternative weighting methods have been applied to test if these methods can be used to identify the same most important impact categories as identified with the Stepwise method. The result of this, applying the ReCiPe and the Impact2002+ methods, is shown in **Figure 8.3**.

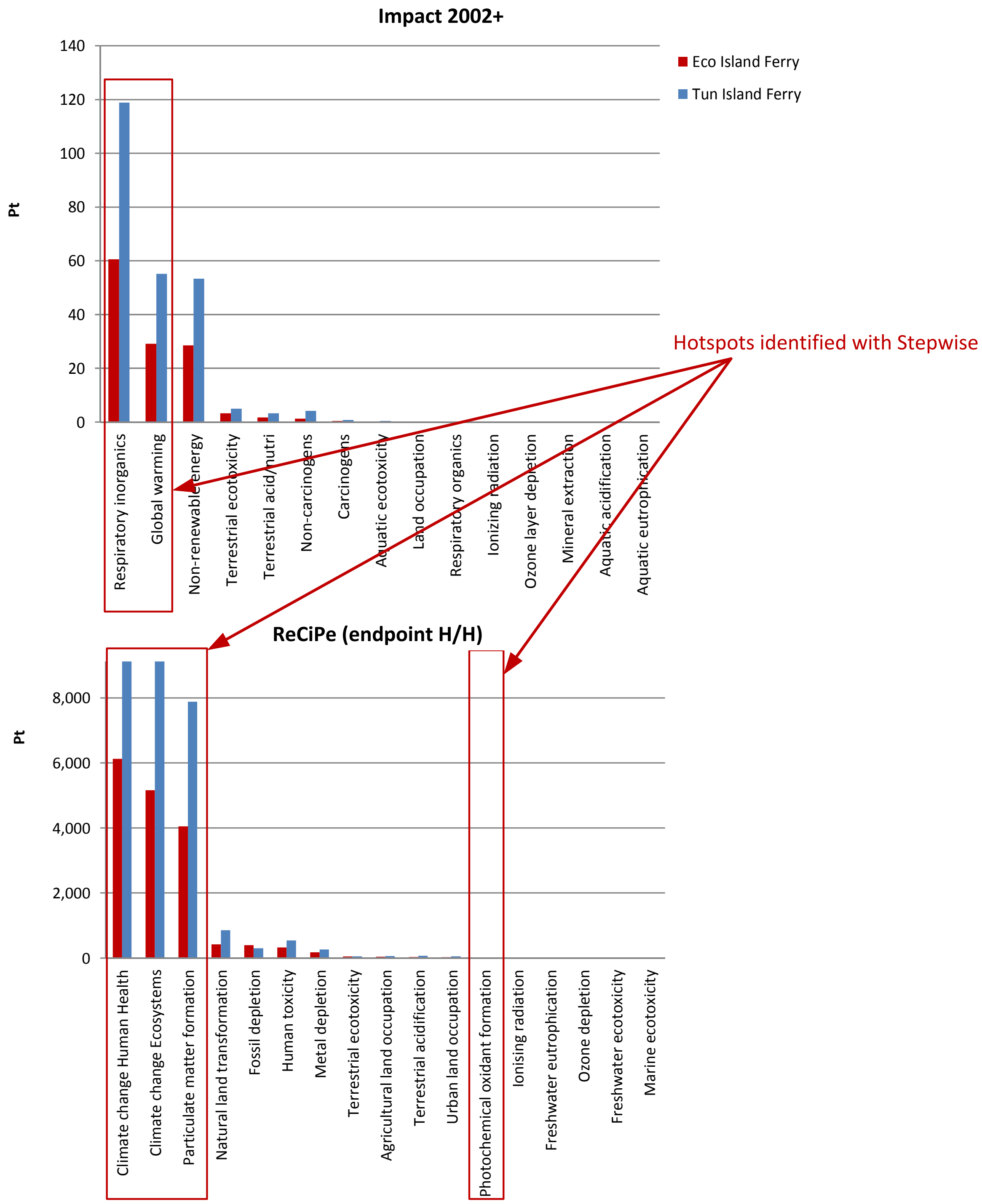

Figure 8.3: Identification of most significant impact categories by using alternative weighting methods: Impact 2002+ (Jolliet et al. 2003) and ReCiPe Endpoint v1.07 / Europe H/H (Goedkoop et al. 2009).

The Impact2002+ and the ReCiPe methods both agree with the Stepwise method that global warming (=climate change) and respiratory inorganics (=particulate matter formation) are among the three most import impact categories. However, the third significant impact category identified with Stepwise; photochemical ozone formation is not identified as significant with the other two LCIA methods. Instead, the Impact2002+ and the ReCiPe methods identify non-renewable energy and natural land transformation respectively as among the three most significant impacts. Therefore, the identification of respiratory inorganics and global warming as the most significant impact categories is regarded as relatively robust. It should be noticed, that this identification does not affect the results/conclusions of the LCA since the Eco Island Ferry performs better than the Tun Island Ferry for all impact categories – and the relative difference between the two ferry alternatives is more or less the same for all impact categories. Further, it should be noticed that weighting often to some degree is related to subjective choices. Therefore, other weighting methods are likely to point out other impact categories as the most significant ones.

8.2 Process contribution

In the following the overall results from the previous section are broken down. This helps understanding the environmental relevance of the difference life cycle stages of the ferries and which emissions are contributing to each impact category. The process contribution analysis is only presented for the three most significant impact categories; respiratory inorganics, global warming and photochemical smog. **Figure 8.4** and **Table 8.2** below present an overview of the contribution to the three impact categories from each of the life cycle stages. Notice that in **Figure 8.4**, the results are normalised by the total impact of the Tun Island Ferry. Then the importance of the same life cycle stage for the two ferry alternatives can also be compared.

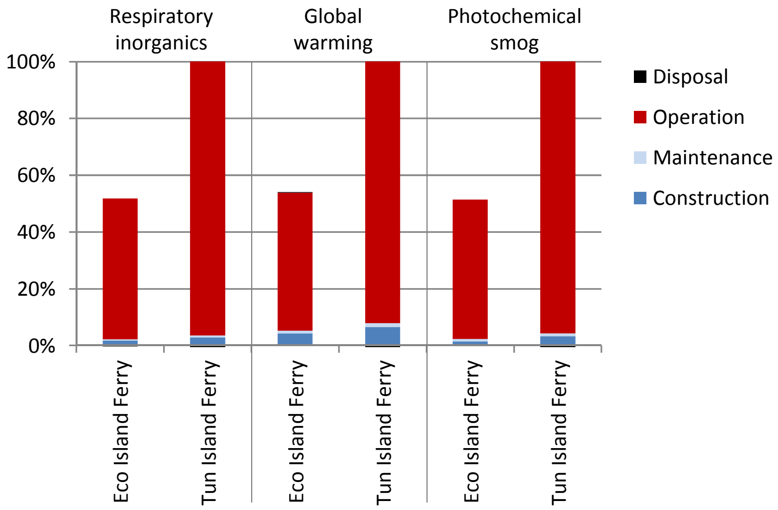

Figure 8.4: Identification of most significant impact categories by using alternative weighting methods: Impact 2002+ (Jolliet et al. 2003) and ReCiPe v1.06 (Goedkoop et al. 2009).

Table 8.2: Process contribution for the Eco Island Ferry for the three most significant impact categories.

Eco Island Ferry	Respiratory inorganics (kg $PM_{2.5}$-eq.)		Global warming (CO_2-eq.)		Photochemical ozone (m^2*ppm*hours)	
	Eco Island Ferry	Tun Island Ferry	Eco Island Ferry	Tun Island Ferry	Eco Island Ferry	Tun Island Ferry
Construction	21	34	23,249	35,405	193,079	429,685
Maintenance	5	8	4,964	7,585	112,804	137,777
Operation	591	1,163	265,974	512,780	6,587,710	13,035,700
Disposal	-4	-12	967	-9,466	-28,788	-190,170
Total	**613**	**1,193**	**295,154**	**546,305**	**6,864,805**	**13,412,992**

It can be seen from **Figure 8.4** that the operation stage completely dominates the contribution to the three impact categories for both ferry alternatives. The second most important life cycle stage is the construction stage.

Eco Island Ferry: The contribution to respiratory inorganics is mainly from NO_x emissions (79%), particulates (14%) and SO_2 (7%). The majority of these emissions originate from the combustion of diesel in the operation stage. The contribution to global warming comes from CO_2 (94%), N_2O (3%) and methane (2%). Again the majority of these emissions come from the combustion of diesel in the operation stage. The contribution to photochemical smog originates from NO_x (88%), CO (5%) and NMVOC (3%). As for the contributions to the other impact categories, the majority of these emissions come from the combustion of diesel in the operation stage.

