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SOLIDE OXIDE FUEL CELL COMBINED WITH GAS TURBINE VERSUS DIESEL ENGINE AS AUXILIARY POWER PRODUCING UNIT ONBOARD A PASSENGER FERRY:

A Comparative Life Cycle Assessment And Life Cycle Cost Assessment

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SOLIDE OXIDE FUEL CELL COMBINED WITH GAS TURBINE VERSUS DIESEL ENGINE AS AUXILIARY POWER PRODUCING UNIT ONBOARD A PASSENGER FERRY:

A COMPARATIVE LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST ASSESSMENT

MASTER THESIS

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PREFACE

The more extreme weather situation the last decade, with floods, storms and drought, has lead to an increasing focus on global warming and the greenhouse gas emissions. The Kyoto protocol, which became operative the 16th of February 2005, sets targets to limit the amount of CO_2 and related greenhouse gas emissions. Other focal points for air emissions regulations are acidification and photochemical oxidation, which are results of release of oxides of nitrogen and oxides sulphur to the atmosphere. These three focal points for air emission influences the emission regulations for the shipping industry, and the regulations for all these emissions are getting stricter in the near future.

To days conventional technology for auxiliary energy productions in ships has largely reached its potential for emission reductions. New and more energy efficient technologies are needed for a further decrease. One of these new technologies is solid oxide fuel cell combined with gas turbine (SOFC/GT). A Life Cycle Assessment (LCA) was performed by Det Norske Veritas (DNV) to evaluate the environmental burdens of the life stages of the SOFC/GT system. Four alternative fuel supply chains were studied. To get a better picture of the real environmental performance of the SOFC/GT system a comparing LCA built on this study was required.

Cost is supposed to be the largest barrier for the commercializing of fuel cell systems. An economic life cycle cost assessment (LCC) to evaluate the cost differences between the conventional diesel engine and the alternative SOFC/GT solution is also desired.

This thesis contains both an LCA, LCC and hybrid analysis of the SOFC/GT versus conventional technology, diesel engine, as auxiliary engines onboard a ship.

I would like to thank all the persons that helped and supported me during my work with this master thesis.
My thanks goes to my supervisors at DNV; Tomas Tronstad, Christopher Garmann, Bente Pretlove and Morten Hjelm, for taking time to give me useful comments and advices during my work on the thesis. My thanks also go to my supervisor at NTNU, Edgar G Hertwich, for supporting me with comments and advice during my work.

I would also like to thank all the employees at DNV Research working on the Energy and Environment programme at Høvik, helping me out with smaller questions and problems that occurred during the process.

SAMMENDRAG

Det er blitt gjennomført en komparativ livsløpsanalyse (LCA) og livsløpskostnadsanalyse (LCC) for å vurdere miljømessig og økonomisk ytelse for en fastoksyd brenselcelle i kombinasjon med gassturbin (SOFC/GT) sammenlignet med en konvensjonell dieselmotor som hjelpemotor i en passasjerferge. Systemene som er vurdert er, for det konvensjonelle systemet, et system med tre dieselmotorer som hver er på 1080kW, mens SOFC/GT systemet består av fem moduler som hver er på 500kW. Fire ulike brenselforsyningsalternativer er vurdert for SOFC/GT systemet, LNG fra Norge, LNG fra import, likvifaksjon av naturgass i Kiel og svovelfri diesel. LCAen omfatter produksjon av hjelpemotorene, drift og brenselforsyning samt avhending (sistnevnte kun kvalitativt), mens LCCen omfatter innkjøpskostnader, vedlikeholdskostnader og energikostnader, samt en kvalitativ vurdering av avhendingskostnader, miljøkostnader samt øvrige driftskostnader. Passasjerfergen er antatt å trafikkere strekningen Oslo-Kiel.

Tre miljøkategorier er inkludert i LCAen, global oppvarmingspotensiale, fotokjemisk oksidasjonspotensiale og forsuringspotensiale, beregnet i henholdsvis CO_2, CH_4 og SO_2 ekvivalenter. Den komparative Livssyklusanalysen indikerte at alle SOFC/GT alternativene hadde lavere utslipp enn konvensjonell dieselmotor for de tre nevnte miljøkategoriene. Fordelen med brenselceller er renere brensler og at de gir en høyere elektrisk virkningsgrad. SOFC/GT systemet som brukte LNG (flytende naturgass) fra Norge var mest fordelaktig av samtlige systemer. Dette på grunn av færre og kortere transportledd.

Vurderingen av livsløpskostnadene til hjelpemotorene identifiserer dieselmotoren som det billigste alternativet. SOFC/GT systemene som går på LNG fra Norge eller import via Kiel er de billigste av SOFC/GT systemene. Grunnet høy usikkerhet og unøyaktighet i kostnadstallene ble det gjennomført flere sensitivitetsanalyser med ulike scenarier. Samtlige LCC scenarioer som ble gjennomført pekte ut innkjøpsprisen på brenselcellen og utskiftingskostnaden av stacken som en stor økonomisk ulempe for brenselcelle systemet og den høye virkningsgraden som en stor fordel.

For å kunne utføre en helhetlig totalvurdering ble en hybridanalyse utviklet. Hybridanalysen presenterete LCCen som en økonomisk belastning sammen med miljøbelastningene fra LCAen. En slik hybridmodell krever en avveiing mellom miljø og økonomi i beslutningstakingen om valg av type hjelpemotor. Konklusjonen er at fergeselskapet må gjøre en avveining om de er villige til å betale mer per kWh for SOFC/GT systemet enn for en dieselmotor for å få et langt mer miljøvennlig hjelpemaskineri.

SUMMARY

A comparative Life Cycle Assessment (LCA) and Life Cycle Cost analysis (LCC) were performed to evaluate the environmental and economical performance of a solid oxide fuel cell combined with gas turbine (SOFC/GT) versus a conventional diesel engine as auxiliary power producing unit onboard a passenger ship. A setup of three diesel engines of 1080kW for the conventional system and five modules each of 500kW for the SOFC/GT system were investigated. Four different SOFC/GT fuel supply scenarios were studied, LNG from Norway, LNG from Import, onsite liquefaction of natural gas and sulphur free car diesel. The LCA includes the manufacturing of the auxiliary systems, operation and fuel supply and decommissioning (discussed qualitatively only), while the LCC includes purchasing cost, maintenance cost, energy costs and decommissioning cost (qualitatively). The vessel is assumed to service the route Oslo-Kiel.

Three environmental categories are included in the LCA: global warming potential, photochemical oxidation potential and acidification potential, calculated in CO_2, CH_4 and SO_2 equivalents respectively. It is found that all SOFC/GT scenarios have a much better environmental performance than the conventional diesel engine in all the three environmental categories. The main advantages for the fuel cell systems are cleaner fuels and higher electric efficiency, compared to the conventional diesel engine. The most environmentally advantageous scenario is a fuel cell system using LNG (liquefied natural gas) produced in Norway. This is due to fewer and shorter fuel transport links.

Evaluation of the life cycle costs of the auxiliary systems identifies the diesel engine to be the cheapest alternative of the auxiliary systems. The SOFC/GT system using LNG from Norway or LNG imported via Kiel is the cheapest SOFC/GT system. Due to the high uncertainty concerning the costs different sensitivity analysis were performed. All LCC scenarios performed pointed out the fuel cell initial cost and stack replacement cost as the crucial cost disadvantages for the SOFC/GT system and low energy costs as a great advantage.

A hybrid model was created, using the total LCC results as an “economical category” combined with the emissions categories in the LCA. Such a hybrid model where the LCA and LCC are integrated requires that the importance of the environment and the economy are weighed when choosing an auxiliary system. In this case the conclusion is that the passenger ferry company has to choose whether it is willing to pay more per kWh for the SOFC/GT system than for the diesel engine, to achieve a distinct improvement of the environmental performance.

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1 INTRODUCTION

Air emission regulations are getting stricter in the near future, with particular focus on the emission of greenhouse gases, of oxides of nitrogen and oxides of sulphur. The Kyoto protocol sets targets to limit the amount of CO_2 and related greenhouse gases that can be produced by various countries. NO_x emissions are regulated through the Gothenburg agreement, and through EU actions, in addition to the maritime MARPOL Annex VI which is expected to enter into force in the near future. On the 4th of December 2003 the EU parliament adopted a report for drafting new NO_x emission standards based on Best Available Technology, as part of the EU shipping strategy. SO_x emission targets for the EU area will also be tightened in a revision of the Sulphur Directive 99/32/EC. Sulphur emission reductions from ships are targeted at 80%, and the EU Parliament is calling on the EU Commission to come forward with proposals for general reductions in air emissions from ships. /5/

Today's conventional technology for propulsion and auxiliary purposes in ships has largely reached its potential for emissions reduction. Internal combustion engines cannot be environmentally optimised much further without compromising fuel efficiency. In order to reduce the overall air emission from shipping, new and more energy efficient solutions must be found. Fuel cell technology is one of several promising technologies with good potential to operate in a more environmentally efficient manner. Fuel cells in particular offer very large reductions in the emission of NO_x due to the omission of a combustion process, and SO_x due to their strict fuel quality requirements. /5/

1.1 Background

In order to quantify the potential for environmental emissions reduction by the use of fuel cell technology in shipping, a study has been undertaken to look at various fuel cell options for auxiliary power generation onboard a passenger ship. The emission profile was investigated in a life cycle perspective, through the manufacture of the fuel cells and components, the operation with various fuel supply alternatives, through various decommissioning alternatives (qualitatively only). This analysis identified the environmental hot-spots in the life cycle of the SOFC/GT. To get a better picture of the real environmental performance of the SOFC/GT system a conventional technology reference case is performed and the systems are compared.

Economical life cycle evaluations are also required, to evaluate the economical performance of the two systems. A simple comparable Life Cycle Cost analysis is performed on all alternatives. Both the Life Cycle Assessment and Life Cycle Cost analysis are summarized and evaluated in a hybrid model.

2 LCA

The first parts of this report contain the comparative LCA of the auxiliary systems.

2.1 Objective

The purpose of this part of the study is to evaluate the environmental burden through the life cycle of a diesel auxiliary power production unit onboard a passenger ship and compare it with the future technology Solid oxide fuel cell integrated with gas turbine (SOFC/GT). A study of the life cycle of SOFC/GT is performed by Pretlove and Garmann /5/, and the study of the existing technology must be adjusted to this study to make the comparison plausible.

2.2 Methodology

Life cycle assessment (LCA) is an analytic tool developed to analyse the environmental impact through the entire lifecycle of a product, process or service. The methodology is developed to draw a more holistic picture of the environmental burdens associated with a product, process or service. By analysing just one process or life stage, just a small part off the total environmental performance is taken into account, and it is necessary to include all life stages to make a more actual picture of the environmental performance. Accounting for environmental burdens in the entire life cycle, LCA is an effective tool to avoid problem shifting, i.e. when solving one environmental problem creating another, by shifting environmental problems from one part of the system to another or creating a new type of environmental problem.

The computational structure of LCA makes it suitable for comparisons of environmental performance within or between systems. Together with other decision making tools, LCA may provide input to the selection of one product before another.

The framework of LCA is formalized by the International Organization for Standardisation (ISO) in the ISO 14040-14043. /1, 2, 3, 4/

An LCA shall include four main phases /1/:

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

The performance of an LCA is an iterative process between these four phases. The four phases are described below.

2.2.1 Goal and scope definition

The goal of the LCA study shall clearly state the intended application, the reason for performing the study and the intended audience. The framework for goal and scope is given in the ISO 14040 standard /1/.

When defining the scope of the study the function(s) of the study shall be clearly described and a *functional unit* should be defined to provide a basis for the assessment. The functional

unit is an expression for the function that the system fulfils. The purpose of the functional unit is to provide a reference which the inputs and outputs are related to. The function of a system can be "provide light in a room", the functional unit is the quantitative expression and may be "lightning of 40m^2 for 20 years", this function can be fulfilled by fore example lighting fixture or candle lights. /1, 7/
Further the *system boundaries* must be defined. This involves making choices about which processes to include or exclude in the analysis. The choice of system boundaries defines the degree of detail in the inventory analysis. In comparing studies, the studies are compared on the basis of the same functional unit, and it is of importance that the system boundaries are the same to make the comparison plausible. Differences in the systems regarding the system boundaries must be identified and reported. The choice of system boundaries will be discussed in chapter 4.2 in this report.

2.2.2 Life cycle inventory analysis

Life cycle inventory analysis (LCI) involves data collection and calculations to quantify relevant inputs and outputs of a product system. Guidelines for the inventory are found in ISO14041 /2/. Product systems are usually subdivided into a set of unit processes, which are linked together by flows of intermediate or final products. The data are often combined with a process tree, which graphically describes the system as a whole with all unit processes included. For each unit process, a reference flow shall be determined. Input and output data of the unit process are calculated in relation to this reference flow.

The methods of data collection differ. Usually combinations of techniques are used to obtain the necessary data for inputs and outputs from the unit processes to perform the analysis. A LCI may consist off process specific data by measurement, data from literature sources or data from process modelling or databases. If a unit process has multiple product outputs, allocation procedures can be used to identify the inputs and outputs to the process under study. The inventory analysis is an iterative process where new data are required as the knowledge of the system increases. /1, 2/

2.2.3 Life cycle impact assessment

In the impact assessment (LCIA) the significance of the potential environmental impacts, connected with the results from the inventory analysis, are evaluated. This involves associating inventory data with specific environmental impacts and perceives to understand those impacts. A guideline for Impact assessment is drawn in ISO 14042 and divides the assessment in several steps. /3/

Selection of impact categories
The selection of impact categories is the first step of LCIA, and should be adjusted to the Goal and scope of the study. To avoid problem shifting it will gain the analysis to include all categories relevant to the study. In a comparing assessment the choice of data categories is important, i.e. by focusing just on one or two categories a wrong picture can be given on the environmental performance of the compared systems; this may result in favouring the wrong alternative in an environmental perspective.

Assignment of LCI results, Classification

Some outputs may affect only one category while others affects several. In the Classification process the LCI results should be assigned to one or more impact categories, i.e. NO_x may be assigned to both ground-level ozone formation and acidification.

Characterization

Characterization involves the LCI data to be multiplied with a characterization factor specific for each category, i.e. for global warning, the emission is given in CO_2 equivalents, CO_2 has a *characterization factor* of 1, while methane, CH_4, has a characterization factor of 21. The characterization process is described in the equation below.

$$E_i = \sum m_i e_i$$ **Equation 2-1**

E_i Total emission for data category I, [g/functional unit].
m_i amount of component i, [kg/functional unit].
e_i characterization factor for data category I, [g/kg].

The aim is to identify the emissions which lead to a significant environmental burden. In most cases there are characterization factors developed for the regional or national geographical conditions.

Optional elements; normalization, grouping and weighting

Normalization, grouping and weighting are considered to be optional steps. It is not recommended to perform these steps in a comparing study and therefore it will not be done in this project. /3/

2.2.4 Life cycle interpretation

The interpretation phase of the LCA is intended to provide a clear presentation of the LCA/LCI results, guidelines are found in ISO 14043 /4/. The aim is to analyse the results, reach conclusions, explain limitations and eventually provide recommendations on the basis of the findings in the results and present the results of the LCA/LCI in a transparent way.

This LCA is performed using the software tool SimaPro by PRé Consultants. A full description off the program can be found at http://www.simapro.com. /9/

3 SYSTEM DESCRIPTION

3.1 *Auxiliary Engines*

The case ship has three engines for auxiliary power production, Wärtsilä 6L20, each with engine power of 1080kW. In this study these machines are upgraded to 6L20LN, (LowNo$_x$). From 1997 Wärtsilä has been delivering Vasa32LN (LowNo$_x$), and upgrading package for Vasa32. In this study it is assumed that also 6L20 will exist as LowNo$_x$ model in 5-10 years, which is the time scope of this analysis. The emission factors are therefore based on emission factors from Vasa32LN. The upgrading results in lower NO$_x$ emission and lower fuel consumption. The characteristics for the engines are presented in the table below.

Table 3-1: Characteristics for auxiliary engines onboard the ro-ro ferry /21/

Engine type	Speed	Engine effect	Generator effect	Weight	Fuel consumption
6L20LN	1000rpm	1080kW	1025kW	16.8t	185g/kWh (75%)

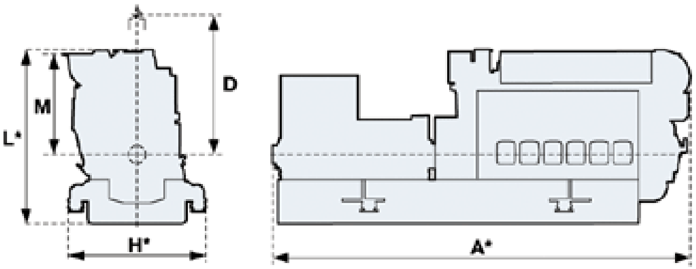

Figure 3-1: Wärtsilä 6L20, /18/

3.2 *Ancillary system*

In general the ancillary system contains four systems:

- Fuel treatment system
- Lubrication system
- Cooling system
- Exhaust system

The lubrication system lubricates all moving parts in the engine and cools the bearings. The lubrication oil flows in a closed system, where the oil is collected in the bottom of the engine after lubrication and led back to the lubrication oil tank. Some of the lubrication oil will be burned in the engine and create air emissions. /19/

The cooling system cools the engine. Freshwater is used as medium and the water is circulating in a closed piping system. The heat from the engine can be utilized for heating.

The fuel system leads the fuel form bunkering to the engine. The fuel oil is bunkered into the storage tank via the bunker station. From the storage tank the fuel oil is then pumped by a transfer pump through a strainer to the settling tank, depending on the level in the settling tank. The temperature in the settling tank is approximately 75-85°C. From the settling tank the fuel oil is pumped through a separator with heater (The oil is heated up to 96-97°C), suction pump, strainer and valves into the day tank. The day tank is held full all the time, and to make the oil as clean as possible another separator with heater, suction pump, strainer and valves, round separates the oil from the day tank and back to the day tank. The temperature in the day tank is about 80-90°C.