Tun Island Ferry: The relative contributions to the three most significant impact categories are almost exactly the same as for the Eco Island Ferry (described above). The reason for this is that the majority >90% of the most contributing emissions are coming from the combustion of diesel (and these emissions are proportional with the quantity of combusted diesel).

The process contributions in **Table 8.2** are further broken down in **Table 8.3** and **Table 8.4**.

Table 8.3: Process contribution for the Eco Island Ferry for the three most significant impact categories.

Eco Island Ferry	**Respiratory inorganics ($kg\ PM_{2.5}$-eq.)**		**Global warming (CO_2-eq.)**		**Photochemical ozone (m^2*ppm*hours)**	
Construction						
Reinforced carbon fibre	5.92		7,765		48,155	
Metal	1.35		1,538		18,395	
Elec. equipment	3.87		2,803		19,936	
Engine	0.26		271		2,854	
Paint	0.20		175		5,988	
Textiles, plastics, insulation and other	2.57		2,771		21,079	
Electricity	0.03		31		236	
Services	6.58	**20.8**	7,894	**23,249**	76,435	**193,079**
Maintenance						
Paint	3.17		2,722		91,291	
Zinc anodes	0.13		82		745	
Services	1.79	**5.09**	2,160	**4,964**	20,767	**112,804**
Operation						
Diesel incl. combustion	572		248,353		6,453,019	
Electricity	19.0	**591**	17,621	**265,974**	134,691	**6,587,710**
Disposal						
Recycling polymer	-0.05		-97		-1,101	
Recycling metals	-2.31		-1,486		-16,524	
Incineration polymer	-1.92		2,566		-11,061	
Incineration other	-0.05		-25		-183	
Landfill polymer and other inert	0.01		6		60	
Landfill metals	0.00	**-4.32**	2	**967**	21	**-28,788**
Total						
Total		**613**		**295,154**		**6,864,805**

Table 8.4: Process contribution for the Tun Island Ferry for the three most significant impact categories.

Tun Island Ferry	Respiratory inorganics (kg $PM_{2.5}$-eq.)		Global warming (CO_2-eq.)		Photochemical ozone (m^2*ppm*hours)	
Construction						
Reinforced carbon fibre	0		0		0	
Metal	16.7		17,669		268,366	
Elec. equipment	5.2		3,774		26,757	
Engine	1.2		1,242		13,024	
Paint	0.3		236		8,037	
Textiles, plastics, insulation and other	3.1		3,082		22,751	
Electricity	0		0		0	
Services	7.8	**34.3**	9,402	**35,405**	90,750	**429,685**
Maintenance						
Paint	3.2		2,722		91,289	
Zinc anodes	0.8		481		4,361	
Services	3.6	**7.6**	4,382	**7,585**	42,127	**137,777**
Operation						
Diesel incl. combustion	1,146		497,104		12,915,877	
Electricity	16.9	**1,163**	15,676	**512,780**	119,823	**13,035,700**
Disposal						
Recycling polymer	-0.1		-102		-1,515	
Recycling metals	-11.2		-9,979		-184,910	
Incineration polymer	-0.6		627		-3,679	
Incineration other	-0.1		-27		-252	
Landfill polymer and other inert	0		8		91	
Landfill metals	0	**-11.9**	8	**-9,466**	94	**-190,170**
Total						
Total		**1,193**		**546,305**		**13,412,992**

9. Sensitivity analysis and uncertainties

Throughout the goal and scope definition as well as the life cycle inventory a number of assumptions have been taken, uncertainties in data have been identified and methodological choices have been made. In order to be able to evaluate the sensitivity of the results in the next chapter, a number of sensitivity analyses are carried out in the current chapter. A screening for significant assumptions and uncertainties has been carried out, and the outcome is summarised in **section 9.12**.

9.1 Ferry life times

Life times at 40 and 30 years have been assumed for the Eco and Tun Island Ferry respectively (**section 2.5**). In this sensitivity analysis, the same life time of the two ferry alternatives at 30 years has been assumed. Since most impact categories are proportional to GHG-emissions, only the results for this impact category have been shown here.

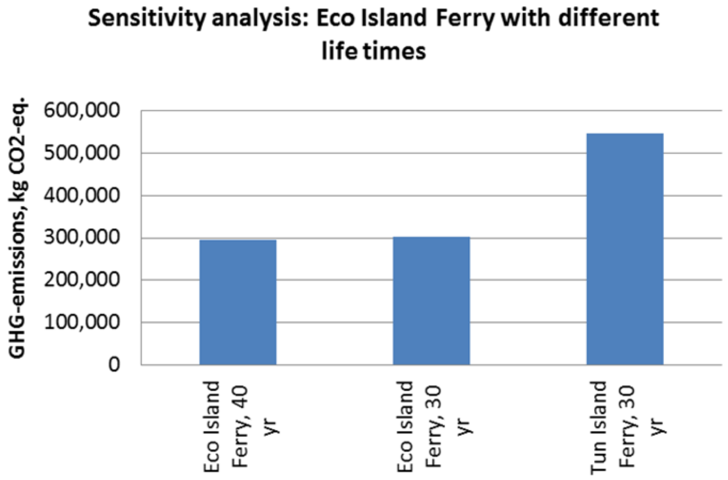

Figure 9.1: Eco Island Ferry with life times at 40 (default scenario) and 30 years (sensitivity analysis) compared with the Tun Island Ferry with life time at 30 years (default scenario). The results represent the functional unit: servicing the Tunø ferry route in one year.

It appears from **Figure 9.1** that the life time of the Eco Island Ferry only influences the results insignificantly.

9.2 Modelling of electricity

Electricity is modelled using a future consequential scenario (**section 3.1**). The results for the Eco Island and the Tun Island Ferries are shown using different electricity models; in addition to the applied consequential future electricity mix, the results have been calculated by using an average mix in year 2008 and 100% coal. The electricity models are implemented throughout the database (ecoinvent) which is used for the modelling of all direct inputs and upstream inputs of electricity in the life cycle inventory.

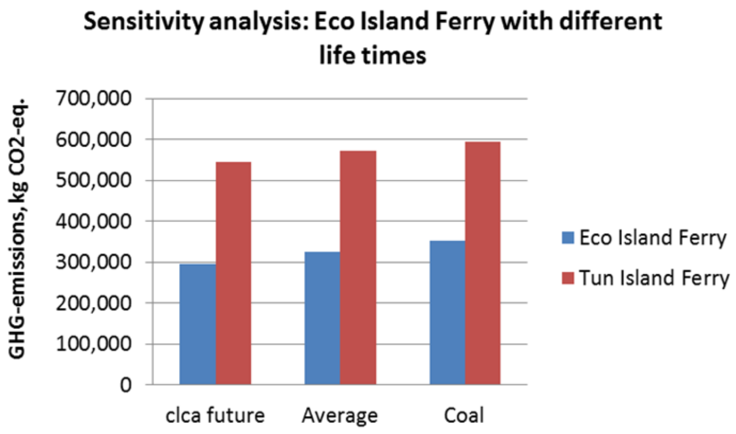

Figure 9.2: GHG-emissions for Eco Island and Tun Island Ferries calculated with different electricity models The results represent the functional unit: servicing the Tunø ferry route in one year.

It appears from **Figure 9.2** that the differences in results by the two ferry alternatives are not affected by the electricity model.

9.3 Quantity of insulation in Tun Island Ferry

Insulation in the Tun Island Ferry is assumed to be 60% of the insulation in the Eco Island Ferry (**chapter 4**). Insulation materials account for <0.5% of the life cycle GHG-emissions for both of the ferries. Hence any uncertainties related to this assumption will affect the results insignificantly.

9.4 Same amount of machinery and equipment in two ferries

For most of the machinery and equipment, the same amount has been assumed for the two ferries (**chapter 4**). Machinery and equipment materials (excl. engine) account for <2% of the life cycle GHG-emissions for both of the ferries. Hence uncertainties related to this assumption will affect the results insignificantly.

9.5 Inconsistent modelling of wood

Wood from forest is not modelled consistent with other materials (allocation) (**section 4.8**). Wood based products account for <0.002% of the life cycle GHG-emissions for both of the ferries. Hence any uncertainties related to inconsistent modelling of wood will have no significant effects on the results.