After the day tank the fuel is sucked into a booster module, a unit to obtain the requested viscosity (ca. 12Cst, or approximately 120°C), in the same process the fuel is also led through filters. After the booster module the fuel is led through valves to a fuel feed pump, which increases the pressure from 3-4bar to 7bar and deliver fuel at the right time through the fuel valve. The feed pump also returns unused fuel oil. The fuel valve atomizes the fuel so that the fuel achieve a spontaneous combustion at given pressure and position of the piston.

Exhaust from the combustion of the fossil fuel in the engine is cooled down by intercoolers in *the exhaust system* before it is led through chimney and released into the air. /20/

4 GOAL AND SCOPE DEFINITION

4.1 *Goal of the study*

The goal of the study is to make a reference case, with present technology, to the LCA "Life cycle assessment of maritime fuel cell applications" and perform a comparison with this study. The reference case will be used to indicate the real environmental performance of the SOFC/GT system relative to conventional technology.

It is of importance that the systems are compared on the basis of equivalent function and system boundaries to make the comparing study plausible. It is essential to follow the ISO standard guidelines when performing a comparative LCA, to make sure that the systems/ products are comparable. The ISO standards require that estimates and data sources should be described in an open and transparent way, though confidential information should be protected. If the comparative LCA study will be open to the public, there are also special requirements to a critical review to make sure the comparison is reasonable. The standard also specifies that weighting is not permitted in a public comparison. Weighting shows the performers subjective view of the importance of the different environmental burdens and may give a misrepresented result. /1, 2, 3, 4, 6, 7/

This study is manly targeted DNV and NTNU, but as a diploma thesis it will be open to the public.

4.2 *Scope*

The diesel engine shall function as auxiliary power source on board a passenger ship.

The functional unit is set to be 1kWh power supplied. Data in this study will be related to this functional unit.

4.2.1 *System boundaries*

The system boundaries decide which processes to include in the LCA study. Ideally the boundaries should be infinite, all the inputs and outputs to fulfil the function, should be included and followed upstream and downstream. If all the flows were followed to the end, this would result in a far too complex system. To reduce the complexity off the analysis, the study should therefore just include the parts of the system that are assumed to be relevant. Processes that have negligible effects, or processes seen to have very little influence on the result, can be excluded from the analysis. /7/

If a comparative LCA is performed, there are special requirements to the system boundaries to make sure that the comparison is credible. A comparison of alternative products, processes or services requires equivalent definition of the system boundaries for the alternatives compared, and that delimitations are made with respect to the goal of the study. Potential differences should be identified and reported. /6, 7/

The system boundaries must be specified on different levels:

- Technological system and nature.
- Other systems
- Geographical area
- Time horizon

Technological system and nature
There is a constant exchange of material and energy between the techno-, litho- and biosphere. The life cycle starts with extraction of natural resources and ends when waste in solid, liquid or gaseous form is released to soil, water or air. If for example wood are used as material in a product, the harvest should be included as well as activities needed to produce the wood. The life cycle ends with final disposal or recycling. Waste water treatment and incineration plants are parts of the technological system and should be included in the inventory. A waste disposal site can be seen as storage in the techno sphere. After some time small parts off the material will leak into the bio- and lithosphere, and finally the site will be left without management and will be a part of the bio- and lithospheres. The time perspective will decide whether the flow should be included as an emission in the techno sphere. /6, 7/

Other systems
Boundaries must be set between the life cycle of the system studied and the lifecycles of other associated systems. To specify all activities involved in the functioning of the system would take far too much time, if not be impossible, when performing a LCA. Most activities in the global technology system is interrelated in one way or another and would make an infinite system if not boundaries were set. /10/

Geographical area
The location of the system has an important role in LCA. The technological levels are quite different in different regions. Infrastructure, transportation system and electricity production differs and the specific local conditions must be taken into account.
The pollutant sensitivity of the environment varies between ecological systems. As a result of variable sensitivity the environment responds different to environmental stress from one area to another and it is of importance to be geographical restricted.
A way to set geographical boundaries is to delimitate consume of a product, service or process to a defined area. Use and waste management is evaluated in this area while production is allowed outside the area.

Time horizon
The time horizon of the study influences the environmental burden of the system, i.e. some compounds may have a long decay period, and even though there are no environmental impact at present time this substance may be of great environmental concern in 50 years. Boundaries in time should be set so that both present and future environmental burdens are taken in to account, not the environmental impacts that have already occurred.

4.2.2 Boundaries for this system

It is of importance that the systems boundaries are the same for the LCA of the diesel engine as the LCA of the SOFC/GT system to make them comparable. All system boundaries in this project were therefore set in accordance with the FCShip project.

- This study does not consider the energy or material use to produce the equipment for production.
- Materials data are SimaPro data and includes mining, transportation and processing.
- The transportation of workers is not included, neither is the work performed.
- The crude oil is refined in Sweden and supplied form locations in Russia, the North Sea, the Middle East and Western Africa.
- The energy for the manufacturing processes is based on power from the UK. (This is done because this is the energy used in the FCShip project)
- Transportation of the machinery from the manufacturing location to the manufacturing location of the ship is not included.
- Transportation within the manufacturing plant is seen as insignificant.
- Data from SimaPro libraries are not older than 1999.
- The case scenario is based on assumption of engine performance, emissions and fuel composition in 2014.

4.3 Process tree

The LCA performed in this project is structured as the FCShip project to make it easy to implement and compare with the FCShip results in SimaPro. The structure of the system is presented in the figure below. Worth noticing is that the disposal phase is discussed qualitatively only. The main processes evaluated in SimaPro are manufacture, fuel supply and operation. Operation involves the energy production and the fuel supply, the emissions released transporting the fuel to the ship. All values are calculated per functional unit, the numbers in the “Production boxes” indicates the fraction of the units needed to produce 1kWh electricity. The maintenance is a part of the operating phase but is chosen to be implemented under Production. The reason for this solution is that the maintenance is seen as extraction and manufacturing of the components replaced during the lifetime of the engines.

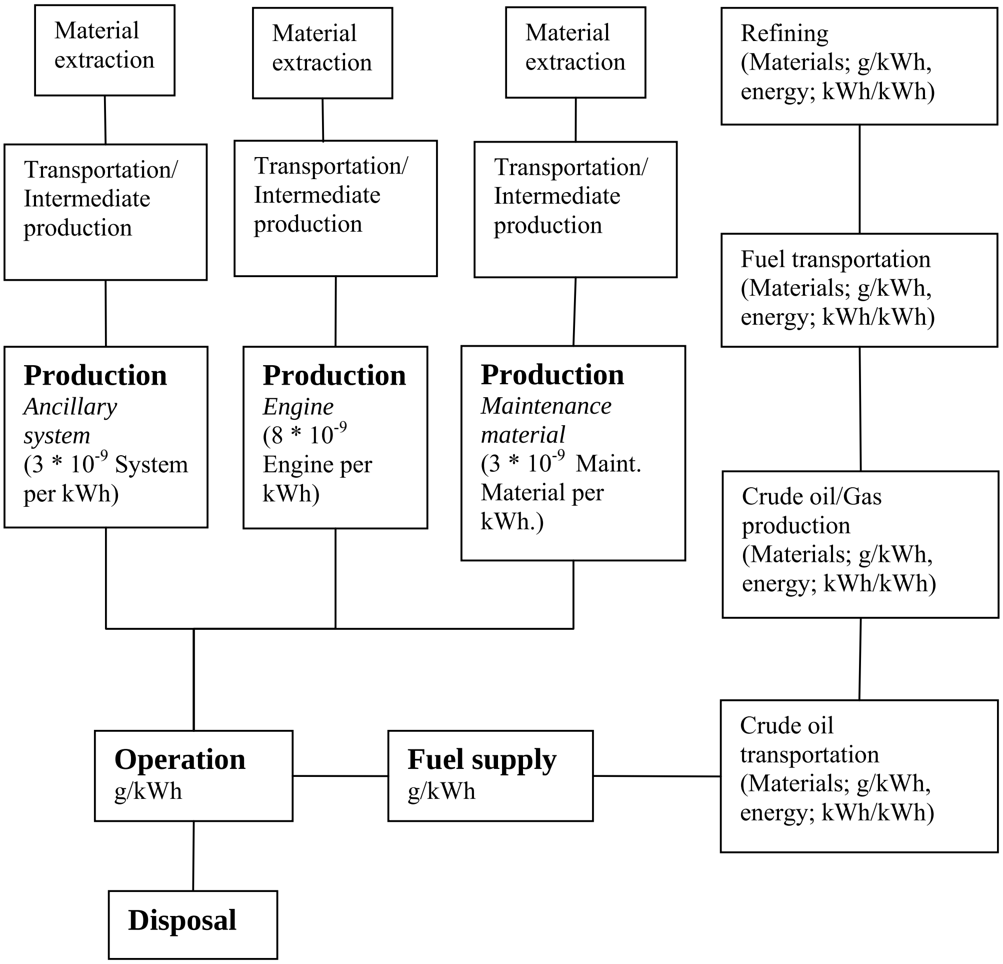

Figure 4-1: Process tree

4.4 Environmental impact and methodology for Impact Assessment

The Impact Assessment part of the study evaluates the environmental burden of the system from the results in the LCI. In this LCA the results are presented using the CML 2 baseline 2001 impact assessment method, an update from the CML 1992 method. The CML 2 baseline method elaborates the problem-oriented (midpoint) approach. In a midpoint approach the actual environmental damage is taken into account, while in an end point approach the consequences of this damage is also taken into account, i.e. the midpoint result of CO_2 pollution is changes in the concentration of greenhouse gases, global warming potential, while the endpoint may be thermal stress, malaria and floods. /9, 11/
The impact categories in the CML methodology are presented in the table underneath.

Table 4-1: Impact categories of CML methodology /5,9/

Impact Category	Unit	Description
Abiotic depletion	Kg Sb eq.	Determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on concentration of reserves and rate of de-accumulation.
Climate change (GWP 100)	Kg CO_2 eq.	Model developed by Intergovernmental Panel on Climate Change (IPCC). Factors expressed as Global Warming Potential for time horizon 100 years, in kg CO_2/kg emission.
Stratospheric Ozone depletion	Kg CFC-11 eq.	Model developed by the World Meteorological Organisation (WMO) and defines ozone depletion potential of different gasses (kg CFC-11 equivalent/kg emission)
Human toxicity	Kg 1.4-DB eq.	Describes fate, exposure and effects of toxic substances for an infinite time horizon. (1.4-dichlorobenzene equivalents/kg emission)
Fresh water aquatic ecotoxicity	Kg 1.4-DB eq	Describes fate, exposure and effects of toxic substances
Marine aquatic ecotoxicity	Kg 1.4-DB eq	Describes fate, exposure and effects of toxic substances
Terrestrial ecotoxicity	Kg 1.4-DB eq	Describes fate, exposure and effects of toxic substances
photochemical oxidation	Kg C_4H_2	Emission of substances to air is calculated with the UNECE Trajectory model (including fate) and expressed in kg ethylene equivalents/kg emission. (Also known as summer smog)
Acidification	Kg SO_2 eq.	Acidification expressed as kg SO_2 equivalents/kg emission.
Eutrophication	Kg PO_4--- eq.	Nutrification potential expressed as kg PO_2 equivalents/kg emission.

Due to difficulties in collecting high quality data for fuel cell manufacture in the SOFC/GT study, a number of impact categories could not be modelled accurately and just a few were found to be supported by data in the LCI. The project was written in the FCShip project of the EU for the shipping industry. As a result of the Kyoto protocol which targets to limit the CO_2 emission and the Gothenburg agreement and EU regulations to reduce NO_X and SO_X pollution the shipping industry seeks more environmental friendly technologies and are particularly concerned about these gasses. As a result of the limitation concerning data and the wishes in the FCShip project, only impact categories for global warming, photochemical oxidation and acidification were therefore included in the study and the other impact categories were omitted.

By just including a small number of emission categories there is a danger that problem shifting occurs. Due to the scope of the FCShip study, which is to provide a picture of the environmental performance for the categories the shipping industry is most concerned about, only global warming, photochemical oxidation and acidification is included. Ideally all categories should be included in this comparison study, but because of leak in data in the SOFC/GT study and the difficulties to provide more detailed data in both FCShip and the diesel engine study, this study will also just include these three categories. This analysis may therefore not identify eventually problem shifting. This is indeed a weakness of this analysis, but the time horizon of this project does not permit enough time to collect the requisite data for a more holistic environmental impact analysis.

4.5 Data quality

It was not within the scope of the FCShip study to gather data directly from suppliers or manufacturers, and to make the reference case comparable to this study, the data of equivalent quality has to be gathered. The inventory data for the FCShip study are presented in Appendix E, for more details refer to /5/.

The inventories in the FCShip study were based upon other studies within the FCShip programme and data available in the public domain. For the manufacturing of the SOFC, Balance of Plant and Gas Turbine, the study made use of average, non-specific plant data, the supply-route for materials is therefore unknown. /5/

To make the diesel engine study comparable with the SOFC/GT study it is important that the data is of equal quality. For the manufacturing of the diesel engine system, the study is making use of average, non-specific plant data. The actual manufacturing processes of the system builds on the processes in the SOFC/GT study /5/ and the operation phase of the life cycle uses specific data form the engine producer in combination with calculations on basis of literature references. The fuel supply stage uses the same assumptions as for the SOFC/GT system. Like this the quality of data should make the systems comparable.

4.6 Critical review

In a study open to the public it is of importance with a critical review. This LCA study is a part of a diploma thesis and will be evaluated of supervisors at DNV and NTNU and an external examiner.

5 LIFE CYCLE INVENTORY, LCI

This chapter discusses the data gathered for each life cycle stage in this study. Please refer to Appendix A, B and C for more details about specific values.

5.1 Fuel Supply

Crude oil for refining to higher value products is supplied from locations in Russia, the North Sea, the Middle East, Western Africa and other locations. The crude oil is refined at a location within Europe, and the location is assumed to be Scanraff refinery on the Swedish coast. At Scanraff the crude oil is processed at various stages and sulphur is removed (including a Claus plant for conversion of sulphur to solid state). The energy for the production process comes from various burners and generators at the refinery, utilising part of the crude oil and products available on site. The further handling of extracted sulphur is not included in the study.

The fuel oil (LSHFO, low sulphur heavy fuel oil with S≈0.2%) is transported the 250km to Oslo by a product tanker of capacity 4,000DWT (Dead weight tonnes), where it is stored. It is delivered to the ship in Oslo harbour by barge once a week. /5/

The fuel system is based on the same assumptions as in the sulphur free diesel scenario in the SOFC/GT study /5/. Energy losses and emissions during extraction, transport and refining are taken into account. The production of the machinery for producing and extracting are not included. All emissions are calculated per kWh. The emissions from transportation to port are justified for transportation with ship instead of truck /43/.

Detailed fuel supply data are found in Appendix C.

5.2 Manufacturing of Diesel engine and ancillary system

5.2.1 Manufacturing of the diesel engine

Production specific data for material content and energy could not be obtained, and the data are calculated based on assumptions. Data for extraction and production of materials are based on the existing libraries in SimaPro and are based on world average data. The material data in SimaPro includes mining, concentration and processing.

The material content in the auxiliary engines are estimated in co-operation with the staff at Marintech in Trondheim/22/. Machinery for producing the engines are not included.
Energy input for production of the engines are estimated based on data in the SOFC/GT. /5/ An assumption is made that the energy required for producing the machinery will be approximately the same per kW as for the gas turbine in the SOFS/GT study.

5.2.2 Ancillary system

The ancillary system consist of Lubricate oil system, Fuel system, Cooling system and exhaust system, mainly piping, pumps and filters. Specific data were not found for material content and production.

The materials in the ancillary system are assumed to be of approximately the same material composition as the engines and the inputs are based on assumptions of % weight of material of the engines. And a rough estimate is made that the ancillary system is approximately 10% of the three engines weight.
Energy input for production of the ancillary system is estimated based on data in the SOFC/GT study. /5, 20/

Lubrication oil is not as clean as the fuel oil and the emission from the lubrication oil burned is much higher per kWh, though the amount of lubrication fuel consumption is so small, 0.6–1.25g/kWh, compared to the fuel oil use, 180-210g/kWh /37/, that it is not included in the study.

Detailed manufacturing data are found in Appendix A.

5.3 Operation and maintenance

5.3.1 Operation

The Auxiliary power producing unit runs on distilled marine fuel oil. The engine is classified as Medium speed engine with 1000rpm (revolutions per minute). Only air emission are considered in this study due to the scope of the SOFC/GT study which only concerns global warming, photochemical oxidation and acidification in the impact assessment.
Both the engines and the ancillary system are assumed to have 30 years, or 262800 hours, lifetime, the same as the ship, and will therefore not be replaced. The engines are running 70% on two engines in average, i.e. the third engine is a backup engine. It is estimated that about 1000kg of components per engine, that means 3000kg for the whole system, will be replaced during the lifetime of the system. All emissions are related to 1kWh/14, 15, 16/.

Fuel consumption
The electric efficiency, μ_{el}, for this auxiliary diesel engine is estimated to be 42%. The efficiency is strongly dependent of the effect of the engine. When running on 70-100% off engine power the efficiency will be stable around 42%, under 70% the efficiency will decline drastically. /22/

The specific fuel consumption is assumed to be the same for the auxiliary engine in this study as for Vasa32LN. Specific fuel consumption are estimated to 187g/kWh for a medium speed engine based on the assumptions by Endresen and Sørgård/14/ and the data for Vasa32L. Endresen and Sørgårds value for specific fuel consumption is estimated using the operating profile in terms of number of operating hours per year and average engine load. Both the operating profile and average engine load are uncertain. In open sea, the ships will probably run the engines on 85% MCR (Maximum Continuous Rating). Taking approach and port operations in to account, 70% MCR are estimated. The value is based on test bed measurement and DNV onboard ship measurement.