9.6 Same amount of paint for maintenance in two ferries

Same quantity of paint for maintenance is assumed for the Eco Island Ferry as for the Tun Island Ferry (**chapter 5**). Generally the Eco Island Ferry requires less anti corrosive protection. Thus, the assumption of same quantity paint overestimates the amount for the Eco Island Ferry. Paint in the maintenance stage accounts for <0.5% of the life cycle emissions of the Eco Island Ferry. Therefore this assumption will not affect the results.

9.7 Zinc anode emissions

It is assumed that 50% of the initial weight of the zinc in the zinc anodes is emitted to seawater during operation (**chapter 5** and **chapter 6**). Zinc emissions are relevant for aquatic ecotoxicity. For the Tun Island

Ferry, which uses much more zinc anode than the Eco Island Ferry, the zinc emissions account for 89% of the total contribution to aquatic ecotoxicity. According to the weighted results, aquatic toxicity is of minor importance. But this relies on the applied weighting principles. Hence, the assumptions on zinc emissions may influence the results for each ferry. However, it does not affect the ranking of the Eco Island Ferry over the Tun Island Ferry.

9.8 Anti-fouling agent emissions

According to **chapter 6** all anti-fouling agents for both ferries are assumed to be based on nano technology. However, in some currently used paints, toxic anti-fouling agents are added, such as tributyl tin oxide or copper (Thrane 2004). If such paints were used instead of a more non-toxic nano-based anti-fouling agent as assumed, this could potentially affect the relative difference in the contribution to toxicity for the two ferry alternatives. However, since the Eco Island Ferry is significant lighter than the Tun Island Ferry (see **Table 2.2**), the area of painted surface under water, i.e. hull surface where anti-fouling is needed, is smaller for the Eco Island Ferry. Therefore, the use of toxic paints for anti-fouling will not change the environmental ranking of the two ferry alternatives.

9.9 Diesel consumption

Diesel consumption in operation stage of Eco Island Ferry is based on theoretical calculations whereas the Tun Island Ferry figures represent actual data (**chapter 6**). The use of diesel is the single most influencing factor on the results since it accounts for 90% and 83% of the total GHG-emissions for the Eco and Tun Island Ferry respectively. Hence, uncertainties in diesel consumption lead to approximately same uncertainties in results. Therefore, despite the uncertainties of diesel use are unknown, they are regarded as significant. However, it does not affect the ranking of the Eco Island Ferry over the Tun Island Ferry.

If diesel consumption in the Eco Island Ferry is underestimated with 10%, then the overall results of the Eco Island Ferry are also underestimated with approximately 10%.

9.10 Marginal source of fuel for operation stage

It has been assumed that the ferries uses mineral diesel throughout the life time, i.e. 30-40 years in the future. Given the current political targets on minimising or even phasing out fossil fuels over the next 40 years, another fuel than fossil diesel might be the marginal one in part of the life time of the ferries. If the future fuel is associated with significant lesser emissions, this could change the results. Especially, the differences in the impact related to the operation stage could be smaller. However, since the sum of the other life cycle stages (construction, maintenance and disposal) are also favourable to the Eco Island Ferry, it is not likely that a very environmentally friendly fuel, would change the ranking of the two ferry alternatives.

9.11 End-of-life scenarios

The applied end-of-life scenario in **chapter 7** represents estimated current waste disposal/recycling of a ferry. Two scenarios have been carried out; one where recycling of polymers is maximised and one where polymers are sent to landfill. Disposal of other materials (mainly steel) have not been changed, since the current practise of steel recycling is well established. The only new technology/material being introduced is the polymers (the composite material). It should be noticed that it is assumed that the carbon fibre cannot be recycled.

The results of the sensitivity analysis are presented in **Figure 9.3**.

Table 9.1: Polymer recycling scenario: Eco Island Ferry. All changes compared to the baseline disposal scenario are marked with red and arrows that show change. The LCI data relating to each of the three disposal options for each waste/scrap category are described in **sections 7.1**, **7.2** and **7.3**.

Polymer recycling scenario	Eco Island Ferry	Waste/scrap category	Share category	Treatment		
				Recycling	Incineration	Landfill
Reference flow	**unit: piece**					
Ferry	1					
Components in ferry	**unit: tonne**					
Carbon fibre	8.538	carbon fibre	100%		100%	
Resin (vinylester)	11.164	resin	100%	**100%**	←	
Core (PVC foam)	7.431	PVC	100%	**100%**	←	
E glass (fibreglass)	0.627	inert	100%			100%
Aluminium, sheet	1.325	aluminium	100%	100%		
Steel, sheet	16.130	steel	100%	90%		10%
Steel, section bar	-	steel	100%	90%		10%
Engine	3.000	steel	100%	90%		10%
Electrical equipment	1.965	steel	55%	50%		50%
		copper	10%	50%		50%
		plastics	35%	**100%**	←	
Cables	3.460	copper	50%	50%		50%
		PVC	50%	**100%**	←	
Transformers	0.300	steel	70%	80%		20%
		copper	30%	80%		20%
Batteries	0.900	steel	40%	80%		20%
		copper	10%	80%		20%
		inert	50%			100%
Insulation	11.161	plastics	96%		100%	
		inert	4%			100%
Textiles	2.000	textile	100%		100%	
Wood products	0.650	wood	100%		100%	
Plastics products	3.170	plastics	100%	50%	50%	
Ceramic products	0.200	inert	100%			100%
Paint – solids and curing agent	7.11	inert	100%			100%

Table 9.2: Polymer landfill scenarios: Eco Island Ferry. All changes compared to the baseline disposal scenario are marked with red and arrows that show change. The LCI data relating to each of the three disposal options for each waste/scrap category are described in **sections 7.1**, **7.2** and **7.3**.

Polymer landfill scenario	**Eco Island Ferry**	**Waste/scrap category**	**Share category**	**Treatment**		
				Recycling	**Incineration**	**Landfill**
Reference flow	**unit: piece**					
Ferry	1					
Components in ferry	**unit: tonne**					
Carbon fibre	8.538	carbon fibre	100%		→	**100%**
Resin (vinylester)	11.164	resin	100%		→	**100%**
Core (PVC foam)	7.431	PVC	100%		→	**100%**
E glass (fibreglass)	0.627	inert	100%			100%
Aluminium, sheet	1.325	aluminium	100%	100%		
Steel, sheet	16.130	steel	100%	90%		10%
Steel, section bar	-	steel	100%	90%		10%
Engine	3.000	steel	100%	90%		10%
Electrical equipment	1.965	steel	55%	50%		50%
		copper	10%	50%		50%
		plastics	35%	→	→	**100%**
Cables	3.460	copper	50%	50%		50%
		PVC	50%	→	→	**100%**
Transformers	0.300	steel	70%	80%		20%
		copper	30%	80%		20%
Batteries	0.900	steel	40%	80%		20%
		copper	10%	80%		20%
		inert	50%			100%
Insulation	11.161	plastics	96%		→	**100%**
		inert	4%			100%
Textiles	2.000	textile	100%		100%	
Wood products	0.650	wood	100%		100%	
Plastics products	3.170	plastics	100%	→	→	**100%**
Ceramic products	0.200	inert	100%			100%
Paint – solids and curing agent	7.11	inert	100%			100%