Fuel consumption dependent air emissions
The emission of SO_2 is directly connected to the fuel consumption and sulphur content in the fuel /15/. Directive 1999 /32/ EC of the European Union (EU) states that a limit of 0.2%, and even as low as 0.1% for the sulphur content in marine fuels used by ships on inland waterways and at berth will be set, with effect from 1st of January 2008. The purpose of this

limit is to improve air quality around ports and inland waterways. The limits of sulphur contents on sailing are in the same directive set to 1.5% sulphur. /19/
The 0.2% limit will be implemented in this study, both when sailing and at berth (This is further discussed in the LCC part in chapter 9.3). An alternative to use the same fuel in all situations is change over; i.e. the ship is using low sulphur fuel in the berth areas and change to heavy oil out in the sea. Long sea shipping may typically use this technique. In this study the ship is sailing within Europe, so-called short sea shipping, and change over will probably not be a preferred alternative. The ship has approximately 16 hours at sea and 8 hours at berth, change over may be problematic due to berth boarders and limited time in open sea. Though, in the end this may probably be an economical question for the shipping companies. Due to the operating profile and the market advantage that may occur as a result of an environmental profile partly due to low sulphur fuels, this study is based on the assumption that change over will not be preferred.

In all combustion processes in which complete combustion of hydrocarbon fuels take place there will be formed Carbon Dioxide and water. CO_2 emission is also directly dependent on the fuel consumption. /13, 15/

Engine dependent air emission factors
Formation of NO from oxidation of atmospheric nitrogen in the combustion chamber depends on the conditions in the combustion chamber. During the passage through the exhaust system a proportion of NO, typically 5-10% will be converted to nitrogen dioxide NO_2, and a limited proportion to nitrous oxide N_2O. Further oxidation after the exhaust system will lead to formation of additional NO_2. The engine in this study is a LowNO_x engine, and will have a rather low NO_x emission compared to conventional engines of the same size.

The hydrocarbon (HC) fraction will consist of unburned or partially combusted fuel and lubricating oil. The HC fraction comprises a myriad of individual organic compounds with almost every chemical allowable configuration of C, H, O, N and S. In this study methane (CH_4), carbon monoxide (CO) and non-methane volatile organic compounds (NMVOC) will be considered. /13/

The emission factors for methane and nitrous oxide are highly uncertain.

Particulates (PM) fraction represents a complex mixture of inorganic and organic substances.

The pollution from the engine depend on activities of the ship because of the variations in electricity need, the engines pollute more on lower effect. The emission data are aggregated for the different activities in /12, 13, 14, 16/.

Air emission factors for auxiliary diesel engine

The air emission per functional unit, 1kWh, are calculated on basis on numbers and methods in /12, 13, 14, 15, 16/ and are shown in table below.

Table 5-1: Air emission factors for auxiliary diesel engine

Component	g/kWh
CO_2	593
SO_x	0.75[a]
NO_x	11.5[b]
CO	0.5[b]
CH_4	0.0561
PM	0.224
NMVOC	0.449
N_2O	0.015

The emission factors are calculated for a special fuel consumption of 187g/kWh /21/
a) 0.2% Sulphur content in fuel /17/
b) Wärtsilä

Detailed operation and maintenance data are found in Appendix B.

Uncertainties

There are significant uncertainties connected with the air emission values based on average numbers for ro-ro passenger ferries. Cooper /12/ summarizes the uncertainty to arise primarily from:

- the number of and how representative they are, the measurements used in deriving the emission factors in comparison to the total number and types of marine engines in use.
- measurement uncertainties within the emission factor data set which vary for different measurement techniques and thus pollutants, and even activities.
- assumptions made in assigning the factors for a given activity, e.g. main engine operation in port.
- the applicability of a universal factor for a given ship category (i.e. uncertainty will increase for inventories covering a smaller number of ships).

The work done by the crew onboard during operation and travelling to/from the working place is not included in the SOFC/GT study and can of this reason not be included in this. The work could probably anyway be let out as a result of that the same number of employees probably will work with the engines in both systems. The composition of the crew may change as a result of the fuel cells, i.e. there may be the need for some workers with more electrical knowledge in the SOFC/GT system. This will however most likely not have any influence on the size of the environmental impact as a result of the work with the engines. Identical stages in a comparative assessment can be omitted.

Operating time

The ship has a lifetime of about 30 years. The operating time of the auxiliary engines and ancillary system are also assumed to be 30 years. In the lifetime of the ship the engines and ancillary system, except smaller parts, are therefore not replaced. The operating time of an engine is obviously dependent on the maintenance quality and frequency. Onboard a ro-ro passenger ferry the machinery crew mostly follows recommended maintenance procedures for the machinery /20/. The machineries are tested and parts are changed after a maintenance program, errors should be detected and be rectified in short time. There may off course be more fatale errors, but it is assumed in this assessment that all errors that may occur can be repaired onboard. The ship has three engines, one is enough to maintain the most essential processes onboard, and two is enough to maintain all needs that may occur. The third engine is not running, unless one is down, which machines that runs alter. An error will therefore not stop the ship, and it may continue while the error is fixed.

5.3.2 Maintenance

As a result of that the work done due to maintenance is not included in the SOFC/GT study it is also omitted in this study. On the other hand the crew is already there, and just in cases of fatal errors special crew will be hired, the work can of this reason probably anyway be omitted. Maintenance is therefore taken into account and evaluated as the material extraction and production of all components replaced during the lifetime of the system. The estimate is based on a maintenance plan for a ro-ro passenger ship /20/, and it is assumed that approximately 1000kg per engine is replaced. Due to the composition of the components replaced it is estimated that the material composition will be almost the same as for the ancillary system.

5.3.3 Decommissioning

In the FCShip project end-of-life options are considered qualitatively only. As many of the materials in the fuel cells are of high value, it is expected that re-cycling and re-use schemes will be set up. Certain materials may also require special care due to their potential environmental impact.

As a result of the choices on decommissioning in the FCShip project, the end of life is excluded also in this study. To day the engines are mostly scrapped with the rest of the ship and are used as for example building steel. Other studies are based on a 95% recycling of the engines /23/. The FCShip study /5/ also concludes with that most of the material probably will be recycled as a result of the scarcity of the materials used. This will probably lead to higher energy needs when recycling, but will also save more energy in manufacturing virgin materials. The two systems will probably come out about equal.

5.4 Changes in LCI in the FCShip analysis

5.4.1 New lifetime assumptions

After the first round of comparison LCIA it was clear that the environmental impacts from manufacturing of the components in the FCShip study were extremely high, compared to the manufacturing of the diesel engine system. The FCShip SOFC/GT system was therefore very sensitive to changes in the manufacturing process. After carefully studying the LCI of the FCShip project in SimaPro it was found that the lifetime of the components was too short, by a factor of 10, due to a misplaced comma. This error was corrected. Though the manufacturing phase was still rough and inaccurate and to make a more accurate picture of the emissions from manufacturing a new lifetime scenario was introduced. This was done to identify, in more detail, which components that have the biggest contribution to environmental impacts.

Originally the FCShip study assumed very little onboard maintenance of the fuel cell modules. The SOFC were assumed to have a service life equivalent to 40000 full load hours, the Balance of Plant 80000 full load hours, and the Gas Turbine 60000 full load hours. Parts found to be in good working order when the components where expected to be taken ashore for replacement and re-conditioning, but further investigation into this were not considered in the report.

The new approach is that the basic parts of Balance of plant (BOP) and Gas turbine have 30 years life due to maintenance while the stack only has 20000 full load hours service life. For the BOP and Gas turbine expendable parts are replaced during maintenance. It is assumed that 10% of the weight of the BOP is replaced every 10 years, i.e. which means that 20% of the weight is replaced during the whole lifetime. For the Gas turbine it is assumed that the hot section components are changed, components of manly nickel alloy, copper and steel. The nickel alloy is replaced every 8th year, while for copper and steel 10% is replaced during the 30 year lifetime. The work done maintaining is, like for the diesel engine system, not included. The Lifetime of the Stack is assumed to be so short due to assumptions that 40000h of lifetime is very optimistic and that 20000 hours gives a more realistic picture.

5.4.2 New CO_2 emission assumptions SOFC/GT

In the FCShip report the CO_2 emission from the operating phase of the SOFC/GT is equal running on natural gas or diesel, which may seam like a wrong assumption. First, the different carbon and energy density in the different fuels indicate that there will be differences in the CO_2 emission per kWh_{el} from fuel cell operation. Second, conditions and processes in the fuel cell might, through different utilisation of different fuels, result in additional differences. An example of a condition that may influences the CO_2 emission is the reformation process. For non-hydrogen fuels, like the fuels used in the FCShip SOFC/GT, it is necessary to reform and convert the fuels into a predominantly H_2-rich gaseous form.

The fuel reformation process results in some energy loss. In the case of a reformer, the efficiency may be defined as described in the equation below. /24/

$$\eta_{ref} = \frac{(Fuel \bullet LHV)_{out}}{(Fuel \bullet LHV)_{in}} \qquad \textbf{Equation 5-1}$$

The heating value differs for different fuels and will result in different reformation efficiency, η_{ref}. For simple fuels such as natural gas, the reformer can be an integrated part of the fuel cell while for diesel a specific stand-alone fuel reformer is needed. Indications are though that integrated reformers for diesel would be feasible in the long run /24/.

Both energy and carbon density in the fuel and the engine configuration indicates that there will be differences in the emissions form the fuel cell running on natural gas or diesel.

It seams like little research has been done on the CO_2 emission from SOFC/GT operation, and no satisfying data were found in any sources examined. Like discussed over there will probably be differences in the electric efficiency for the SOFC/GT system running on natural gas or diesel, no numbers were however found on this. In this study the CO_2 emissions from operation with gas or diesel has therefore been calculated from energy content and emission factors for natural gas and diesel assuming the same overall efficiency of 70% for the SOFC/GT system running on gas or diesel. The energy content and emission factors are showed in the table below.

Table 5-2: Energy content and Emission factors /25/

Fuel	Energy content	Emission factor
LNG	45 MJ/kg	2.75 kg CO_2/kg
Diesel	43.1 MJ/kg	3.17 kg CO_2/kg

Table 5-3: CO_2 emission SOFC/GT, 70% efficiency

Fuel	CO_2 emission[1)]
LNG	314 g CO_2/kWh_{el}
Diesel	378 g CO_2/kWh_{el}

[1)] Calculations in appendix D

6 IMPACT ASSESSMENT

The results from the impact assessment give a picture of the environmental performance of the different systems and life stages. In this chapter the results will be presented graphically and further discussed. First the results of the life cycle of the diesel engine are presented then the results for the corrected SOFC/GT study before the systems are compared. The emissions are characterized in equivalents to the three categories. The contribution to the global warning category is given in CO_2 (carbon dioxide) equivalents, photochemical oxidation is given in C_2H_4 (methane) equivalents and acidification in SO_2 (sulphur dioxide) equivalents.

6.1 Impact assessment diesel engine

The impact assessment of the life cycle of the diesel engine, exclusive end of life/disposal shows the contribution to the three selected impact categories from each life stage.

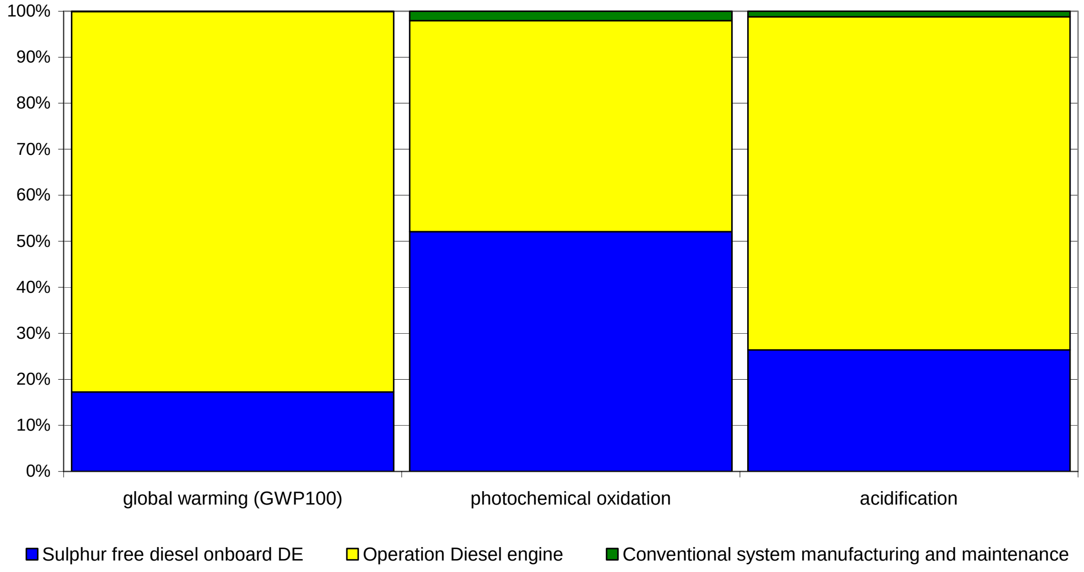

Figure 6-1: LCA diesel engine

Table 6-1: LCA diesel engine

Impact category	Unit	Total	Sulphur free diesel onboard	Operation	Manufacturing and maintenance
Global warming (GWP100)	kg CO_2 eq. /kWh	0.725	0.125	0.599	0.000489
Photochemical oxidation	kg C_2H_4/kWh	3.38E-5	1.76E-05	1.55E-05	6.98E-07
Acidification	kg SO_2 eq /kWh.	0.00124	0.000328	0.0009	1.50E-05

The environmental emission contribution from extraction of raw materials and manufacturing of the engines are nearly insignificant compared with the fuel supply and operation in all the environmental categories. The contributions from the extraction and manufacture to the environmental categories are 0.07%, 2% and 1.4% for global warming, photochemical oxidation and acidification respectively. The operating phase has the largest contribution in the global warming category and acidification category, 83% and 73% respectively. In the

photochemical oxidation category the fuel supply has the largest contribution with 52%, while the operation phase contributes with 46% of the over all contribution to this category.
The operation phase has such a high contribution to all categories as a result of the combustion process of fossil fuel. The contribution to acidification is strongly dependent on the fuel consumption and the sulphur content in the fuel, the photochemical oxidation mainly on the nitrogen oxide emission (as a result of the conditions in the engine) and the global warning potential depends on the fuel consumption and the composition, i.e. carbon content in the fuel. The diesel engine has 42% el-efficiency, low sulphur content in the fuel and is a LowNO$_x$ machine. The low NO$_x$ emission is a reason for a bit lower contribution to the photochemical oxidation category compared to fuel treatment in the other categories. All stages in the fuel treatment gradually contribute to all categories, from extraction via refining and transportation.

6.2 Impact assessment for the correction of the FCShip study

6.2.1 New assumptions in the CO_2 emissions from SOFC/GT system operation

The new CO_2 emissions from the SOFC/GT system, discussed in chapter 5.4.2, are compared with the old FCShip assumptions in the figure and table below.

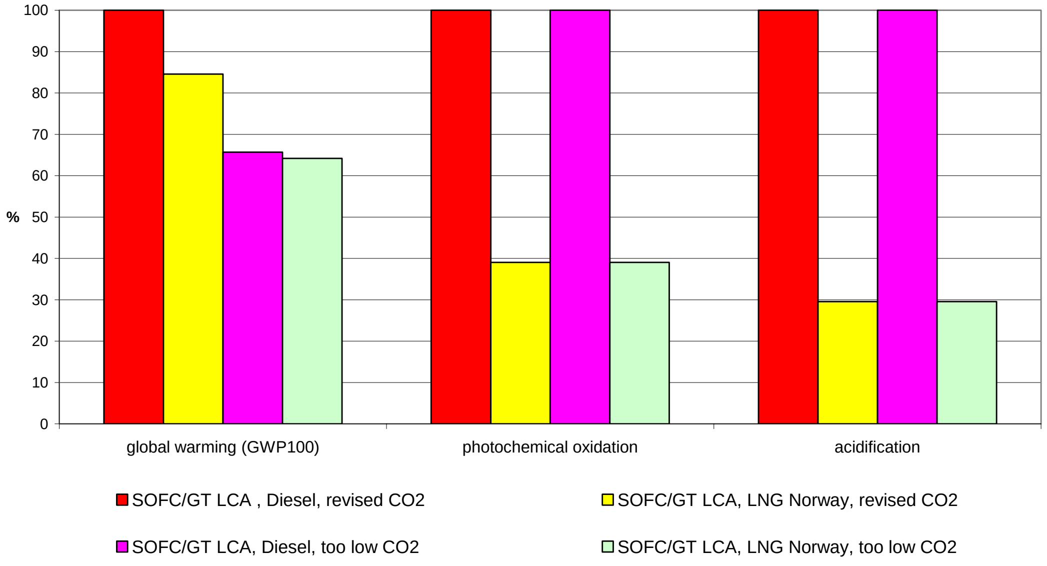

Figure 6-2: Revised CO_2 emission

Table 6-2: Revised CO_2 emission

Impact category	Unit	SOFC/GT LCA , Diesel, revised CO_2	SOFC/GT LCA, LNG Norway, revised CO_2	SOFC/GT LCA, Diesel, too low CO_2	SOFC/GT LCA, LNG Norway, too low CO_2
global warming (GWP100)	kg CO_2 eq. /kWh	0.466	0.394	0.306	0.299
photochemical oxidation	kg C_2H_4/kWh	1.20E-05	4.68E-06	1.20E-05	4.68E-06
acidification	kg SO_2 eq /kWh.	0.000276	8.15E-05	0.000276	8.15E-05

The new CO_2 emission assumptions lead to a 34% and 24% increase in the global warming category through the life cycle of the SOFC/GT running on diesel and natural gas respectively.

6.2.2 LCA SOFC/GT corrected FCShip lifetime and new lifetime assumptions

The figure below presents the LCA for corrected lifetime in SimaPro, FCShip lifetime, and the new lifetime assumptions. The first four columns in each category represent the different SOFC/GT alternatives with the FCShip lifetime, the four last the new assumptions. The new lifetime assumptions were discussed in chapter 5.4.1. All alternatives have corrected CO_2 emissions in the operating phase.

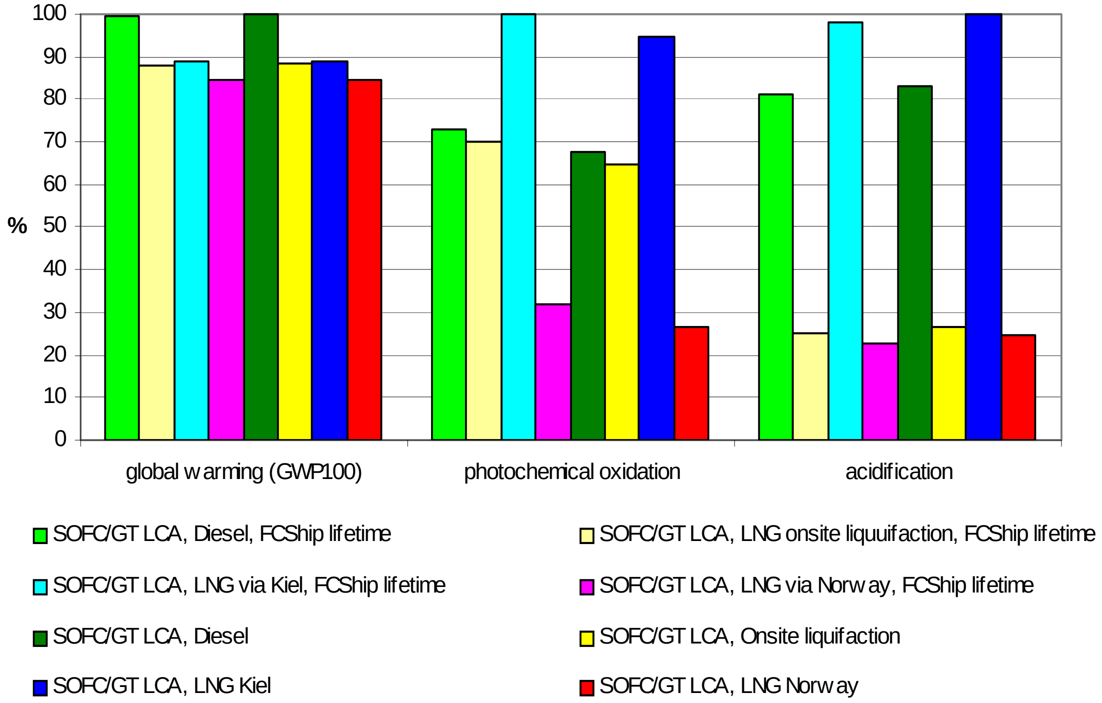

Figure 6-3: LCA SOFC/GT corrected FCShip lifetime and new lifetime assumptions

Table 6-3: LCA SOFC/GT FCShip lifetime

Impact category	Unit	SOFC/GT, Sulphur free diesel, FCShip lifetime	SOFC/GT, LNG onsite liquefaction, FCShip lifetime	SOFC/GT, LNG via Kiel, FCShip lifetime	SOFC/GT, LNG via Norway, FCShip lietime
global warming (GWP100)	kg CO_2 eq. /kWh	0.464	0.41	0.414	0.393
photochemical oxidation	kg C_2H_4/kWh	1.29E-05	1.24E-05	1.77E-05	5.64E-06
Acidification	kg SO_2 eq /kWh.	0.000271	8.30E-05	0.000327	7.62E-05

Table 6-4: LCA SOFC/GT new lifetime assumptions

Impact category	Unit	SOFC/GT, Sulphur free Diesel, new lifetime	SOFC/GT, LNG onsite liquefaction, new lifetime	SOFC/GT, LNG Kiel, new lifetime	SOFC/GT, LNG Norway, new lifetime
global warming (GWP100)	kg CO_2 eq. /kWh	0.466	0.411	0.415	0.394
photochemical oxidation	kg C_2H_4/kWh	1.20E-05	1.15E-05	1.68E-05	4.68E-06
Acidification	kg SO_2 eq /kWh.	0.000276	8.83E-05	0.000333	8.15E-05

The total contributions to the three impact categories are nearly equal after the change in lifetime assumptions. It makes no difference in the total environmental performance, but the more realistic lifetime scenario gives a more nuanced picture of the system. The revision of lifetimes and the introduction of maintenance parts identify which parts of the SOFC/GT system that has significant contributions to the three emission categories.

6.2.3 LCA new lifetime assumptions

After correcting the lifetime of the SOFC/GT system, the environmental contribution from the manufacturing phase is 10 times smaller; this makes a significant difference in the total environmental performance of the system.

The life cycle of the Fuel via Kiel SOFC/GT system with the original and corrected lifetime is presented underneath. The old lifetime assumptions are presented in the first figure below. /5/

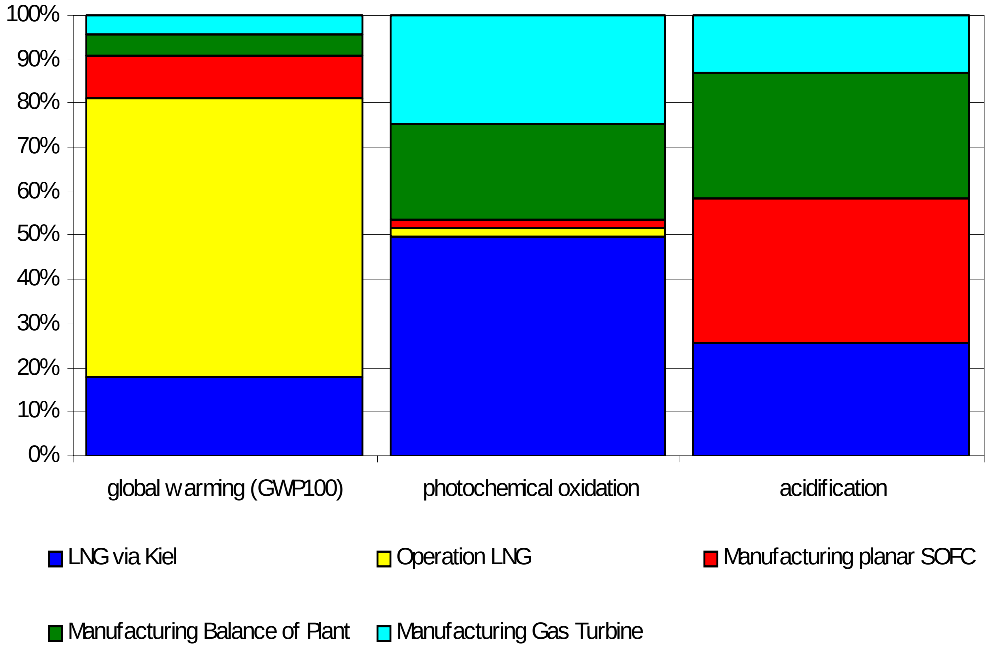

Figure 6-4: LCA characterisation SOFC/GT old lifetime in the FCShip project

Table 6-5: LCA characterisation table SOFC/GT old lifetime in the FCShip project

Impact category	Unit	Total	LNG supply via Kiel	Operation LNG	Manufacturing planar SOFC	Manufacturing Balance of Plant	Manufacturing Gas Turbine
global warming (GWP100)	kg CO_2 eq./kWh	0.498	0.089	0.315	0.0474	0.024	0.0222
Photochemical oxidation	kg C_2H_4/kWh	3.14E-5	1.57E-05	5.34E-07	6.22E-07	6.77E-06	7.82E-06
Acidification	kg SO_2 eq/kWh.	0.00099	0.000254	0	0.000327	0.000282	0.000128

The FCShip report concluded with that for the GHG emissions, operation was important, whilst for the other impact categories it was negligible. This due to the coarser fuels utilised in the fuel extraction and transport stages. Manufacture was of less importance for GHG emissions, but important for other impacts, acidification in particular.

The environmental contribution from the manufacturing phase is reduced significantly after the correction and new lifetime assumptions, i.e. from having a large contribution to all categories, and as much as 75% for acidification, manufacturing is of much less importance with the correction in SimaPro and new lifetime assumptions. This is showed in the figure and table under.

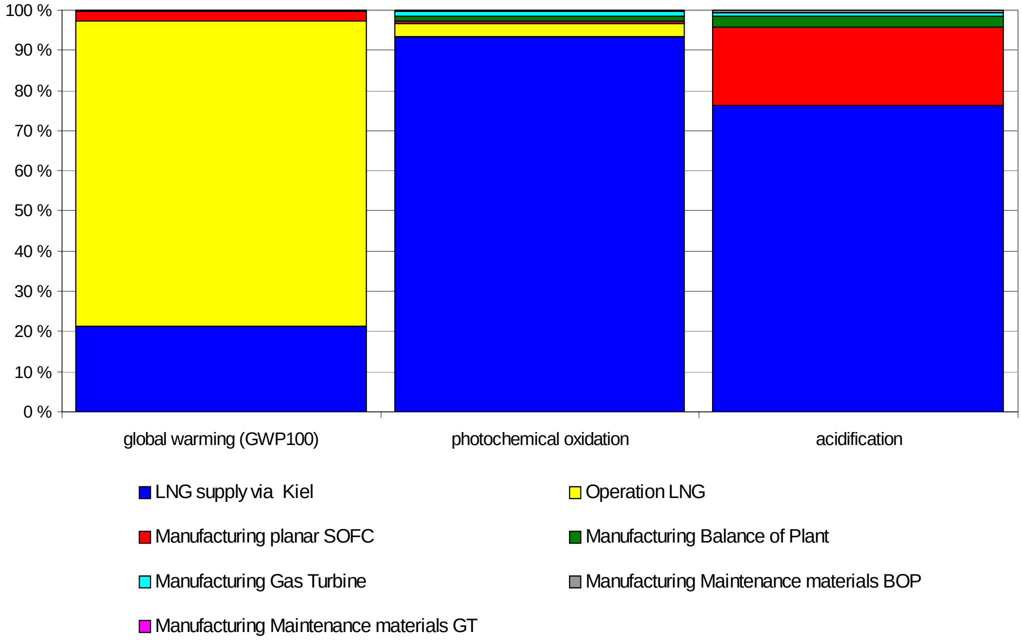

Figure 6-5: LCA Characterisation SOFC/GT new lifetime assumptions

Table 6-6: LCA Characterisation table SOFC/GT new lifetime assumptions

Impact category	Unit	Total	LNG supply via Kiel	Operation LNG	Manufacturing planar SOFC	Manufacturing Balance of Plant
global warming (GWP100)	kg CO$_2$ eq./kWh	0.415	0.089	0.315	0.00949	0.00073
photochemical oxidation	kg C$_2$H$_4$/kWh	1.68E-05	1.57E-05	5.34E-07	1.24E-07	2.06E-07
Acidification	kg SO$_2$ eq /kWh.	0.000333	0.000254	0	6.53E-05	8.58E-06

Impact category	Unit	Manufacturing Gas Turbine	Manufacturing Maintenance materials BOP	Manufacturing Maintenance materials GT
global warming (GWP100)	kg CO$_2$ eq./kWh	0.000505	0.000146	5.43E-05
photochemical oxidation	kg C$_2$H$_4$/kWh	1.78E-07	4.12E-08	1.91E-08
Acidification	kg SO$_2$ eq/kWh.	2.91E-06	1.72E-06	4.14E-07

The new assumptions that the lifetime is 20000 hours for the stack, and that the BOP and gas turbine can be used the whole lifetime of the ship, due to the introduction of the maintenance, makes the impact contributions from the manufacturing part significant smaller. It also gives a more nuanced picture of the contribution from the manufacturing of the different components. The manufacturing of the stack (here represented as Manufacture planar SOFC) has around 10 times higher contribution from manufacturing phase in the global warning and acidification categories than the manufacturing of the other components. For photochemical oxidation the three components has almost the same contributions in a lifecycle perspective. The manufacturing of the maintenance material is about 10 times smaller than manufacturing of BOP and gas turbine in all categories.

Due to the lower emissions in the manufacturing phase the operating phase and fuel supply phase has relative much higher contribution to all categories. The operating phase has the highest contribution to the global warming category, 76% of total contribution to this category, while the fuel supply phase has the highest contribution to the photochemical oxidation and acidification category, 93% and 76% respectively. The two phases represents 95-97% of the contribution to both the global warming potential and photochemical oxidation. The manufacture of the planar SOFC has the second largest contribution to the acidification category and contributes with 20% to the over all contribution to this category.

6.3 Comparison

6.3.1 Comparison operation

The comparison of the operating phase of the three alternatives for auxiliary power production onboard the ro-ro ship, conventional diesel engine, LNG fuelled SOFC/GT or sulphur free diesel fuelled SOFC/GT are showed below.

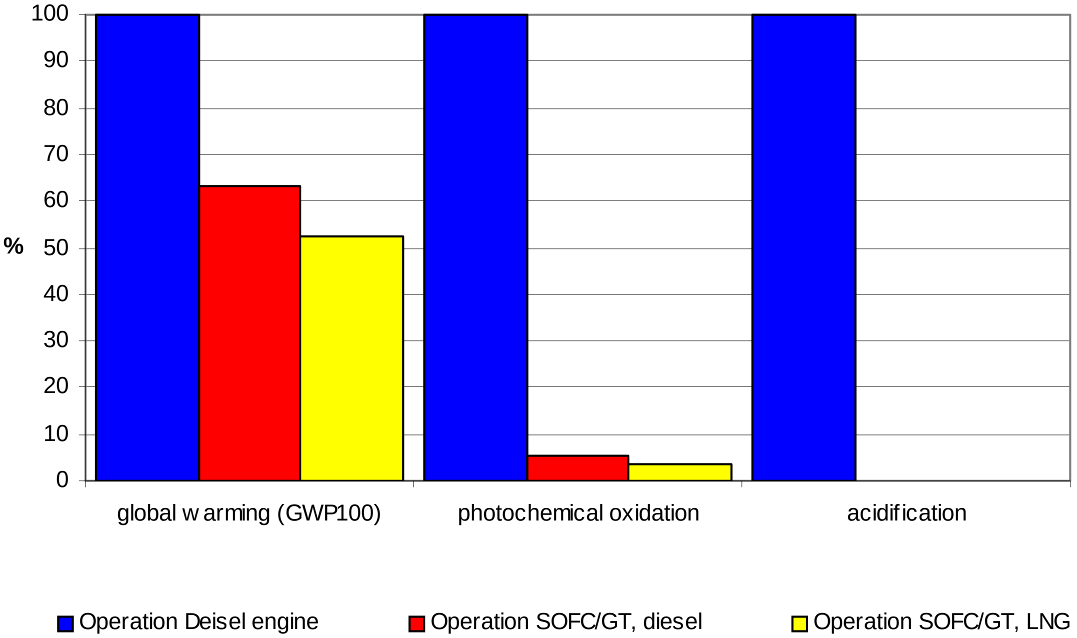

Figure 6-6: Comparison operation

Table 6-7: Comparison operation

Impact category	Unit	Operation Deisel engine	Operation Diesel	Operation LNG
global warming (GWP100)	kg CO_2 eq. /kWh	0.599	0.379	0.315
photochemical oxidation	kg C_2H_4/kWh	1.55E-05	8.11E-07	5.34E-07
Acidification	kg SO_2 eq /kWh.	0.0009	0	0

The comparison of the operation shows significant differences in the environmental performance for the three operation alternatives. For the global warming potential, operation with natural gas contributes with 53% of the contribution from the conventional diesel engine, while operation with sulphur free diesel has a contribution 36% smaller than the conventional engine to the global warming potential. The contribution from the SOFC/GT system to the photochemical oxidation is 3-5% of the contribution from diesel engine, while the contribution to acidification is zero. The much higher contribution to global warming potential from the diesel engine is mainly a result of the engine efficiency, which is only 42%, compared with 70% for the SOFC/GT. The zero contribution to acidification in the operating phase of the SOFC/GT systems is a result of the natural gas and sulphur free diesel.

6.3.2 Comparison manufacturing

The comparison of the manufacturing of the two systems shows a rather different size of contribution to the three categories and is presented in the figure and table below.