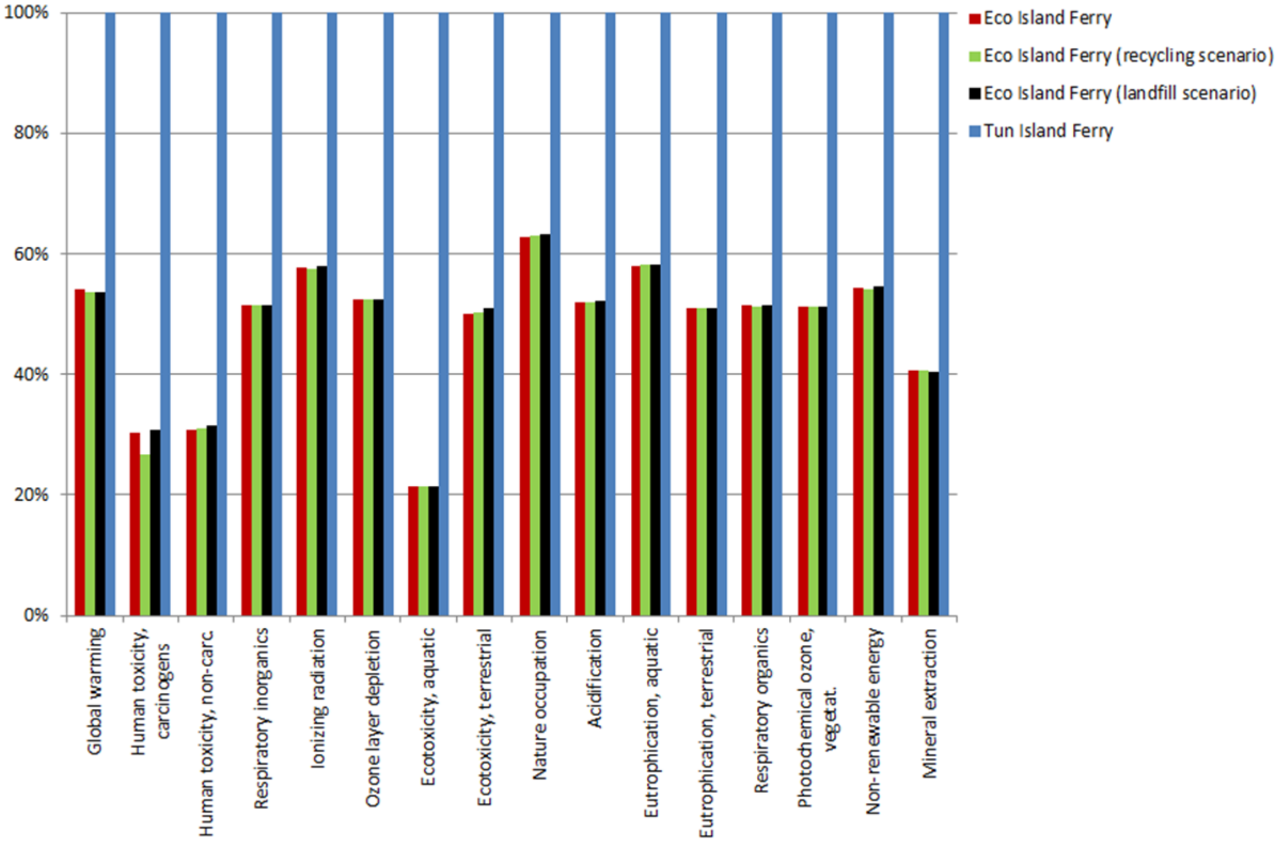

Figure 9.3: End-of-life scenarios for the Eco Island Ferry.

It appears from the end-of-life sensitivity analysis that the life cycle impacts of the Eco Island Ferry can only be insignificantly affected by different disposal/recycling systems for the polymers in the ferry.

9.12 Concluding remark on the sensitivity analysis

It appears from the sensitivity analyses that the result that the Eco Island Ferry is performing significantly better than the Tun Island Ferry is not sensitive to assumptions and uncertainties. Most assumptions and uncertainties can only affect the results insignificantly. Two issues were identified as being significant:

- The assumption that 50% of zinc in zinc anodes is emitted to sea water during operation significantly affects the result on aquatic ecotoxicity (this impact category is given a low significance in all weighted results)
- Uncertainties in diesel consumption lead to approximately the same uncertainties in results

10. Evaluation of sensitivity, completeness and consistency

According to ISO 14044 (2006) an evaluation in the interpretation phase including sensitivity, completeness and consistency check must be carried out in order to establish confidence in the results of the LCA.

10.1 Sensitivity check

The objective of the sensitivity check is to assess the reliability of the results and how they are affected by system boundaries, uncertainties in data, assumptions and LCIA-methods (ISO 14044 2006). Given that the results show that 80-90% of most impacts are related to one activity, diesel combustion, the results are not sensitive to changes in system boundaries, uncertainties in data, assumptions or the LCIA methods applied here.

The sensitivity analysis in chapter 9 also shows that the result that the Eco Island Ferry is performing significantly better than the Tun Island Ferry is not sensitive to assumptions and uncertainties. Most assumptions and uncertainties can only affect the results insignificantly. Two issues were identified as being significant:

- The assumption that 50% of zinc in zinc anodes is emitted to sea water during operation significantly affects the result on aquatic ecotoxicity (this impact category is given a low significance in all weighted results)
- Uncertainties in diesel consumption lead to approximately the same uncertainties in results

10.2 Completeness check

The objective of a completeness check is to ensure that the information provided in the difference phases of the LCA is sufficient for the interpretation of the results (ISO 14044 2006). This LCA is considered to be very complete given that almost data or processes were excluded from the study. The life cycle inventory consistently operates with a cut-off criterion of close to 0%. Only services in the operation stage have not been included. Further, uncertainties in the hybridization of process data and input-output data may have caused that some minor transactions have not been accounted for.

10.3 Consistency check

The objective of the consistency check is to verify that the assumptions, methods and data are consistent with the goal and scope. Especially the consistency regarding data quality along the product chain, regional/temporal differences, allocation rules/system boundaries and LCIA are important (ISO 14044).

In general the model is based on a very consistent and well-defined methodological framework as presented in **chapter 2.4**.

In this study, consequential modelling was applied throughout and, in general, is regarded as having a very high degree of consistency.

11. Conclusions

The comparative LCA of the Eco Island Ferry with a carbon FRP structure and the Tun Island Ferry with a steel structure is prepared to evaluate the environmental impacts of the reference ferry and its alternative, and to aid decision-makers when considering the inclusion of FRP materials as an option for passenger ferries.

The results indicate that the Eco Ferry outperforms the Tun Island Ferry by a factor of 2 for almost all impact categories. The explanation of the difference is related to the reduced fuel consumption in the Eco Island Ferry. The lighter materials used for the structure, carbon fibre composite, allows for a reduction of the ferry's light weight from 262 tonne to 72 tonne, i.e. a factor of around 3.5. This means that the depth of hull of the Eco Island Ferry is lesser and thereby less energy is required for propulsion. This also allows for a smaller engine and thereby less energy when the ferry is not sailing. Given that the Eco Island Ferry requires less fuel for operation, it surpasses the Tun Island Ferry in all impact categories.

Generally, the results are regarded as robust and not sensitive to assumptions and uncertainty in data. The major issues regarding sensitivity are:

- The assumption that 50% of zinc in zinc anodes is emitted to sea water during operation significantly affects the result on aquatic ecotoxicity (this impact category is given a low significance in all weighted results)
- Uncertainties in diesel consumption lead to approximately the same uncertainties in results

Sensitivity analysis investigating different end-of-life scenarios were carried out. The baseline scenario assumed that most of the composite materials are incinerated. A recycling scenario, where the polymers were assumed to be 100% recycled and a landfill scenario, where the polymers were assumed to be 100% landfilled was defined. The results of the end-of-life scenario showed that the life cycle results were only insignificantly affected by alternative end-of-life strategies. The explanation hereof is that the materials of which the Eco Island Ferry is made originates from oil and gas. The diesel combusted in the operation stage amounts roughly 80 times the amount of oil and gas used for the composite materials.

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Appendix 1: Detailed Components Lists