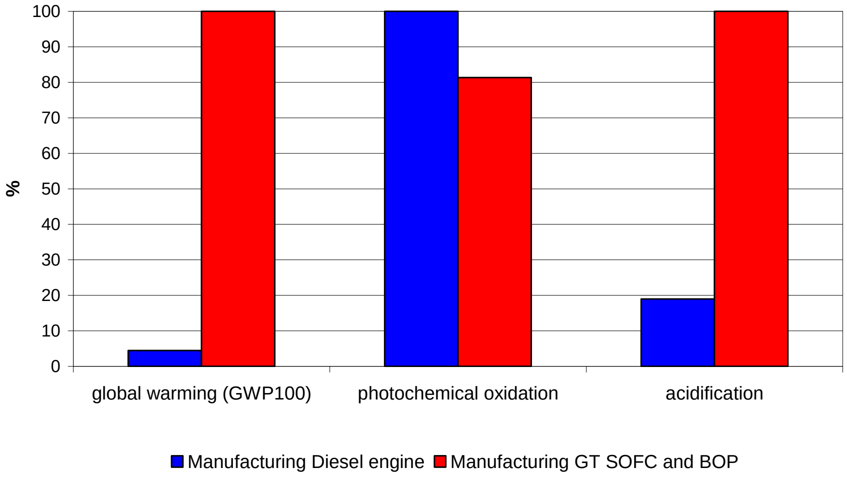

Figure 6-7: Comparison manufacturing

Table 6-8: Comparison manufacturing

Impact category	Unit	Manufacturing Diesel engine	Manufacturing GT SOFC and BOP
global warming (GWP100)	kg CO_2 eq. /kWh	0.000489	0.0109
photochemical oxidation	kg C_2H_4/kWh	6.98E-07	5.68E-07
Acidification	kg SO_2 eq /kWh.	1.50E-05	7.89E-05

While the SOFC/GT system has a much higher contribution to global warming and acidification, the diesel engine has the highest score in the photochemical oxidation. The largest contribution to the manufacturing of the SOFC/GT system comes from the manufacturing of the fuel cell stack. The Cromium-Yttrium alloy is responsible for about 80-90% of the contribution to all three categories, as a result of the large amount of the alloy needed and the energy requirement to produce the material. The major contribution from the manufacturing of the diesel engine system comes from material use and manufacturing of the engine, about 90-98% in all categories.

6.3.3 Comparison fuel supply

The fuel supply scenarios, diesel to the diesel engine, LNG from Norway, import via Kiel and onsite liquefaction to the SOFC/GT and sulphur free diesel to the SOFC/GT are presented underneath.

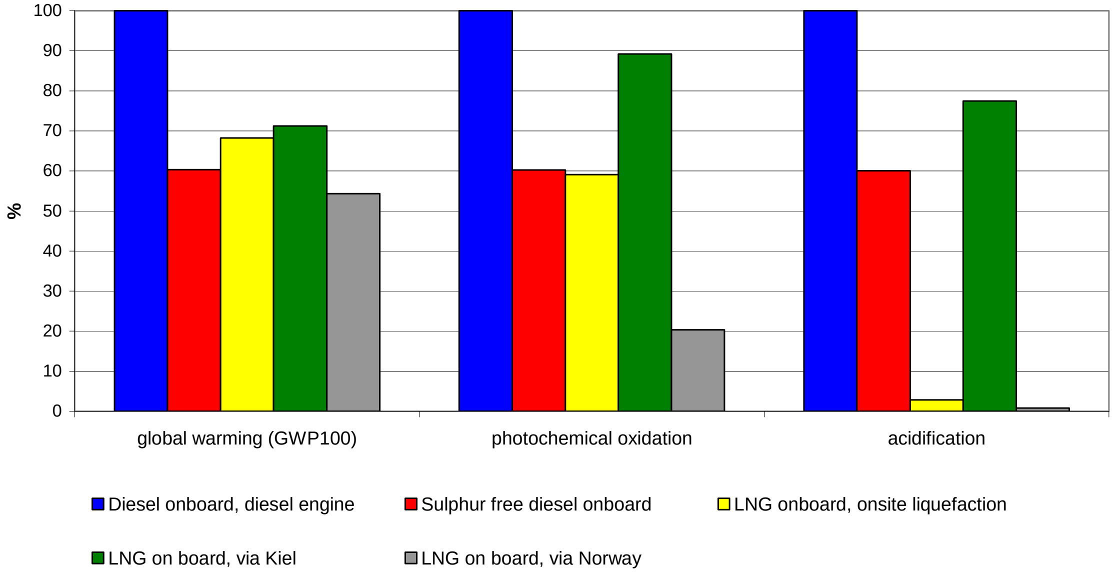

Figure 6-8: Fuel Supply

Table 6-9: Comparison fuel supply

Impact category	Unit	Diesel onboard, diesel engine	Sulphur free diesel onboard	LNG onboard, onsite liquefaction	LNG on board, via Kiel	LNG on board, via Norway
global warming (GWP100)	kgCO_2eq./kWh	0.125	0.0754	0.0853	0.089	0.0679
Photochemical oxidation	kg C_2H_4/kWh	1.76E-05	1.06E-05	1.04E-05	1.57E-05	3.58E-06
Acidification	kgSO_2eq/kWh.	0.000328	0.000197	9.35E-06	0.000254	2.61E-06

The fuel supply scenario for the diesel engine, is based on the same data sources as the sulphur free diesel scenario for SOFC/GT, and has the highest contribution to all the environmental categories. The contributions are 10-30% higher. The LNG import via Kiel scenario has the highest environmental impact of the SOFC/GT supply alternatives, while the LNG supply via Norway has the best environmental performance. The high score from the fuel supply to the diesel engine is a result of the much lower el-efficiency of the engine, 42% for diesel engine compared to 70% for the SOFC/GT system.

6.4 Full LCA

The full Life cycle assessment is presented in the figure and table under.

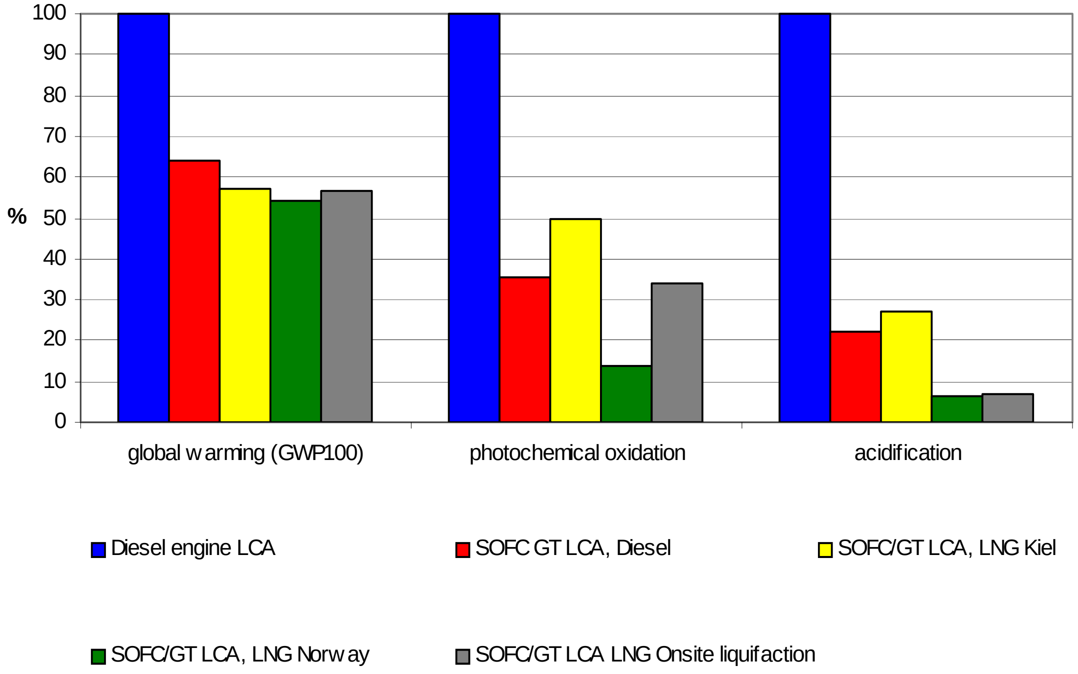

Figure 6-9: Full LCA

Table 6-10: Full LCA

Impact category	Unit	Diesel engine LCA	SOFC/GT, Sulphurfree Diesel, LCA	SOFC/GT, LNG via Kiel, LCA	SOFC/GT, LNG via Norway, LCA	SOFC/GT, Onsite liquefaction,LCA
global warming (GWP100)	kg CO_2 eq. /kWh	0.725	0.466	0.415	0.394	0.411
Photochemical oxidation	kg C_2H_4/kWh	3.38E-05	1.20E-05	1.68E-05	4.68E-06	1.15E-05
Acidification	kg SO_2 eq /kWh.	0.00124	0.000276	0.000333	8.15E-05	8.83E-05

The SOFC/GT system has 35-93% lower contribution in all the categories. In the global warming category the diesel engine contributes with about 35% more emission than the sulphur free diesel SOFC/GT and nearly 55% more than the natural gas SOFC/GT alternatives. The el-efficiency is the major reason for the much higher values in this category. For photochemical oxidation the contribution from the diesel engine is 50-75% higher than the fuel cell alternatives. Fuel use is the main reason for the high contribution also in this category. For the acidification category the diesel engine has a 75–93% larger contribution than the other alternatives. The low contribution from the SOFC/GT alternatives is a result of the absence of sulphur in the fuel for all SOFC/GT systems, and only manufacturing and fuel supply contributes to this category.

7 SENSITIVITY ANAYLYSIS

Several of assumptions are done in this study. A sensitivity analysis has been performed to evaluate the sensitivity of the decisions made, both for the new lifetime for the stack, the lifetime of the stack and emissions and material assumptions for the diesel engine.

7.1 *Stack Lifetime, SOFC/GT*

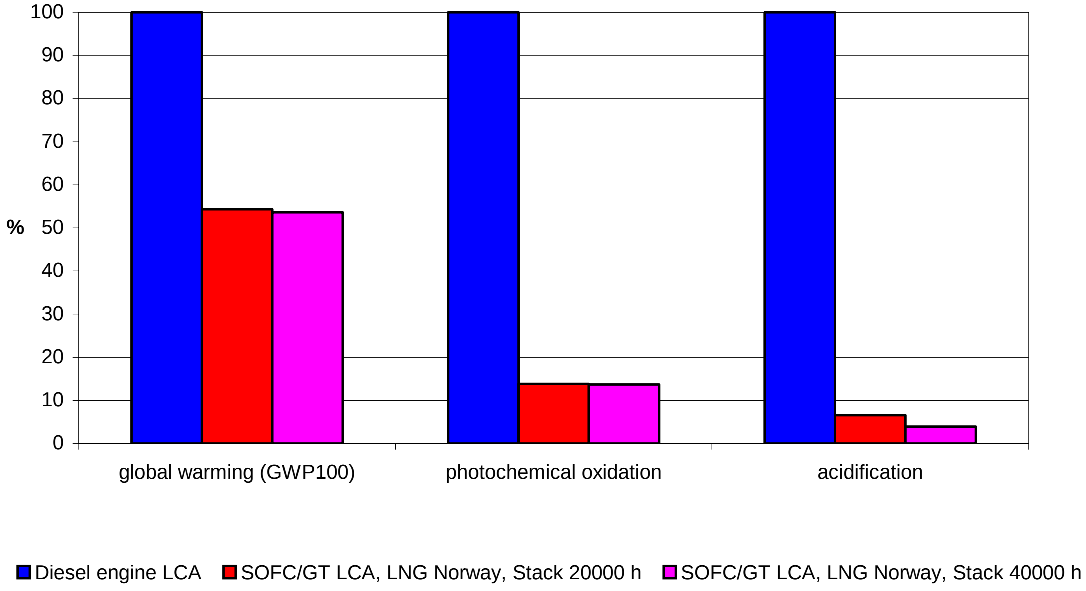

Figure 7-1: LCA, sensitivity Stack lifetime, SOFC/GT

Table 7-1: Sensitivity Stack lifetime, SOFC/GT

Impact category	Unit	LCA, Diesel engine	LCA, LNG via Norway, double lifetime stack	LCA, LNG via Norway
global warming (GWP100)	kg CO_2 eq. /kWh	0.725	0.394	0.389
photochemical oxidation	kg C_2H_4/kWh	3.38E-05	4.68E-06	4.62E-06
Acidification	kg SO_2 eq /kWh.	0.00124	8.15E-05	4.89E-05

A full LCA of the diesel engine and two lifetime scenarios, 20000 and 40000h, for the stack in the SOFC/GT system fuelled on LNG via Norway were performed. The table and graphics shows that the different lifetimes has little influence on the total environmental performance compared to the conventional system. The increase in the contribution to the different categories, because of doubling the lifetime of the stack, is between 1-3% in the three categories, most in the acidification category which is a result of zero-contribution from the operation phase in this category and that the manufacture of the stack has a rather big contribution to this category (5.2.2). The over all LCA is therefore not very sensitive for changes in the SOFC/GT lifetime.

7.2 SOFC/GT efficiency

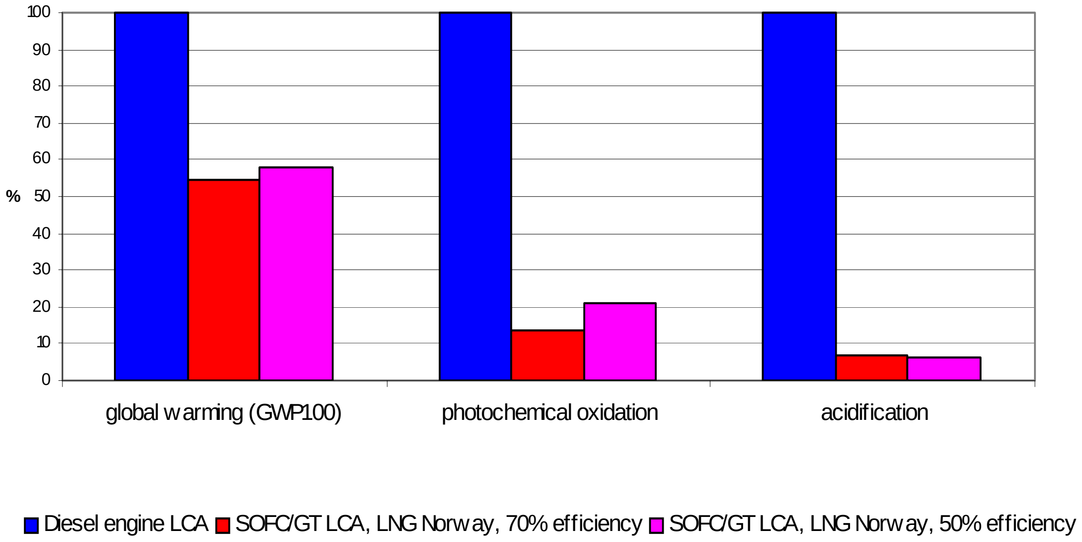

Figure 7-2: SOFC/GT efficiency

Table 7-2: SOFC/GT efficiency

Impact category	Unit	LCA, Diesel engine	LCA, SOFC/GT LNG via Norway, 70% efficiency	LCA, SOFC/GT, LNG via Norway, 50% efficiency
global warming (GWP100)	kg CO_2 eq. /kWh	0.725	0.394	0.42
photochemical oxidation	kg C_2H_4/kWh	3.38E-05	4.68E-06	7.06E-06
Acidification	kg SO_2 eq /kWh.	0.00124	8.15E-05	7.73E-05

A reduction in SOFC/GT efficiency from 70 to 50% results in a 6% higher contribution to the global warming and acidification category, while 33% higher for photochemical oxidation category relative to the contribution from the diesel engine.

The reasons for the increases in the emissions in the SOFC/GT operation phase are the higher fuel use as a result of the lower efficiency. More fuel is needed to produce the same amount of energy and higher emissions are connected with both fuel supply and operation for each unit of energy produced. Reduced efficiency makes a little difference in the over all comparing LCA, but the environmental performance of the SOFC/GT is still significant better.

7.3 Higher emissions from the diesel engine

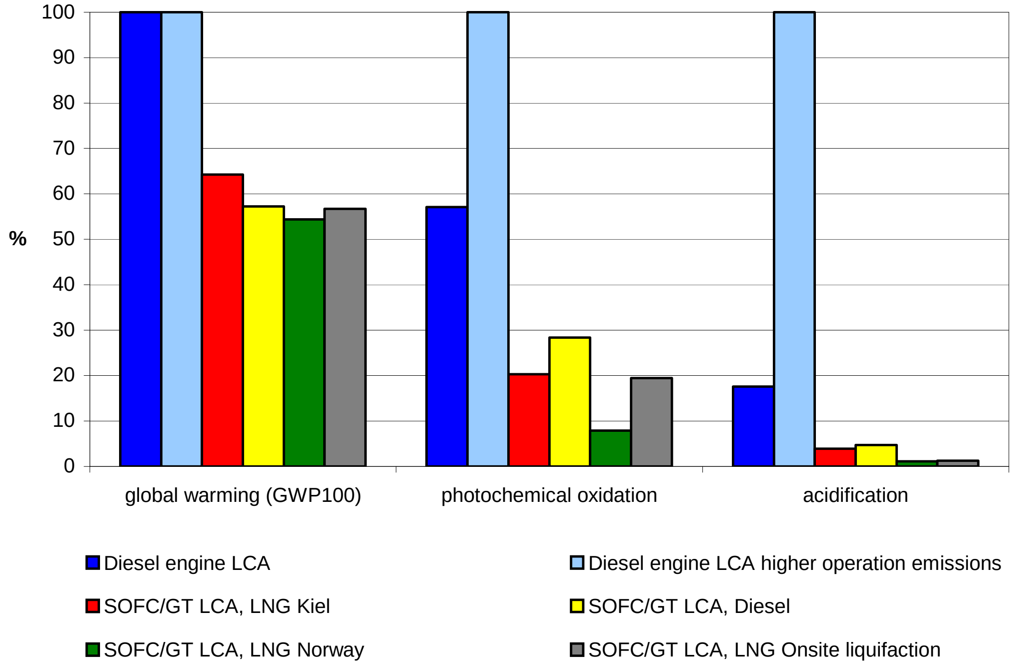

Figure 7-3: Higher emission diesel engine

Table 7-3: Higher emission diesel engine

Impact category	Unit	Diesel engine, LCA	Diesel engine, higher operation emission, LCA	SOFC/GT, Diesel, LCA	SOFC/GT, LNG via Kiel, LCA	SOFC/GT, LNG via Norway, LCA	SOFC/GT, Onsite liquifaction, LCA
global warming (GWP100)	kg CO_2 eq./kWh	0.725	0.725	0.466	0.415	0.394	0.411
photochemical oxidation	kg C_2H_4/kWh	3.38E-05	5.92E-05	1.20E-05	1.68E-05	4.68E-06	1.15E-05
acidification	kg SO_2 eq /kWh.	0.00124	0.00706	0.000276	0.000333	8.15E-05	8.83E-05

The LowNo$_x$ diesel engine, has both low contributions to the photochemical oxidation and acidification, by increasing the NO$_x$ emission factor and sulphur content in the fuel, from 0.2 to 1.5% which is a worst case, and increasing the CO emission three times, the emission profile for this two categories increased significantly, 45% for photochemical oxidation and about 80% for acidification. The global warming category remained the same. The configuration of the engine decides the NO$_x$ emissions, the emission is given from a engine producer for a bit larger engine, but in ten years it is likely that the emissions is so low for the size in this report as well. The sulphur content in the fuel is not very likely to be so high due to the EU regulations, but this analysis shows the sensibility for fuel type and engine configuration. This is a result of what was found in chapter 6.1; the operating phase has a major influence on all three categories.