Detailed Components List for the Tun Island Ferry in kilograms

	Sub-components	**Steel sheet**	**Steel section bar**	**Elec equipment**	**Cables**	**Transformers**	**Batteries**	**Engine**	**Wood**	**Ceramic**	**Plastic**	**Insulation**	**Textiles**	**Paint**	**Total**
Structure															
	Structure	**106,891**	**106,891**												**213,782**
	Paint solids													1,346	**1,346**
Total, structure		**106,891**	**106,891**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1,346**	**215,128**
Equipment															
	Equipment for Cargo (Group 3)														
	Smaller hatches, grain hatches, manhole covers, manholes w. cover	600													**600**
	Stern ports	3,000													**3,000**
	Side ports, side entrance doors	600													**600**
	Deck/hold cargo pillars, bins, shelves, cases, car lashing gear	300													**300**
	Sub-total, equipment for cargo	**4,500**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**4,500**
	Ship Equipment (Group 4)														
	Rudder w/welded parts rudder	400													**400**
	Steering gear/columns, telemotor sys., rudder ind., emerg st. Steering gear	750													**750**
	Side thrusters	900													**900**
	Radar plants, navigation and radio equipment			600											**600**
	Light and signal equipment, lanterns, typhons, light and signal equipment				150										**150**
	Anchors w/chains & equipment	600													**600**
	Fixed mooring equipment	1,200													**1,200**
	Loose mooring equipment	200													**200**
	Machine tools, cutting & welding equipment, spare parts	100													**100**
	Sub-total, equipment for ship	**4,150**	**0**	**600**	**150**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**4,900**
	Equipment for crew and passengers (Group 5)														
	Lifeboats w/equipment	640									960				**1,600**
	Life rafts w/equipment										1,060				**1,060**
	Loose fire fighting apparatuses & equipment, firemen's outfit												200		**200**
	Insulation, partition bulkheads, panelling, wallpaper											6,697			**6,697**
	Doors w/coamings in accommodation	560													**560**
	External doors w/coamings	560													**560**
	Side scuttles & windows w/equipment	1,500													**1,500**
	Internal deck top covering (linoleum, tiles, parquet, etc.)								300						**300**
	Loose floor plates, platforms, steps & ladders in accomod., stair to wheel house	300													**300**
	Handrails, railing, rail gates, handrails	400													**400**
	External platforms, steps, ladders & grating w/equipment	200													**200**
	Deck tables & chairs, swimming pools, deck furniture								150		150				**300**
	Furniture for crew, standard furniture								100						**100**
	Office equip. & spec furniture in wheelh., chart & radio								100						**100**
	Curtains, carpets												800		**800**
	Hobby, sports & entertainment equipment										50				**50**
	Furniture for passengers												1,000		**1,000**
	Heating system (oil)	850													**850**
	Sanitary supply systems										250				**250**
	Sanitary discharge systems, accommodation drainage systems										300				**300**
	Bathtubs, bidets, shower cabinets, W.C., washbasins, toilets, showers									200					**200**

	Sub-total, equipment for crew and passengers	**5,010**	**0**	**0**	**0**	**0**	**0**	**0**	**650**	**200**	**2,770**	**6,697**	**2,000**	**0**	**17,327**
Total, equipment		**13,660**	**0**	**600**	**150**	**0**	**0**	**0**	**650**	**200**	**2,770**	**6,697**	**2,000**	**0**	**26,727**
Machinery and systems															
	Machinery Main Components (Group 6)														
	Diesel engines							10,000							**10,000**
	Sub-total, machinery main components	**0**	**0**	**0**	**0**	**0**	**0**	**10,000**	**0**	**0**	**0**	**0**	**0**	**0**	**10,000**
	Systems for Machinery Main Components (Group 7)														
	Fuel oil transfer & drain systems	580													**580**
	Fuel oil supply systems	350													**350**
	Lube oil transfer & drain systems, sludge drain systems	140													**140**
	Sea water cooling systems	700													**700**
	Exhaust gas systems for propulsion machinery	400													**400**
	Exhaust gas systems for motor aggregates	200													**200**
	manoeuvre consoles, main consoles, wheel house console	100													**100**
	Common automation equipment, engine room alarm systems, alarm and monitoring system			235											**235**
	Sub-total, system for machinery	**2,470**	**0**	**235**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2,705**
	Ship common systems (Group 8)														
	Gutter pipes outside accommodation										100				**100**
	Fire detection, fire & lifeboat alarm systems			30											**30**
	Fire/wash down syst., emergency fire pumps, sprinkler syst., fire main and deck wash down system			550											**550**
	Fire fighting systems w/gas (CO2, HALON, etc.): fire fighting system engine room, fire fighting system interior				775										**775**
	Air & sounding systems from tanks to deck, air and sounding pipes										300				**300**
	Transformers					200									**200**
	Batteries & chargers						900								**900**
	Rectifiers & converters					100									**100**
	Electric shore supply systems, shore power supply			50											**50**
	Main switch boards			400											**400**
	Emergency switch boards			50											**50**
	Distribution panels & boards			50											**50**
	Cables (EL cables)				2,000										**2,000**
	Cable trays & installation in engine and boiler rooms				50										**50**
	Cable trays w/installation in accommodation				160										**160**
	Electric lighting systems for engine & boiler room				75										**75**
	Electric lighting systems for accommodation, electric lighting in interior				200										**200**
	Electric lighting systems for deck & cargo holds, electric lighting on decks				50										**50**
	Ballast system	800						200							**1,000**
	Sub-total, common systems	**800**	**0**	**1,130**	**3,310**	**300**	**900**	**200**	**0**	**0**	**400**	**0**	**0**	**0**	**7,040**
Total, machinery and systems		**3,270**	**0**	**1,365**	**3,310**	**300**	**900**	**10,200**	**0**	**0**	**400**	**0**	**0**	**0**	**19,745**
Total		**123,821**	**106,891**	**1,965**	**3,460**	**300**	**900**	**10,200**	**650**	**200**	**3,170**	**6,697**	**2,000**	**1,346**	**261,600**

Detailed Components List for the Eco Island Ferry in kilograms

Main components	Sub-copmponents	Carbon Fiber	Material resin (vinylester)	Core (PVC foam)	E Glassfiber	Aluminium	Steel sheet	Elec equipment	Cables	Transformers	Batteries	Engine	Wood	Ceramic	Plastic	Insulation	Textiles	Paint	Total
Structure																			
	Structure - hull																		
	Structure - hull	657	1,194	648	83														**2,582**
	Ice reinforcement	350	567	518	97														**1,532**
	Bow	18	31	0	5														**55**
	Topside	573	1,135	513	82														**2,304**
	Hull CL reinforcement/keel	70	96	0	80														**246**
	Transverse beam reinforcement	96	68	0	0														**164**
	Transverse Bulkheads	313	363	328	0														**1,004**
	Transom	56	64	45	7														**171**
	Aft shaft bracket stiffener	7	8	7	0														**22**
	Shaft bracket stiffener bonding	4	3	0	0														**7**
	Tunnel	506	613	468	75														**1,663**
	Tunnel bonding	53	61	0	0														**113**
	Bonding transverse bulkheads	49	38	0	0														**87**
	Long. Girders	192	207	216	0														**615**
	Bonding long. Girders	19	14	0	0														**33**
	Engine foundation	3	4	4	0														**10**
	Hull stif aft	56	41	16	0														**113**
	Hull stif. Fwd	64	47	19	0														**130**
	Hull stif aft bonding	6	7	0	0														**13**
	Hull stif. Fwd bonding	24	19	0	0														**43**
	Various (5%)	177	229	139	0														**545**
	Sub-total, structure	**3,292**	**4,809**	**2,922**	**430**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**11,453**
	Structure - deck, tunnels, topsides																		
	Deck 1*	1,695	985	831	55	1,325													**4,890**
	Deck 2	803	1,269	936	80														**3,088**
	Deck beams	116	81	124	0														**321**
	Deck reinforcement UD	15	11	0	0														**27**
	Deck beams bonding	32	24	0	0														**56**
	Deck bonding	43	35	0	5														**83**
	Long bkh CL	80	93	84	0														**258**
	Long bkh CL bonding	43	32	0	0														**75**
	Deck/bow fender reinforcement	2	2	0	0														**4**
	Deck Stiffeners	137	95	0	0														**232**
	Deck stif. Bonding	46	34	0	0														**80**
	Deck stif. Fwd	61	43	0	0														**104**
	Deck stif. Fwd bonding	29	24	0	0														**53**
	Various (5%)	162	136	99	0														**397**
	Sub-total, structure	**3,265**	**2,865**	**2,074**	**140**	**1,325**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**9,669**
	Structure - Super structure																		
	House panels	460	1,013	785	0														**2,258**
	Accommodation deck	722	1,083	816	0														**2,621**
	Internal bkh	143	290	142	0														**575**
	Wheelhouse	349	744	531	57														**1,682**
	Mulions	15	25	16	0														**56**
	Beams 2	6	7	3	0														**17**
	Beams 1	3	4	2	0														**9**
	House bonding out side	32	24	0	0														**56**