7.4 Materials diesel engine

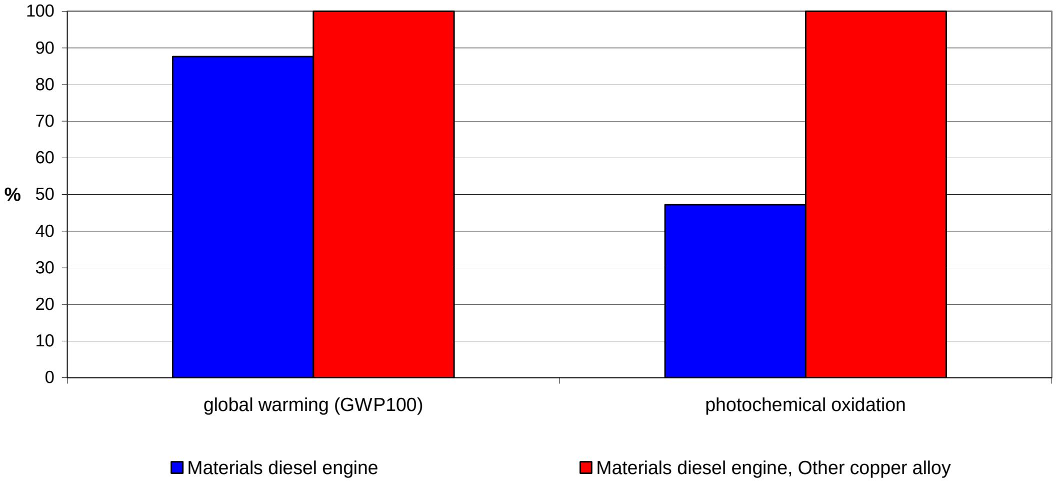

Figure 7-4: Materials diesel engine

Table 7-4: Materials diesel engine

Impact category	Unit	Materials diesel engine	Materials diesel engine, Other copper alloy
global warming (GWP100)	kg CO_2 eq. /kWh	3.05E+04	3.48E+04
photochemical oxidation	kg C_2H_4/kWh	68.9	146
acidification	kg SO_2 eq /kWh.	1.50E+03	3.43E+03

Some of the materials in the diesel engine system are casual average composition materials. In the assessment above the copper alloy which is the most important alloy, of environmental concern, in the production of the diesel engine system. The copper alloy, which is a part of the generator, is assumed to be CuZn40 in this study. In the sensitivity analysis this alloy is compared with CuAl5. The contribution from the different alloys is rather different and for photochemical oxidation the difference in the contribution to this category is over 50%. This is a rather big variance and the exact choice of materials seams to be important, though the manufacturing process is not so important in the over all LCA and the choice makes a small difference. This is showed in the figure below. The LCA for alternative alloy is presented in the second bar, the original LCA for the diesel engine in the first bar.

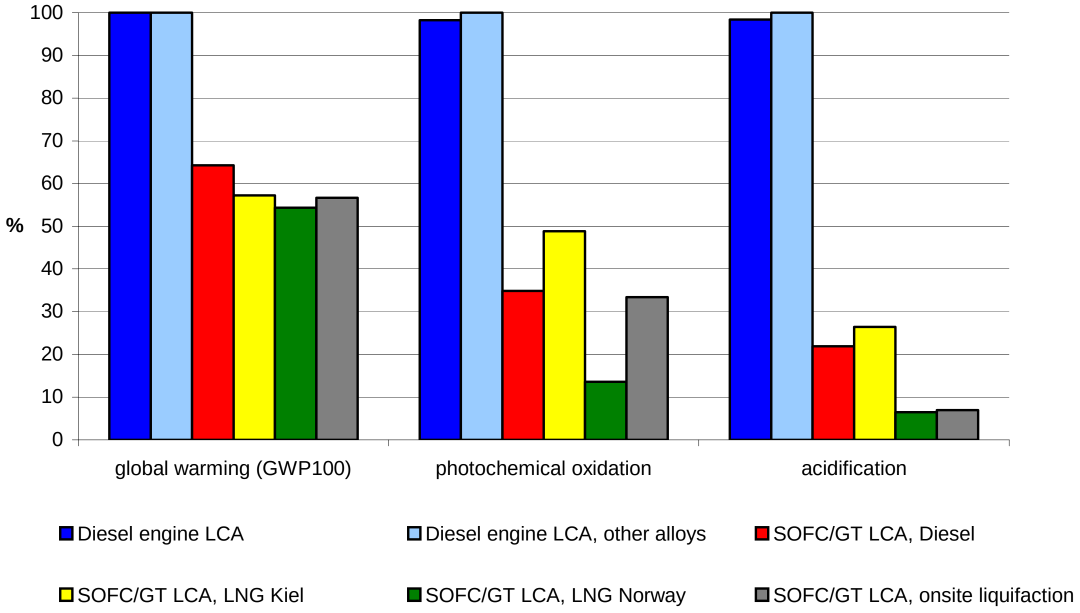

Figure 7-5: Comparative LCA, alternative materials diesel engine

8 LCC

8.1 Methodology

In a Life Cycle Cost (LCC) the cost-effectiveness of alternative investments or business decisions from the perspective of an economic decision maker such as a manufacturing firm or a consumer are compared, i.e. identifying the most cost efficient alternative so that the lowest long-term cost of ownership is achieved. /26/ LCC is usually performed on a private cost basis but it is also possible to perform a socio-economic LCC. In this project a simplified private cost analysis is performed.

Procurement costs are widely used as primary criteria for decisions for acquisition; it is easy to use but may result in bad financial decisions. The major cost lies in care and supplying the equipment during its life and the sum of operation, maintenance and disposal costs far exceed procurement costs /28/. LCC helps companies justify equipment and process selection based on total costs rather than initial purchasing price.

The methodology for Life cycle costing is standardized by the International organisation of standardization (ISO) in the ISO 15686 “Service life planning” series. Part five, ISO 15686-5; Life cycle costs (LCC), provides guidance on assessment of the life cycle cost for buildings. /31/

In a Life cycle costs analysis (LCC) total costs through the economical lifetime of products or projects is evaluated. LCC can be defined as “The sum of present values of investment costs, capital costs, energy costs, operating costs, maintenance costs and disposal costs over the lifetime of the project or product.” The output may be expressed in several ways, but the most used indicator is present worth (PW) or present value (PV). /27/

LCC consist of several costs and can be described as:

$$LCC = C_{ic} + C_{in} + C_e + C_o + C_m + C_s + C_{env} + C_d$$ **Equation 8-1**

C_{ic}- initial cost
C_{in} - installation cost
C_e - energy cost
C_o - operating cost
C_m - maintenance cost
C_s - downtime cost
C_{env} - environmental cost
C_d - decommissioning cost

All costs are described in more detail underneath. This approach is based on the approach found in Ravenmarks report /27/.

Initial cost

Initial cost is the purchasing price of the component/system. This cost may be paid immediately or in several down payments over more years.

If the price is paid immediately the initial cost is expressed as:

C_{ic} = purchasing price

If the cost is spread over several years, the cost is expressed in net present value (NPV):

$$C_{ic} = \sum_{i=0}^{N} \frac{C_i}{(1+rate)^i}$$ **Equation 8-2**

Where C_i is cost year i and rate is the interest rate

Installation cost
Startup costs that are not included in the purchasing price and is assumed to occur the first year of production, for example staff training costs.
C_{in} = Installation cost

Energy costs
Energy costs are the costs of energy supplied to the system during use, or energy consumption of the system.
C_e = energy costs
or

$$C_e = \sum_j E_j * EC_j$$ **Equation 8-3**

Where E_j is the yearly amount of type j used and EC_j is the cost of energy type j. i.e. yearly consumption of electricity, oil and gas. The cost of an energy type includes all costs, i.e. CO_2 taxes are included in the energy cost.

Operating costs
Yearly operating cost (excluding energy cost).

$C_o = NP*H_{py}*C_h$ **Equation 8-4**

Where NP is numbers of persons employed for operation, H_{py} is man-hours per year and H_h is man-hour cost.
If the studied system only needs a limited number of man-hours:

$C_o = NH_o*C_h$ **Equation 8-5**

Where NH is number of yearly man-hours needed for operation and C_h is the man-hour cost. NH_o or $NP*H_{py}$ is assumed to be constant over the operating time while C_h is assumed to increase with inflation.

Maintenance cost
The maintenance cost is costs of service and repairs and consist of man-hour and spare part costs.

$C_m = NH_m*C_h + C_{spare}$ **Equation 8-6**

Where NH_m is number of yearly man-hours needed for maintenance, C_h is man-hour cost and C_{spare} is the cost of spare parts. NH_m is assumed to be constant over time while C_h and C_{spare} are assumed to increase with inflation.

Downtime costs

Downtime costs are costs related to downtime, i.e. stops in operation.
C_s = downtime costs

$$C_s = SC*HC \qquad \textbf{Equation 8-7}$$

Where SC is hourly stop costs and HS is yearly hours of unplanned downtimes
If start-up costs (SuC) and number of stops are included (nS):

$$C_s = SC*HC*nS*SuC \qquad \textbf{Equation 8-8}$$

Environmental costs

Environmental costs, C_{env}, are complex costs, some difficult to estimate, and include:

- Potentially hidden costs.
    - Regulatory costs; costs connected to regulations. The magnitude of these costs may be difficult to determine as a result of that they are being pooled in overhead accounts. Examples on regulatory costs are reporting, studies/modelling and testing.
    - Up front costs, costs that are incurred prior to the operation of a process, system or facility. These can include costs related to siting (ex. site studies and site preparation) or design of environmentally preferable products (ex. engineering and procurement).
    - Voluntary (Beyond Compliance), voluntary environmental costs that lies close to image and relationship costs and are a result of the companies policy. Examples of such costs are Recycling, habitat and wetland protection and landscaping.
    - Back-End, environmental costs that will occur more or less well defined points in the future. Example; Closure/ decommissioning and site survey.
- Image and relationship costs. Costs that are incurred to subjective (though measurable) perceptions of management, customers, employees, communities and regulators. This category can include the costs of annual environmental activities (ex. tree planting). The costs them selves can easily be quantified the benefits often not. The aim of such costs are; corporate image, relationship with costumers and investors.
- Contingent costs. Examples include the cost remedying and compensating for future accidental releases of contaminants into the environment (i.e. oil spill), fines and penalties for future regulatory infractions and future costs due to unexpected consequences of permitted or intentional releases

Decommissioning costs

Decommissioning cost is an estimate of the cost to decommission a unit and can be expressed as a cost occurring at the end of the lifetime. The net present value of the decommissioning cost can be expressed as follows, where C^* is the cost in the end of the lifetime of N years:

$$C_d = \frac{C_d^*}{(1+rate)^N} \qquad \textbf{Equation 8-9}$$

Other approaches, as the “SAE model” /29/, classify the cost a little bit differently. The SAE model has five cost segments: Acquisition Cost (Includes initial and installation costs), Operating Cost (includes operation and energy costs), Scheduled Maintenance Cost, Unscheduled Maintenance cost (Down time costs) and Conversion/Decommissioning Cost. Some of the environmental costs are included different places in this approach. There is no standardized method for the performance; the importance is in including as many costs through the economical lifecycle as possible.

This LCC is based on a combination of Ravenmarks approach and the SAE model, but strongly simplified. Downtime costs, environmental costs and decommissioning costs are, due to the time scope of this project, not included in this study but will be briefly described qualitatively. Initial cost and installation costs are merged in C_{ic}, and only maintenance costs are included in operation and maintenance. One reason for letting out the operating cost is that it is assumed that about the same numbers of employees work with the main and auxiliary engines if it is a diesel engine or SOFC/GT system as auxiliary system. The fuel cell is assumed to need less maintenance than the diesel engine, this is reflected in the maintenance cost.
The simplified LCC will include costs as described under:

$$LCC = C_{ic} + C_e + C_o \qquad \textbf{Equation 8-10}$$

The Downtime costs, environmental costs and decommissioning costs are, as mentioned above, all let out of this LCC. Letting these cost factors out, may indeed influence the results.
Down time costs are directly related to reliability of the systems and is difficult to estimate, especially for the SOFC/GT system where long term, large scale experience lacks. An auxiliary system usually run part load, the SOFC/GT system runs well on part load while a diesel engine does not perform so well on such a load. This may lead to higher downtime costs for the diesel engine. However, a problem for the fuel cell is a gradually decline in performance due to contamination on the stack, this may lead to lover reliability in the end of the stack lifetime. Downtime costs may be crucial for the choice of system, because it may cause huge costs to the shipping company. Eventually better reliability may be an important quality for the fuel cell system, but will not be evaluated in this project.
The environmental costs are very difficult and complex to evaluate, and they are, due to the time scope of this project not included. There may however be significant differences between the systems because of the much better environmental performance of the SOFC/GT.
The end of life scenarios for the two systems are not known for both systems. While diesel engines often are reused after scrapping what will happen with the fuel cell systems is not known because of lack of large scale experiences. Decommission costs are assumed to be very low compared to the other costs of the system, are not included in the LCA, and will therefore not be included in the LCC.

8.2 Scope

The process scope of LCC includes only those processes imposing direct economic costs or benefits upon decision maker. I.e. The salvage value of a computer is subtracted from the life cycle cost of the computer, the sum of the purchase price, a pair of replacement batteries and electricity used during its lifetime. Costs that are expected to be equivalent among alternatives may be omitted, i.e. for the computer this may be software and customer support. The danger omitting equivalent costs is a distorted view of the differences in the two systems, small differences total may look huge when letting all or some data out, this illustrated in the figures below.

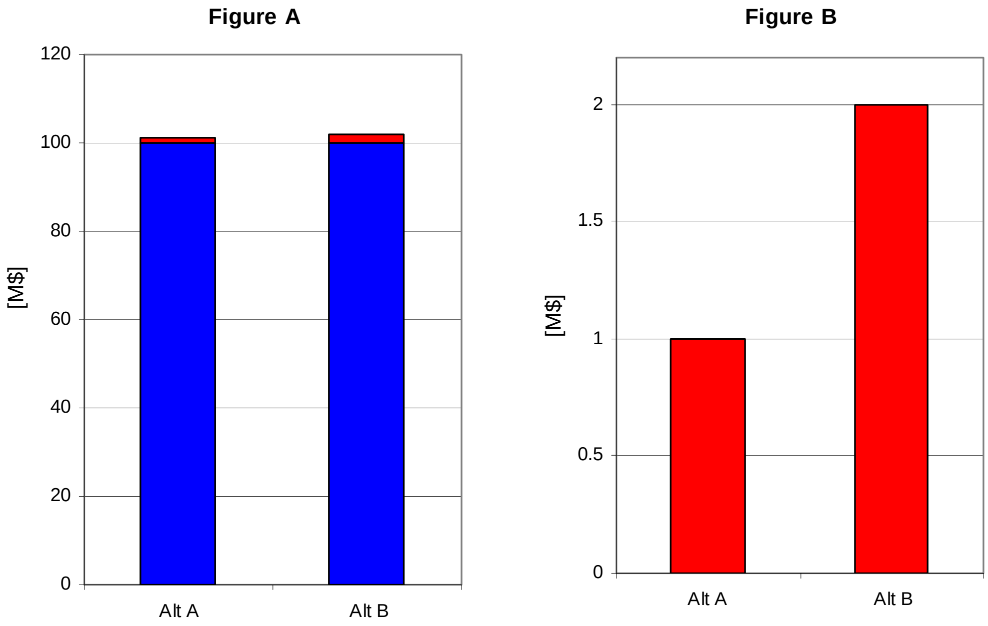

Figure 8-1: Figure A (left) and figure B (right)

Figure A shows the situation where two life stages are taken into account, the red part of the bar may represent the purchasing price while the blue may represent the usage stage. In Figure B only the purchasing stages are taken into account. Figure A indicates that it is a nearly insignificant difference in price, less than 1%, for the two alternatives. In Figure B the use phase is omitted, and the price difference for the two alternatives is then 50%. This example shows that by omitting life stages decisions may be taken on the wrong basis

The scope of this study is to create a rough estimation of the cost differences between a fuel cell and a diesel engine auxiliary system. Only investment costs, maintenance costs and energy costs are included. The lack of other categories may influence the results but the results should, when treated carefully, be sufficient to draw a rough picture of the cost situation.

The costs are calculated as equal annual cost (EAC)/50/, that means that no inflation are accounted for and that the costs are equal distributed over the lifetime.