	Superstructure stiffeners	16	20	10	0														**45**
	Int. Bkh bonding	20	16	0	0														**36**
	Wheelhouse bonding	43	33	0	0														**76**
	Accommodation deck beams	61	56	15	0														**132**
	Accommodation deck beams bonding	13	9	0	0														**22**
	Various 5 %	86	155	105	0														**345**
	Sub-total, structure	**1,969**	**3,479**	**2,424**	**57**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**7,929**
	Structure - Paint																		
	Paint solids																	1,346	**1,346**
Total, structure		**8,527**	**11,153**	**7,420**	**627**	**1,325**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1,346**	**29,052**
Equipment																			
	Equipment for Cargo (Group 3)																		
	Smaller hatches, grain hatches, manhole covers, manholes w. cover						600												**600**
	Stern ports						3,000												**3,000**
	Side ports, side entrance doors						600												**600**
	Deck/hold cargo pillars, bins, shelves, cases, car lashing gear						300												**300**
	Sub-total, equipment for cargo	**0**	**0**	**0**	**0**	**0**	**4,500**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**4,500**
	Ship Equipment (Group 4)																		
	Rudder w/welded parts rudder						400												**400**
	Steering gear/columns, telemotor sys., rudder ind., emerg st. Steering gear						750												**750**
	Side thrusters						900												**900**
	Radar plants, navigation and radio equipment							600											**600**
	Light and signal equipment, lanterns, typhons, light and signal equipment								150										**150**
	Anchors w/chains & equipment						600												**600**
	Fixed mooring equipment						1,200												**1,200**
	Loose mooring equipment						200												**200**
	Machine tools, cutting & welding equipment, spare parts						100												**100**
	Sub-total, equipment for ship	**0**	**0**	**0**	**0**	**0**	**4,150**	**600**	**150**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**4,900**
	Equipment for crew and passengers (Group 5)																		
	Lifeboats w/equipment						640								960				**1,600**
	Life rafts w/equipment														1,060				**1,060**
	Loose fire fighting apparatuses & equipment, firemen's outfit																200		**200**
	Insulation, partition bulkheads, paneling, wallpaper															11,161			**11,161**
	Doors w/coamings in accommodation						560												**560**
	External doors w/coamings						560												**560**
	Side scuttles & windows w/equipment						1,500												**1,500**
	Internal deck top covering (linoleum, tiles, parquet, etc.)												300						**300**
	Loose floor plates, platforms, steps & ladders in accomod., stair to wheel house						300												**300**
	Handrails, railing, rail gates, handrails						400												**400**
	External platforms, steps, ladders & grating w/equipment						200												**200**
	Deck tables & chairs, swimming pools, deck furniture												150		150				**300**
	Furniture for crew, standard furniture												100						**100**
	Office equip. & spec furniture in wheelh., chart & radio												100						**100**
	Curtains, carpets																800		**800**
	Hobby, sports & entertainment equipment														50				**50**

	Furniture for passengers																1,000		**1,000**
	Ventilation/air-conditioning systems for accommodation (AC for interior)						600												**600**
	Ventilation/air-conditioning systems for provision rooms (mechanical ventilation)						50												**50**
	Ventilation/air-conditioning systems for boiler/eng. rooms (ventilation for engine rooms)						200												**200**
	Sanitary supply systems														250				**250**
	Sanitary discharge systems, accommodation drainage systems														300				**300**
	Bathtubs, bidets, shower cabinets, W.C., washbasins, toilets, showers													200					**200**
	Sub-total, equipment for crew and passengers	**0**	**0**	**0**	**0**	**0**	**5,010**	**0**	**0**	**0**	**0**	**0**	**650**	**200**	**2,770**	**11,161**	**2,000**	**0**	**21,791**
Total, equipment		**0**	**0**	**0**	**0**	**0**	**13,660**	**600**	**150**	**0**	**0**	**0**	**650**	**200**	**2,770**	**11,161**	**2,000**	**0**	**31,191**
Machinery and systems																			
	Machinery Main Components (Group 6)																		
	Diesel engines											700							**700**
	Controllable pitch propeller plants inc. Nozzles											800							**800**
	Motor aggregates, auxiliary engines											1,500							**1,500**
	Sub-total, machinery main components	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3,000**	**0**	**0**	**0**	**0**	**0**	**0**	**3,000**
	Systems for Machinery Main Components (Group 7)																		
	Fuel oil transfer & drain systems						580												**580**
	Fuel oil supply systems						350												**350**
	Lube oil transfer & drain systems, sludge drain systems						140												**140**
	Sea water cooling systems						700												**700**
	Exhaust gas systems for propulsion machinery						400												**400**
	Exhaust gas systems for motor aggregates						200												**200**
	Maneuvre consoles, main consoles, wheel house console						100												**100**
	Common automation equipment, engine room alarm systems, alarm and monitoring system							235											**235**
	Sub-total, system for machinery	**0**	**0**	**0**	**0**	**0**	**2,470**	**235**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2,705**
	Ship common systems (Group 8)																		
	Gutter pipes outside accommodation														100				**100**
	Fire detection, fire & lifeboat alarm systems							30											**30**
	Fire/wash down syst., emergency fire pumps, sprinkler syst., fire main and deck wash down system							550											**550**
	Fire fighting systems w/gas (CO2, HALON, etc.): fire fighting system engine room, fire fighting system interior								775										**775**
	Air & sounding systems from tanks to deck, air and sounding pipes														300				**300**
	Transformers									200									**200**
	Batteries & chargers										900								**900**
	Rectifiers & converters									100									**100**
	Electric shore supply systems, shore power supply							50											**50**
	Main switch boards							400											**400**
	Emergency switch boards							50											**50**
	Distribution panels & boards							50											**50**
	Cables (EL cables)								2,000										**2,000**
	Cable trays & installation in engine and boiler rooms								50										**50**
	Cable trays w/installation in								160										**160**

	accommodation																		
	Electric lighting systems for engine & boiler room								75										**75**
	Electric lighting systems for accommodation, electric lighting in interior								200										**200**
	Electric lighting systems for deck & cargo holds, electric lighting on decks								50										**50**
	Sub-total, common systems	**0**	**0**	**0**	**0**	**0**	**0**	**1,130**	**3,310**	**300**	**900**	**0**	**0**	**0**	**400**	**0**	**0**	**0**	**6,040**
Total, machinery and systems		**0**	**0**	**0**	**0**	**0**	**2,470**	**1,365**	**3,310**	**300**	**900**	**3,000**	**0**	**0**	**400**	**0**	**0**	**0**	**11,745**
Total		**8,527**	**11,153**	**7,420**	**627**	**1,325**	**16,130**	**1,965**	**3,460**	**300**	**900**	**3,000**	**650**	**200**	**3,170**	**11,161**	**2,000**	**1,346**	**71,988**

Appendix 2: Paint and zinc anode calculations

Detailed Paint Calculations for Eco Island Ferry

The paint applied on the Eco Island Ferry in the construction stage is assumed to be the same for the Tun Island Ferry. Data on type and quantities of paint are provided by Hjoernet (2012). Product specifications for each of the used paints are downloaded from the specific paint supplier's webpage. From here data on dosage, density, mixing ratio and VOC content are obtained.

Painting spec							Total amount		Sub-division, applied		Sub-division paint/emission	
Surface	Paint	Area (m2)	Dosage (m2/litre)	Density (kg/litre)	VOC (g/litre)	Mixing ratio (% curing agent)	Amount (litre)	Amount (kg)	Epoxy resin and pigment, applied (kg)	Amine curing, applied (kg)	Amount that stays as paint (kg)	Amount lost as VOC emission (kg
Bottom	HEMPADUR QUATTRO 17634	328	4.8	1.4	275	20%	68.3	95.7	76.5	19.1	76.9	18.8
	HEMPADUR QUATTRO 17634	328	4.8	1.4	270	20%	68.3	95.7	76.5	19.1	77.2	18.5
	HEMPADUR 45182	328	9.2	1.3	485	20%	35.7	46.3	37.1	9.3	29.1	17.3
	HEMPEL'S A/F GLOBIC NCT 8195M	328	5.8	1.8	446	0%	56.6	101.8	101.8	0.0	76.6	25.2
Top side blue	HEMPADUR QUATTRO 17634	462	4.8	1.4	275	20%	96.3	134.8	107.8	27.0	108.3	26.5
	HEMPADUR QUATTRO 17634	462	4.8	1.4	270	20%	96.3	134.8	107.8	27.0	108.8	26.0
	HEMPATHANE TOPCOAT 55210	462	9.8	1.2	452	13%	47.1	56.6	49.2	7.4	35.3	21.3
Exterior decks	HEMPADUR QUATTRO 17634	211	4.8	1.4	275	20%	44.0	61.5	49.2	12.3	49.5	12.1
	HEMPADUR QUATTRO 17634	211	4.8	1.4	270	20%	44.0	61.5	49.2	12.3	49.7	11.9
	HEMPATHANE TOPCOAT 55210	211	10	1.2	440	13%	21.1	25.3	22.0	3.3	16.0	9.3
	HEMPEL'S ANTI-SLINT 67500	211			0			0.0	0.0	0.0	0.0	0.0
Superstructure	HEMPADUR QUATTRO 17634	249	4.8	1.4	275	20%	51.9	72.6	58.1	14.5	58.4	14.3
	HEMPADUR QUATTRO 17634	249	4.8	1.4	270	20%	51.9	72.6	58.1	14.5	58.6	14.0

	HEMPATHANE TOPCOAT 55210	249	9.8	1.2	440	13%	25.4	30.5	26.5	4.0	19.3	11.2
Storage rooms, Inside lockers	HEMPADUR QUATTRO 17634	20	5.8	1.4	275	20%	3.4	4.8	3.9	1.0	3.9	0.9
	HEMPADUR QUATTRO 17634	20	5.8	1.4	270	20%	3.4	4.8	3.9	1.0	3.9	0.9
	HEMPATHANE TOPCOAT 55210	20	9.8	1.2	445	13%	2.0	2.4	2.1	0.3	1.5	0.9
	HEMPATHANE TOPCOAT 55210	20	9.8	1.2	445	13%	2.0	2.4	2.1	0.3	1.5	0.9
Bilges	HEMPADUR QUATTRO 17634	58	5.8	1.4	275	20%	10.0	14.0	11.2	2.8	11.3	2.8
	HEMPADUR QUATTRO 17634	58	5.8	1.4	270	20%	10.0	14.0	11.2	2.8	11.3	2.7
	HEMPATHANE TOPCOAT 55210	58	9.8	1.2	445	13%	5.9	7.1	6.2	0.9	4.5	2.6
	HEMPATHANE TOPCOAT 55210	58	9.8	1.2	445	13%	5.9	7.1	6.2	0.9	4.5	2.6
Integrated ballast watertanks	HEMPADUR QUATTRO 17634	303	4.5	1.4	275	20%	67.3	94.3	75.4	18.9	75.8	18.5
	HEMPADUR QUATTRO 17634	303	4.5	1.4	270	20%	67.3	94.3	75.4	18.9	76.1	18.2
Integrated freshwater tanks	HEMPADUR 35560	11	5.0	1.3	0	23%	2.2	2.9	2.2	0.7	2.9	0.0
	HEMPADUR 35560	11	5.0	1.3	0	23%	2.2	2.9	2.2	0.7	2.9	0.0
Integrated black & greywater tanks	HEMPADUR 85671	12	4.5	1.7	316	12%	2.7	4.5	4.0	0.5	3.7	0.8
	HEMPADUR 85671	12	4.5	1.7	317	12%	2.7	4.5	4.0	0.5	3.7	0.8
	HEMPADUR 85671	12	4.5	1.7	316	12%	2.7	4.5	4.0	0.5	3.7	0.8
Integrated fuel & lube oil tanks	HEMPADUR 85671	81	4.5	1.7	316	12%	18.0	30.6	26.9	3.7	24.9	5.7
	HEMPADUR 85671	81	4.5	1.7	317	12%	18.0	30.6	26.9	3.7	24.9	5.7
	HEMPADUR 85671	81	4.5	1.7	316	12%	18.0	30.6	26.9	3.7	24.9	5.7
Total		**5508**					**950.6**	**1346.099**	**1114.7**	**231.4**	**1049.2**	**296.9**

Detailed paint calculations for the Tun Island Ferry

The paint applied on the Tun Island Ferry in the maintenance stage is assumed to be the same for the Eco Island Ferry. Data on type and quantities of paint are provided by Moellgaard (2012). Product specifications for each of the used paints are downloaded from the specific paint supplier’s webpage. From here data on density, mixing ratio and VOC content are obtained.

Painting spec					**Total**	**Sub-division, applied**		**Sub-division paint/emission**	
Paint	**Amount (Litre)**	**Density (kg/litre)**	**VOC (g/litre)**	**Mixing ratio (% curing agent)**	**Amount (kg)**	**Epoxy resin and pigment, applied (kg)**	**Amine curing, applied (kg)**	**Amount that stays as paint (kg)**	**Amount lost as VOC emission (kg)**
HEMPATEX ENAMEL 56360	87.5	1	615	15%	87.5	74.4	13.1	33.7	53.8
HEMPALIN ENAMEL 52140	15	1.1	430	15%	16.5	14.0	2.5	10.1	6.5
HEMPEL’S UNIPRIMER 13140	5	1.4	555	10%	7.0	6.3	0.7	4.2	2.8
HEMPADUR QUATTRO 17634	136	1.4	275	20%	190.4	152.3	38.1	153.0	37.4
HEMPADUR 45182	40	1.3	485	20%	52.0	41.6	10.4	32.6	19.4
HEMPEL’S ANTIFOULING GLOBIC NCT 8190M	70	1.8	435	5%	126.0	119.7	6.3	95.6	30.5
HEMPEL’S THINNER	30	0.87	870	100%	26.1	26.1	0.0	0.0	26.1
Total					**505.5**	**434.4**	**71.1**	**329.1**	**176.4**

Detailed Zinc Anode Calculation for the Tun Island Ferry

The zinc anode used by the Tun Island Ferry in the maintenance stage is assumed to be the same for the Eco Island Ferry. Data on type and quantities zinc anode are provided by Moellgaard (2012). The annual zinc anode use is obtained from data on two years consumption. Product specifications for each of the used zinc anodes are downloaded from the specific zinc anode supplier's webpage. From here data on net weight (Zn content) and gross weight (Zn and steel) are obtained.

Annual Zinc Anode Use				Calculated	
Type	**Quantity (pieces)**	**Unit weight, net (kg/piece)**	**Unit weight, gross (kg/piece)**	**Weight, Zn (kg)**	**Weight, steel (kg)**
BERA 35	**5**	**3.2**	**3.5**	**16.0**	**1.5**
BERA 55	**5**	**5.1**	**5.5**	**25.5**	**2.0**
BERA 102	**7**	**9.3**	**10.2**	**65.1**	**6.3**
Total				**106.6**	**9.8**
Total combined weight					**116.4**

Appendix 3: Detailed Insulation Data

Detailed insulation data as provided by Hjoernet (2012)

Area:	Total	FRD60	FRM1	FRM2	FRM3	FRM4	Glass cloth	Sole 1	Ceiling	Sole 2
		No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9
	$[m^2]$	$[m^2]$	$[m^2]$	$[m^2]$	$[m^2]$	$[m^2]$	$[m^2]$	$[m^2]$	$[m^2]$	$[m^2]$
Wheelhouse:										
Sole	62									62
Ceiling	34				34				34	
Bulkheads long.	12					12				
Bulkheads transv.	10					10				
Hulle inner skin	43					43				
Accomodation:										
Sole	154							154		
Ceiling	140	140							140	
Bulkheads long.	50	50				50				
Bulkheads transv.	109	50				50				
Hulle inner skin	88	88				88				
Car deck:										
Sole										
Ceiling										
Bulkheads long.										
Bulkheads transv.	59	59				59				
Hulle inner skin										
Ventilation duct:										
Sole										
Ceiling										
Bulkheads long.										
Bulkheads transv.	8			8			8			
Hulle inner skin										
Tank compartment:										
Sole										
Ceiling										
Bulkheads long.										
Bulkheads transv.	14	14								
Hulle inner skin										
Steering gear room:										
Sole										
Ceiling	21			21						
Bulkheads long.										
Bulkheads transv.	11			11			11			
Hulle inner skin	54		54				54			
Engine room:										
Sole										
Ceiling	31	31								
Bulkheads long.	14	14					14			
Bulkheads transv.	23	23					23			
Hulle inner skin	44						44			
Bow thruster room:										
Sole										
Ceiling	10		10							
Bulkheads long.										
Bulkheads transv.	10		10				10			
Hulle inner skin	36		36				36			

Weight of insulation by type and by ferry component in kilograms

Specification:	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9
Weight: [kg/m^2]	7.99	1.6	2.125	0.96	11	0.6	15.8	3.1	9.6

Weight: [kg]										Total kg
Wheelhouse	0	0	0	33	715	0	0	105	595	1448
Accommodation	2621	0	0	0	2068	0	2433	434	0	7556
Car deck	471	0	0	0	649	0	0	0	0	1120
Ventilation duct	0	0	17	0	0	5	0	0	0	22
Tank compartment	112	0	0	0	0	0	0	0	0	112
Steering gear room	0	86	68	0	0	39	0	0	0	193
Engine room	543	0	0	0	0	49	0	0	0	592
Bow thruster room	0	90	0	0	0	28	0	0	0	117
Total: [kg]	3747	176	85	33	3432	120	2433	539	595	11161

Weight by insulation type in kilograms

Weight by material type	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8	No. 9	**Total (kg)**
Rockwool		176.0	85.0	10.9						272
Polystyrene	3747.3			21.8	3364.7		2433.2	539.4	595.2	10702
Fibre glass cloth						120.0				120
Laminate					67.3					67

Appendix 4: Explanation of indicators in the Stepwise LCIA method

This appendix briefly explains the impact categories included in the applied LCIA method: Stepwise 2006 (version 1.3) (Weidema et al. 2007). If no literature reference is given in the table, this means that the information is obtained from Weidema et al. (2007).