8.3 Uncertainty

Usually the procurement cost, or initial cost, is the only well known and clearly identified cost in a systems lifetime, but it's only the tip of the iceberg, and the other costs are important to include giving a more holistic economical picture. As with all cost techniques and all engineering tools there are limitations connected with LCC/29/:

- LCC is not an exact science. The method is based on estimates and the same system may result in different answers depending on the performer of the analysis. A producer and a consumer may come up with rather different results. There are no wrong and right results only reasonable and unreasonable.
- The accuracy depends on the accuracy of the inputs, estimates, which are the base of LCC studies, lack accuracy, and so do the LCC.
- LCC results are not good budgeting tools. They are effective only as comparison/ trade-off tools.
- LCC should be an integral part of the design and support process to design the lowest long term cost of ownership.

This LCC omits several cost steps and the data quality may be poor, mainly because the SOFC/GT technology is not commercialised but also problems with gathering information around the mature diesel engine technology. The largest uncertainty is connected with the fuel cell, because of the state of fuel cell development there have been few long-term demonstrations, which results in a lack of actually cost data from marine fuel cell application.
Since it is not yet commercialised even the initial cost is imprecise. It is based on assumptions from the producers and some may be a little to optimistic. The maintenance and reliability of the system still needs to be proven in a large-scale, long-term demonstration and the production costs will be reduced with increased production volumes, possible different configurations and better production methods.
There are also significant uncertainties connected with the fuel price market development. Fluctuations in the oil market influences the oil based fuel prices, and do also have some influence on the LNG prices.

9 Cost

In this chapter the costs in the different life stages of the auxiliary systems will be discussed. As described in chapter 8.1 all costs are calculated as equal average costs (EAC).

9.1 Exchange rates

The costs for the auxiliary systems are gathered in different currencies but are all changed into US dollars. It is very difficult to make any estimation of the development of the exchange rates between the different monetary units in the next decade. The exchange rates used in this LCC are therefore based on the exchange rates in January 2005.

Table 9-1: Exchange rates 21.01.2003

USD ($)	EUR (€)	ATS (schilling)	NOK
1	0.737	10.21	6.3

9.2 Investment cost

Cost is likely to be a major barrier to the widespread development of fuel cells. One of the main challenges for the developers of fuel cells is to reach feasible technical solutions that are not to expensive. A prediction is that it can take 40-50 years before the technology are fully commercialised due to their high price. /32/

Because the fuel cell technology is on an early development stage, and not yet large scale commercialised, it should have a potential for price drop in the next decades, while the diesel engine technology, which are a mature technology, probably will remain at the current price level. The case studied is an auxiliary system in the next decade, and estimations of the prices will of this reason be decided of assumptions of the price development the next decade.

9.2.1 Investment cost diesel engine

The diesel engine investment cost is a result of negotiations between buyer and supplier of the engines, of this reason there is, even if this is a mature technology, no exact market price available. Karni et al. reported that the investment cost for conventional propulsion diesel engines would typically be about 2000$/kW, or about 2mill$ for a 1000kW diesel engine. Color Line estimates 4.5millNOK, or 0.7mill$, for a 1000kW engine with ancillary systems. This price includes the engines, fire-extinguishing system, air-, ventilation- and cooling system and the installation. Because of the maturity of the diesel engine technology the price level will most likely be the same in the next decade and the, first hand; Color Line numbers are the numbers that will be used in this LCC. The engine cost is presented in the table below.

Table 9-2: Investment cost diesel engine /36/

Initial cost	Value	Valuta
Engine	1300000	NOK
Installation	1000000	NOK
Cooling system	700000	NOK
Air/ ventilation	1000000	NOK
Fire-extinguishing	500000	NOK
Total system (3 eng)	13500000	NOK
Total system (3 eng)	2142857	$*

*USD($)/NOK 6.5

9.2.2 Investment cost fuel cell and micro gas turbine

Investment costs using state-of-the-art fuel cell technology are typically estimated to 4000-7000$/kW /32, 33/, while some predicted prices ranges from 1000-1500$/kW /34/. Karni et al/13/ have performed a detailed LCC analysis comparing fuel cell systems with diesel engines. In this LCC they reported that the investment cost for conventional diesel engines would typically be about 2000$/kW, integrated diesel electric engines 4500$/kW and fuel cell about 6700$/kW. California Energy commission /38/ reports that the only fuel cell product available commercially today is the PureCell 200 (formerly PC-25)™ built by UTC Power. The cost of the unit is approximately 4000$/kW. The installed cost of the unit approaches 1.1mill$. At a rated output of 200kW, this translates to about 5500$/kW, installed. Like most new technologies, as more units are installed and new players join the market, prices are likely to fall. Price projections vary among fuel cell developers, but most are targeting costs below 1500$/kW based on volume production, according to California Energy commission. /38/

The variation in cost estimates mainly reflects that reliable estimates cannot be obtained at the current stage of development. In this LCC it is assumed that the fuel cell price will be 4500$/kW, including installation, in the next decade, which is the time scope of the analysis. This may be a rather optimistic assumption in the near future. An usual service time estimation is 40000 full load hours and such a lifetime target is reached most easily fuelled on natural gas /32, 35/, this may however be a rather too optimistic assumption and the assumption in this project is that the fuel cell may have to be replaced every 20000 full load hours, or about every 3.5 years of service /44/. Stack replacement cost must be accounted for along with the maintenance requirements, but most of the fuel power system can probably live as long as other engines, typically 20-30 years /32/. The fuel cell power system is therefore estimated to live 30 years, which is the lifetime of the passenger ferry and the diesel engine, and the stack replacement is included in the maintenance cost.

Simander and Hasslacher /39/ reports the investment costs for a conventional 100kW$_{el}$ micro gas turbine to be approximately 10000ATS/kW or 900$/kW. (Exchange rate; ATS/$: 10.21) The size of the micro gas turbine in the case auxiliary system is 125kW and the price is assumed to be approximately the same as for a 100kW turbine. The cost numbers are from 2001, no estimates are found about predicted price in the next decade. The technology is under development, which may indicate potentially lower prices, however this is an uncertain assumption. The 2001 value is used in the LCC, this represent a slightly higher cost to day, 2005, and then a potential slightly price reduction.

The Investment costs, for fuel cell, gas turbine and diesel engine per kW, are shown in the table below.

Table 9-3: Investment costs Diesel engine and SOFC/GT.

Type	Best estimate ($/kW)
Diesel engine	700[1)]
Fuel cell	4500[2)]
Micro gas turbine	900[3)]

[1)] Color Line /36/ [2)] Kari et al /33/ [3)] Simander, Hasslacher/39/

9.3 Operating cost

According to Sødal/32/ the main cost advantage of fuel cell lies in a potential for lower operating costs. Fuel cells are energy efficient, this because their electric power is produced directly from a chemical reaction with no mechanical losses. While the efficiency of a combustion engine typically ranges between 25-45% the fuel cell has an efficiency of 40-60%, in combination with a gas turbine even higher. In this case study the over all electric efficiency for the SOFC/GT system is 70% and for the diesel engine 42%. Low fuel consumption per energy unit makes the operating cost low, but it obviously depends on the fuel choice.

9.3.1 Fuel selection and cost

The fuel alternatives selected for the application of SOFC/GT onboard the Case Ship are /5/:

- Liquefied Natural Gas (LNG)
  - Imported from outside Europe
  - Liquefied onsite
  - Produced in Norway
- Sulphur free car diesel

As a result of the EU Sulphur Directive it is uncertainties connected with future fuel selection for ships operating in Europe. The fuel choice for the diesel engine depends on the sulphur content, price and reliability of the fuel oil.

The proposed amendments to the EU Sulphur Directive 99/32/EC /17/ regarding the sulphur content of marine fuels include limitations on sulphur content on fuels in EU SOx controlled areas and at berth in EU ports. For passenger vessels on regular service to or from ports in the EU the maximum allowed sulphur content on any fuel used on board is 1.5%, whilst at berth in EU ports the maximum sulphur content is 0.2%. This limit may be lowered to 0.1% from 2008, but the feasibility of this requirement is debated due to fuel instability and safety of operation.

To fulfil the amendments to the EU Sulphur Directive the shipping industry has to make some changes in the fuel use. For the auxiliary engines, the new directive requires that the engines have to run on low sulphur fuels in the berth areas within the EU. Solutions to meet these requirements are to run the engines on low sulphur heavy fuel oil, marine gas oil or on regular heavy fuel with scrubbing of the exhaust gasses. Another solution is changeover, where the engine changes between different fuels in different geographical areas, like this the vessel can run on 0.2% sulphur in the berth areas and 1.5% sulphur at sea.

The vessel in this study travels the distance from Oslo to Kiel and back, spending a significant amount of time at berth, and with only in the order of 16 hours at sea each way. This operating profile does not fit changeover. Flushing of the fuel system, ensuring that the fuel used in the engine at the time the vessel is considered "at berth" may take considerably longer than this, dependent on the fuel system arrangement. Switching between such different grades of fuels also raises demand for changes in lubricating oil requirements, and operation of the engines. /43/

It is therefore anticipated that the vessel will utilise fuel with less than 0.2% sulphur for the auxiliary engines, both at berth and at sea or that scrubbers are installed. The main engines, which are outside the scope of this study, may use fuel with sulphur content up to 1.5%.

Fuel prices and supply may be crucial for the fuel selection. Forecasting prices on fuel is difficult and extremely uncertain and depends on the crude oil prices and the volumes refined. To day a conservative high price estimation is a crude oil price of about 35$/barrel in the near future with an annual increase in price of approximately 1.5% /42/. These numbers are highly insecure and the uncertainty in oil price estimations is illustrated in the figure below. The figure shows crude oil forecasts from 1980-1995, all are over-optimistic. /40/

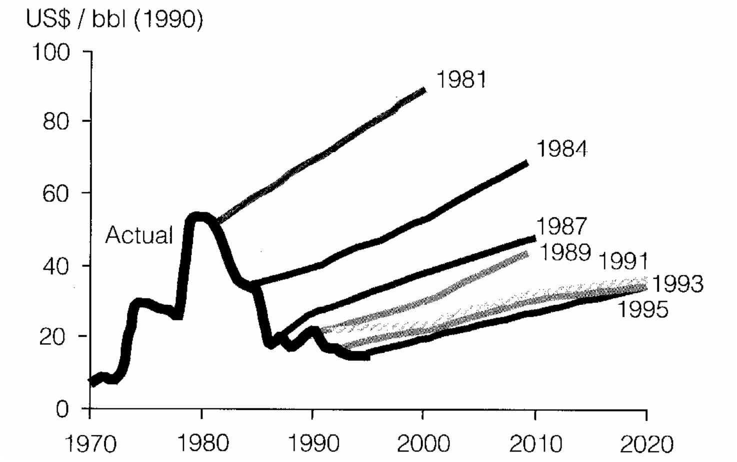

Figure 8-1: Crude oil price forecasts /40/

9.3.2 *Fuel oil prices*

The prices on heavy fuel oil (HFO) increases with the decrease in sulphur content in the fuel, 3rd of December 2004 the prices for HFO with sulphur content of 3.5 and 0.5-0.7 were 130 and 190$/t respectively /41/. Fuels with even lower sulphur content will be even more expensive. The prices on both heavy oil and low sulphur fuel is expected to increase with 25-200$ in the next ten years /42/.

The cost of marine gas oil were 400$/t 3rd of December 2004 /41/, this price may drop in the future as result of increased demand and production. To use marine gas oil the engines will have to be adjusted to fit this fuel /42/.

Low sulphur fuel oil is the cheaper of the two sulphur poor fuels, if just the fuel price is taken into account. Though, the demand for Low Sulphur fuel oil is high, and there is a danger that the demand will exceed the supply if the shipping industry increases the use of this fuel. The fuel supply is mostly based on long term contracts. The ground-based industry and power industry are willing to pay more than the shipping industry and a cold winter, for example, may result in scarcity of fuel for the shipping industry. There are though also indications that the industry will base more of its energy use on natural gas, scarcity in Low sulphur fuel oil may then not occur. The production of Marine gas oil has to increase a lot to cover an increased demand, this will probably also lead to lower costs for this fuel /42/.
In the next decades, however, low sulphur fuel oil may seem to be the cheapest alternative.

An alternative to the low sulphur fuels is to run the engines on heavy fuel oil and install scrubbing witch almost remove all sulphur emission. There are though some problems connected with the conventional sea water scrubbing technology /42/, some of them listed underneath.

- A negative environmental result of scrubber is sludge produced in the cleaning process (50-100kg for the main engines of a large vessel), this will have to be cleaned before it is released in to the sea which may result in a polluted berth area
- There are space considerations in the engine room and more specifically the funnel. Although it has been indicated that the more advanced scrubber types can replace standard silencers, the associated piping systems may represent a challenge. Pressure drop in scrubbers has also been indicated as a limitation, particular in way of main engines uptakes.
- Tanker owners have had mixed experiences with corrosion of inert gas scrubbers and associated piping systems.

Unfortunately, the number of development projects related to new scrubber technology appears to be limited. However, some projects currently in the prototype phase show promising results in terms of overcoming the above-indicated constraints. It should also be taken into account that exhaust gas cleaning alternatives will reduce the emission of particulate matter (PM). Particulate matter is considered to be on of the next focal points of IMO and this increases the future relevance of exhaust gas cleaning systems /42/. Installing a scrubber a shipping company will be ahead of the regulative authorities.

Despite the indicated installation costs of 1-2mill$, future legislation and elimination of the problems associated with low sulphur fuel bunker management and operation, may lead to exhaust gas cleaning systems becoming a cost-beneficial alternative worthwhile exploring /42/.

There is a lot of uncertainty connected to the selection of fuel the next decades, neither prices nor supply amount are known and there are some problems in connection with the conventional scrubbing technology. In this study, Low sulphur fuel with sulphur content of 0.2% is chosen as fuel for the diesel engine. This is the cheapest low sulphur alternative and no scrubber is needed to satisfy the EU sulphur-regulations.

9.3.3 LSFO prices

In Altman et al's report/30/ the heavy fuel oil prices were estimated to range between 50 and 90€/t. Altman operates with a price difference between heavy fuel oil and low sulphur fuel oil of 145€/t, this lead to a total price for low sulphur fuel oil of about 195–235€/t (265-318$/t) or

0.017-0.021€/kWh. Statistics from the International Energy agency shows an average Low sulphur industry fuel price in Europe of approximately 250$/t, and almost 280$/t in the end of the year. It is difficult to predict fuel prices in the future; they depend on the oil price and the amount refined. The Heavy fuel oil prices in December 2004 were 130$/t or 95€/t, which will represent a low sulphur fuel oil price of approximately 325$/t using 145€/t as difference between the two fuels. This calculated price is higher than the European low sulphur fuel price given by International energy agency, though the low sulphur fuel oil for Japan were even higher than this, so there are price differences between the areas. The conservative high price increase estimation of annual increase in price of approximately 1.5% /42/ indicates that also the low sulphur fuel oil price will increase with approximately 1.5% annual. The International energy agency expects an oil price fall in the near future and then an annual increase in price. It is, however, difficult to know when and if there will be, or how big the price drops will be and the annual increase after this potential drop. The price is therefore based on an over middle price in 2004, which may be a feasible price, with expected price drop and then increase. The low sulphur fuel oil price is assumed to be approximately 265$/t; which is, like calculated in the beginning of this paragraph, approximately 0.023$/kWh (0.017€/kWh). /30/

9.3.4 Sulphur free diesel prices

Altman operates with 0.25€/l or 0,025€/kWh (0.033$/kWh) for car diesel (S<10ppm) in his report/30/, this is based on a crude oil price between 20 and 25$/bbl. IEA reports a diesel price 0.6 and 1.1$/l in Europe in 2004, which means between 0.06 and 0.11$/kWh. To day the crude oil price is approximately 45$/bbl, the OPEC target, 22.00-28.00$, is far below this value. Price has been above old target range since December 2nd 2003. It is difficult to estimate a crude oil price with such an oscillating market price. A conservative estimate is 35$/bbl /42/ in the nearest years, the sulphur free diesel price is based on this assumption in this study. 35$/bbl, this means approximately 0.33€/l for sulphur free diesel or 0,033€/kWh. In US$ terms this is 0.044$/kWh.

Table 9-4: Prices Crude oil based fuels

Fuel	Cost
LSFO	0.023 $\$/kWh_{fuel}$.
Sulphurfree diesel	0.044 $\$/kWh_{fuel}$

9.3.5 Gas prices

Because of high long distances transportation costs for gas, natural gas markets are, unlike oil, highly regionalised. Prices often diverge substantially across and within nations. Never less, regional prices usually move broadly in parallel with each other because of their link to the international oil price. Historically, Asian gas price has been the highest, American gas prices the lowest and European in between. The last years, however there has been a rise in the gas price in all three regions, American gas prices have risen significantly and have exceeded both European and Asian prices. The International Energy Agency /45/ assumes the gas prices to fall back in all three regions in 2006, and then rise steadily from 2010 in line with oil prices. European gas prices are assumed to rice slightly relative to oil prices, and regional prices are expected to converge to some degree over the next decades as increased spot trading of LNG allows arbitrage between markets. The linkage between Natural Gas prices and Oil prices are expected to be about 0.8 for Europe. /45/

European LNG prices are assumed to fall back to 3.30$/MBtu in the end of this decade and then rise gradually to 4.30$/MBtu in 2030, which means 0.05 $ annual. This study is based on a system 5-10 years form now, or 2010-2015, with expected LNG price between 3.30-3.55$/MBtu. /45/. In this study the LNG price is set to 3.50$/MBtu. This means a market price for LNG ex import terminal of 0.012$/kWh /30/.

The fuel supply cost for the three SOFC/GT LNG alternatives are presented under, please refer to Altman et al /30/ for more details. Altman operates with a long-term 1/1 exchange rate between USD and Euro. The fuel prices is given in dollar and transformed to Euro, using this 1/1 relationship, while the investment costs are given in Euro. A result of this is lower fuel prices than calculations with to days and expected future exchange rate development. The investment and transportations costs are given in Euros in Altman report, and will be relatively higher when converted into dollar. The exchange rates are moving rapidly, this report uses an exchange rate of 1/0.737$/€.