Impact category	Unit	Original source		Explanation
		EDIP 2003	Impact 2002+	
Global warming	kg CO_2-eq	x		The unit is GWP100 (kg CO_2 equivalents) based on the IPCC status reports.
Nature occupation	m^2 agr.land		x	The unit 'm^2-equivalents arable land', represents the impact from the occupation of one m^2 of arable land during one year. Impact 2002+ (Jolliet et al. 2003) has obtained the method for LCIA from EcoIndicator (Goedkoop and Spriensma 2001) where the impact is assessed on the basis of the duration of area occupied (m2*years) multiplied with a severity score, representing the potentially disappeared fraction (PDF) of species on that area during the specified time. In order to include the impacts from transformation, the Stepwise method introduces an additional severity of 0.88 to represent the secondary impacts from this transformation (deforestation), calculated as the nature occupation during the later relaxation from deforestation.
Acidification	m^2 UES	x		The unit expresses the area ofecosystem within the full deposition area (in Europe) which isbrought to exceed thecritical load of acidification as a consequence of the emission (area ofunprotected ecosystem = m^2 UES). The impact indicator is based on modelling of deposition in Europe. (Hauchild and Potting 2005, p47)
Eutrophication, aquatic	kg NO_3-eq	x		The aquatic eutrophication potentials of a nutrient emissionexpress the maximum exposure of aquatic systems that it can cause. The aquatic eutrophication potentials are expressed as N- or P-equivalents. (Hauchild and Potting 2005, p 73-74)
Eutrophication, terrestrial	m^2 UES	x		Same as for acidification.
Photochemical ozone, vegetat.	m^2*ppm*h	x		The impact is expressed as the accumulated exposure(duration times exceedance of threshold) above the threshold of 40 ppb times the area that is exposed as a consequence of the emission.The threshold of 40 ppb is chosen as an exposure level below which no or only small effects occur. The unit for vegetation exposure is m^2*ppm*hours. (Hauchild and Potting 2005, p 93)
Respiratory inorganics	kg $PM_{2.5}$-eq		x	The impact on human health related to respiratory inorganics is expressed as equivalents of particles ($PM_{2.5}$).
Respiratory organics	pers*ppm*h	x		The category covers the impact on human health from photochemical ozone formation. The impact is expressed as the accumulated exposureabove the threshold of 60 ppb times the number of persons which areexposed as a consequence of the emission. No threshold for chronicexposure of humans to ozone has been established. Instead,the threshold of 60 ppb is chosen as the long-term environmental objectivefor the EU ozone strategy proposed by the World Health Organisation,WHO. The unit for human exposure is pers*ppm*hours. (Hauchild and Potting 2005, p 93)
Human toxicity, carcinogens	kg C_2H_3Cl-eq		x	The impact on human health related to carcinogens is expressed as equivalents of chloroethylene (C_2H_3Cl). The Impact2002+ method determines the damage on human heatth in terms of DALY (disability adjusted life years). Since there is no real mid-point for human toxicity, the Impact2002+ method has chosen C_2H_3Cl-eq. as a reference substance. (Jolliet et al. 2003)
Human toxicity, non-carc.	kg C_2H_3Cl-eq		x	Same as for human toxicity, carcinogens
Ecotoxicity, aquatic	kg TEG-eq w		x	The impact on ecosystems related to ecotoxicity is expressed as equivalents of chloroethylenetriethylene glycol (TEG) into water. The Impact2002+ method determines the damage on ecosystems in terms of PAF (potentially affected fraction). Since there is no real

				mid-point for ecotoxicity, the Impact2002+ method has chosen TEG-eq. into water as a reference. (Jolliet et al. 2003)
Ecotoxicity, terrestrial	kg TEG-eq s		**x**	Same as for ecotoxicity, aquatic
Ozone layer depletion	kg CFC_{11}-eq		**x**	The unit is equivalents of CFC11 which is an important contributyor to ozone layer depletion.
Non-renewable energy	MJ primary		**x**	Total use of primary non-renewable energy resources measured in MJ.
Mineral extraction	MJ extra		**x**	This is the expected increase in extraction energy per kg extracted material. The reasoning is based on the fact that extraction of minerals expoits the ores with the highest concentrates (most accessible) resources first. (Goedkoop and Spriensma 2001, p 14)

Appendix 5: Critical review report including author's response

In the following, the critical review report from Henrik Wenzel is shown. In the report, each of the issues raised are commented by the author of the current LCA report. The author's responses are marked with grey.

Brandholt 2013-03-10

Critical review of LCA study: ”Eco Island Ferry – comparative LCA of island ferry with carbon fibre composite based and steel based structures”

This is a critical review review of the LCA study: ”Eco Island Ferry – comparative LCA of island ferry with carbon fibre composite based and steel based structures.

My review comments will take outset in the conclusions.

The authors of the study conclude (LCA report page 63):
“The results indicate that the Eco Ferry outperforms the Tun Island Ferry by a factor of 2 for almost all impact categories. The explanation of the difference is related to the reduced fuel consumption in the Eco Island Ferry. The lighter materials used for the structure, carbon fibre composite, allows for a reduction of the ferry’s light weight from 262 tons to 72 tons, i.e. a factor of around 3.5. This means that the depth of hull of the Eco Island Ferry is lesser and thereby less energy is required for propulsion. This also allows for a smaller engine and thereby less energy when the ferry is not sailing. Given that the Eco Island Ferry requires less fuel for operation, it surpasses the Tun Island Ferry in all impact categories”.

Further, it is found (LCA report page 56) that the fuel consumption during sailing is the dominating source of environmental impact:
“The use of diesel is the single most influencing factor on the results since it accounts for 90% and 83% of the total GHG-emissions for the Eco and Tun Island Ferry respectively”.

This latter statement was checked and found to be true. This overarching influence of fuel consumption during sailing was also expected as experience from many other LCA studies point in the same direction. Given the dominating influence of fuel consumption for sailing compared to all other life stages of the ferries and given their large difference in fuel consumption during sailing, the overall results and conclusions of the study stand out as both evident and robust.

The only change in assumptions that can really influence the robustness of the results and conclusions is if very environmentally friendly fuels of some kind are assumed during sailing. Assuming a diesel like bio-fuel of some kind could, thus, potentially change the results significantly. Not so much in case of a conventional bio-diesel, because the environmental impacts from the use of land for growing the energy crops behind the fuel in this case would imply the same large environmental advantage of the fuel saving alternative. But in an ultimate case of e.g. diesel or di-methyl-ether (DME) produced through a wind power-to-liquid-fuel type of scenario, the environmental comparison between the two ferries would be confined to comparing all other life phases than the sailing itself. In such a case, fuels would be much more expensive, and the fuel saving ferry would be even more economically attractive, of course. With the present very ambitious common energy agreement in Parliament, and the even more ambitious long term energy strategy of our Government to be completely free of fossil fuels in 2050, it is not completely unrealistic to assume that such fuels could be foreseen for at least the latest part of the life time of the ferries. It seems, however, that even in such a scenario, the much lighter weight of the Eco Ferry will imply smaller environmental impact potentials from this compared to the heavier alternative.

This review comment is not a very significant one, because a fossil based diesel fuel is expected to be the most realistic alternative many years ahead. But as it is the only aspect that has any potential of changing the outcome of the study significantly, it could beneficially be addressed in the study and LCA report.

[Author's comment #1]: A qualitative sensitivity consideration has been included in section 9.10.

The scope of the study is in general both comprehensive and exhaustive, including even aspects of secondary activities related to the life of the ferries (the so-called 'services' in the study). A consequential LCA approach is followed, which is believed to be best practice. Sensitivity analyses are believed to cover the most essential assumptions and uncertainties, besides the aspect of environmentally friendly fuels mentioned here already.

All in all, therefore, the LCA is found to be well performed and results and conclusions robust to foreseeable changes in assumptions.

Brandholt
March 10th, 2013

Henrik Wenzel