9.3.6 Costs LNG fuel supply to Kiel

For the fuel supply to Kiel it is assumed that the natural gas is extracted and processed in a remote location. Natural gas is then piped to a liquefaction plant nearby the production site, and transported as LNG by ship 5000-6000 nautical miles to Zeebrugge, Belgium, and by truck 800km to Kiel, were it is stored. The vessel is refuelled by truck from the quay. /5, 30/

The international Energy agency (IEA) expects the market price of LNG in 10 years, exclusive import terminal, to be approximately 3.50$/MMBtu, or 0.012$/kWh /30/. The transportation to the ferry has to be added to the price. Altman et al /30/ has calculated the transportation cost to 0.0092€/kWh$_{el}$, or 0.013$/kWh$_{el}$. The total price for LNG fuelled in Kiel is then 0.025$/kWh.

9.3.7 Costs LNG fuel supply Norway

For fuel supply in Norway (Oslo) natural gas is extracted offshore in the North Sea and piped to shore where it is liquefied using electricity from CCGTs on site. It is then transported 300km by truck to a depot in the port area. It is delivered to the vessel by truck, each truck carrying 19t of LNG /5, 30/. Altman et al /30/ has calculated the costs of Natural Gas (NG) extraction, NG liquefaction, LNG transport from Karmøy to depot at the port in Oslo (300km) and from depot to ferry (10km). The total cost for LNG to Oslo is 0.025$/kWh.

9.3.8 LNG from onsite NG liquefaction

For onsite liquefaction it is assumed that the natural gas is liquefied where the ferry is refuelled. As natural gas is not available in Oslo it is assumed to be located in Kiel and the ferry is refuelled from the quay in Kiel. It is assumed that natural gas is transported via pipelines to Kiel. For compensation of pressure drop every 150 to 250km, compression is required. The compressors are powered by natural gas fuelled gas turbines. The LNG price for onsite liquefaction includes NG cost, liquefaction plant costs and LNG transportation cost from plant to ferry. Altman et al. calculates the onsite liquefaction LNG price to be 0.053$.

Table 9-5: LNG cost SOFC/GT

Fuel	Cost
LNG, Kiel	0.025\$/kWh$_{LNG}$.
LNG Norway	0.025\$/kWh$_{LNG}$
LNG Onsite liquefaction	0.053\$/kWh$_{LNG}$

9.4 Maintenance cost

Because a fuel cell has no moving parts, maintenance cost will be low compared to conventional engines. For diesel engines the maintenance cost will vary with the type of engine (speed/ numbers of cylinders), fuel type and quality and the age of the engine. New engines may have a interval for main maintenance of 30000h and the maintenance cost the first years will then be minimal. Depending on the fuel quality, type of separator for fuel- and lubrication oil, the maintenance interval and costs may be twice as big/small /37/.

Karni et al./33/ reported 7$/h, or 0.05$/kWh, of operations in maintenance costs of molten carbonate fuel cell, while 9-18$/h, or 0.06-0.013$/kWh, for diesel engines. However, for the fuel cell, stack replacement is a major expense, estimated to 300-320$/kW. The replacement cost in Karni (2004) is based on discussion with Fuel Cell Energy, Inc. (FCE), formerly Energy Research Corporation (ERC) /33/. This LCC bases the stack replacement cost on the average value in this cost interval, 310$/kW.
It is of importance to recognize that it is a lack of actually cost data from marine fuel cell application, and there are indeed uncertainties connected with this numbers.

Fuel cells are expected to have minimum maintenance requirements. The fuel supply systems and reformer system may need periodic (about once a year) inspection and maintenance. The cell stack itself will not require maintenance until the end of its service life. The maintenance and reliability of the system still needs to be proven in a large-scale, long-term demonstration.
Maintenance costs of a fuel cell are, according to California Energy commission (CEC) /38/, expected to be comparable to that of a microturbine, ranging from 0.005-0.010$/kWh (based on an annual inspection visit to the unit).
Simander and Hasslacher report 1.0–1.10€-cent/kWh in maintenance cost for a micro gas turbine, which is 1.35-1.5$-cent/kWh, or 0.0135-0.015$/kWh.

Budget numbers for a ship with five 36 cylinders diesel generators is, according Iversen/37/, varying from 45000-90000$ annual (depending on the age of the ship) running 4200h annual per engine. For a 1000kW engine this means 1-3.6$/h, or 3-10.8$/h for all three engines.

Table 9-6: Maintenance cost Diesel engine, Fuel cell and Micro gas turbine

Diesel engine	Fuel cell	Micro gas turbine	Reference
0.006-0.013\$	0.005\$		Karni et al./33/
	0.005-0.01\$	0.005-0.01\$	CEC/38/
0.0021-0.0075\$			Iversen/37/
		0.0135-0.015\$	Simander/ Hasslacher/39/

The different references operate with rather similar values. In this LCC the Diesel engine maintenance cost is assumed to be to 0.0075$/kWh, this value is in the middle of the two intervals given in by Iversen and Karni. The SOFC GT maintenance cost is based on Karni et al’s value, assumed to be 0.005$/kWh, this is also the lower value given by CEC. The gas turbine maintenance cost is set to be the same as for the fuel cell 0.005$/kWh. The overall maintenance cost for the SOFC/GT system is therefore 0.005$/kWh.

The stack replacement cost are treated separated from the other maintenance cost, as an own post in the economic analysis. This to illustrate the importance of this cost, and a result of that the future solution of stack replacement when the system is commercialized is still not known. A leasing system for the stacks, where they are replaced after their service life, and parts that can be reused are overhauled, may be a good solution and may probably reduce the replacement cost.

9.5 *Emission trading*

For the SOFC/GT system potential income is also expected from emission trading, according to very low emissions. However, the potential incomes depend on emission component considered and the area of operation, as well as time horizon/46/. The reduction of ship SO_x, NO_x and PM emissions are high on the agenda (EU, 2002; EPA, 2003a,b; IMO, 2002). Beside this, economic instruments have been introduced in some countries and ports around the world to encourage ships to reduce their atmospheric emissions. These include differential taxes on marine fuels, differentiated port and fairway dues, and differentiated tonnage taxes.

9.6 *Cost/functional unit*

The costs are calculated per functional unit, as average annual cost divided on yearly electricity production (Equal annual cost). Average yearly production for the auxiliary system is the production of two 1080kW diesel engines running 70% in average. A 1080kW diesel engine gives a 1025kW electric output which results in 12’570’600kWh annual electricity production. The fuel cell serves the same system and therefore has to produce the same amount of energy.

10 LCC results

The life cycle cost for the diesel engine and SOFC/GT alternatives per kWh is presented in the graph and table below.

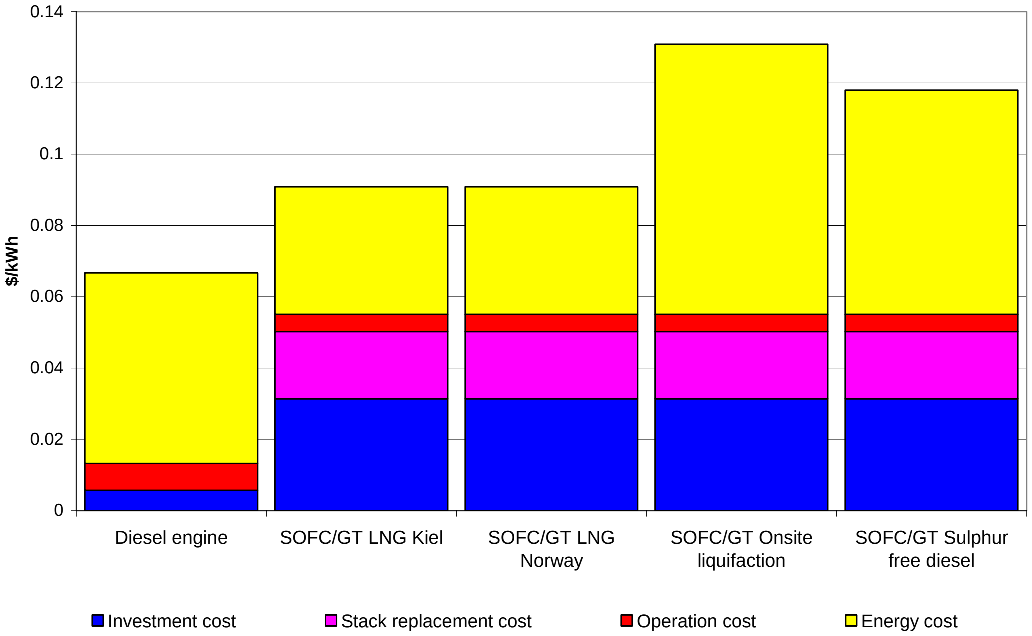

Figure 10-1: LCC results $/kWh for Diesel engine and SOFC/GT

Table 10-1: Life Cycle Cost

Cost [$/kWh]	Diesel engine	SOFC/GT LNG Kiel	SOFC/GT LNG Norway	SOFC/GT Onsite liquifaction	SOFC/GT Sulphur free diesel
Investment cost	0.0057	0.0313	0.0313	0.0313	0.0313
Stack replacement cost	-	0.0189	0.0189	0.0189	0.0189
Operation cost	0.0075	0.0049	0.0049	0.0049	0.0049
Energy cost	0.0535	0.0357	0.0357	0.0757	0.0629
Total cost	0.0667	0.0908	0.0908	0.1308	0.1180

Using the cost numbers discussed earlier the diesel engine is the over all cheapest alternative as a result of lower investment and operation/maintenance cost. The diesel engine cost is approximately 25% lower than the two cheapest SOFC/GT alternatives. The potential for lower energy and operating costs is assumed to be the main cost advantage of fuel cells. As can be seen in the figure the general operating costs for the SOFC/GT systems are smaller than the diesel engine costs. Stack replacement is, however, a major extra expense that also has to be included in the operating cost this makes the over all operating cost 70% higher for the SOFC/GT system than for the diesel engine. Stack replacement is illustrated as an own item in the table and figure to illustrate the economical consequences of the replacement. With an electricity efficiency of 43%, which is rather high to be a diesel engine, the fuel use for the diesel engine is much higher than for the combined fuel cell gas turbine system which has an electric efficiency of 70%. The diesel engine runs on Low sulphur heavy fuel oil (LSFO), which is the cheapest fuel alternative in this LCC, this makes, despite lower efficiency, the energy use 15-30% cheaper than the SOFC/GT systems. The LNG from Norway and import (Kiel), are assumed to cost 0.025$/kWh, while LSFO cost 0.023$/kWh, which does not make a big difference in price. The energy cost is as a result of this approximately 33% lower for the SOFC/GT systems fuelled on LNG from Norway and import. The differences in energy cost are illustrated in the figure below.

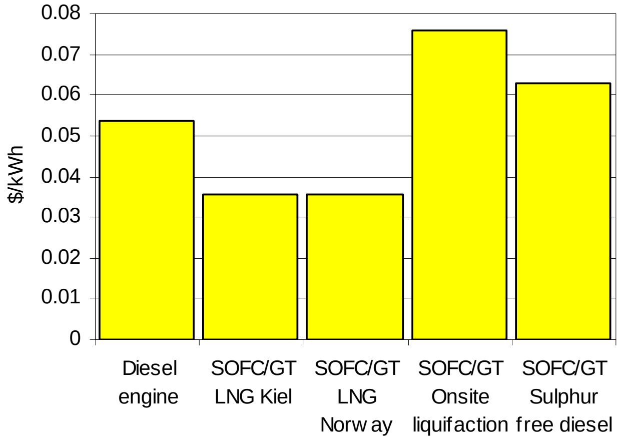

Figure 10-2: Energy cost

Running on fuels of approximately the same cost, the fuel cell has a much lower energy cost than the diesel engine.
The high purchasing price of the SOFC/GT system and short stack lifetime makes the fuel cell life cycle cost, excluded energy cost, approximately 75% higher than the diesel engine. This is illustrated in the figure below.

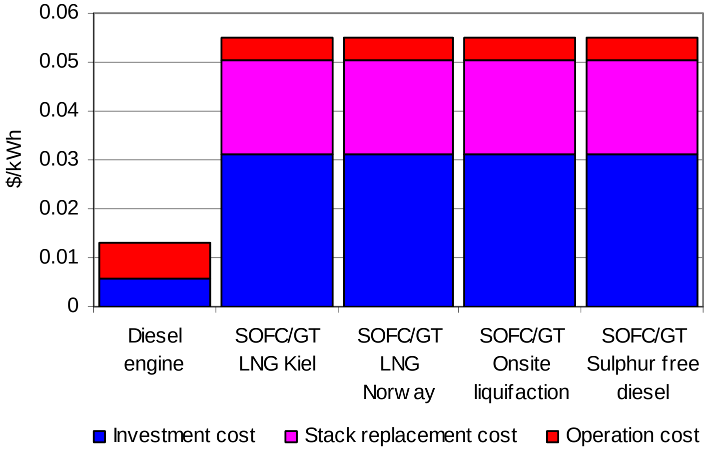

Figure 10-3: Investment and operation cost

There are indeed huge uncertainty connected with the numbers used in this analysis, and indeed for the fuel cell prices, but it gives a signal that the fuel cell purchasing price has to be lowered a lot to be competitive with the conventional system. It therefore seams like the greatest challenge for the fuel cell developers will be to make technical good solutions to a much lower cost.

11 Cost Sensitivity analysis

Five sensitivity scenarios were performed to evaluate some of the uncertain parameters in the study. A scenario for lower fuel cell price, double lifetime of the stack scenario, a scenario using the fuel costs calculated by Altman et al., a more expensive diesel engine scenario and a scenario for higher maintenance cost for the diesel engine.

11.1 Lower Fuel cell price

Some fuel cell producers expect the prices too fall too 1000-1500$/kW. This is a very optimistic exception. If these prices are reached however, this will make the SOFC/GT system compatible with the diesel engine. For 1500$/kW, the Life cycle cost of the cheapest SOFC/GT alternatives were about 6% higher than the diesel engine, while with 1000$/kWh the life cycle cost were about equal. The 1000$/kW fuel cell scenario is presented in the figure and table below. It is worth noticing that the stack replacement cost is kept the same, lower fuel cell system prices will probably also lead to lower replacement prices, but they are held equal in this sensitivity analysis.

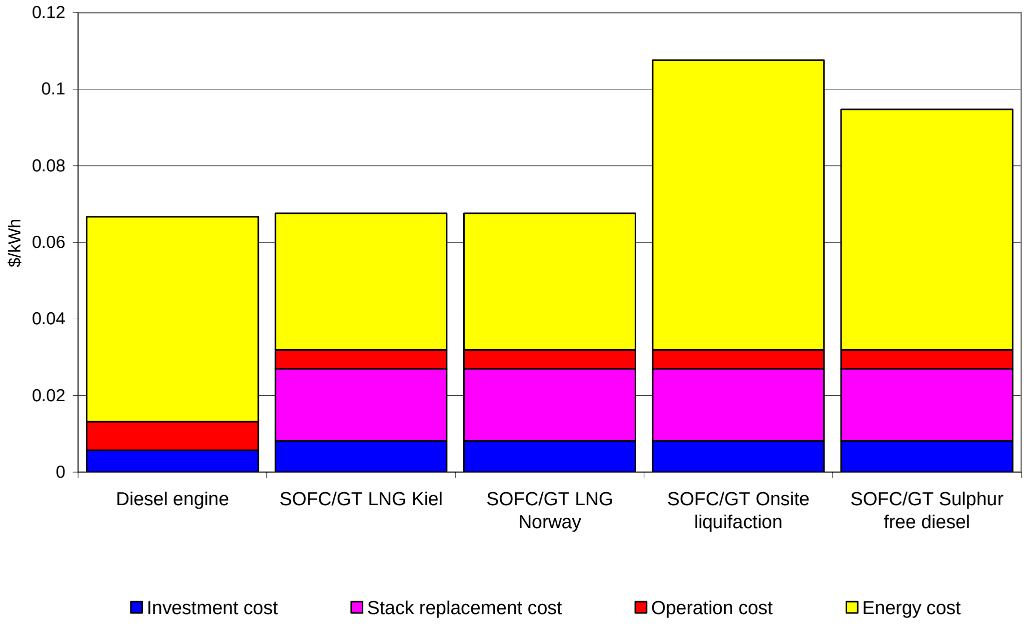

Figure 11-1: LCC results $/kWh for Diesel engine and SOFC/GT lower fuel cell price

Table 11-1: LCC lower fuel cell price

Cost [$/kWh]	Diesel engine	SOFC/GT LNG Kiel	SOFC/GT LNG Norway	SOFC/GT Onsite liquifaction	SOFC/GT Sulphur free diesel
Investment cost	0.0057	0.0081	0.0081	0.0081	0.0081
Stack replacement cost	-	0.0189	0.0189	0.0189	0.0189
Operation cost	0.0075	0.0049	0.0049	0.0049	0.0049
Energy cost	0.0535	0.0357	0.0357	0.0757	0.0629
Total cost	0.0667	0.0676	0.0676	0.1076	0.0948

When the fuel cell price reaches 1000$/kW the fuel cell has equal life cycle cost as the diesel engine. With just 6% difference for 1500$/kW, and so much uncertainty in the numbers in general, a 1500$/kW price may indeed be enough to make the SOFC/GT system compatible. If the stack replacement costs are reduced as much as the procurement costs of the system, the fuel cell systems, fuelled on LNG from import via Kiel and LNG from Norway, may be the cheapest alternatives both for 1000 and 1500$/kW.

11.2 Higher purchasing price for the Diesel engine

If the diesel engine initial cost is increased to 2000$/kW, the difference between the cheapest SOFC/GT systems and the diesel engine are reduced. This is shoved in the figure and table below.

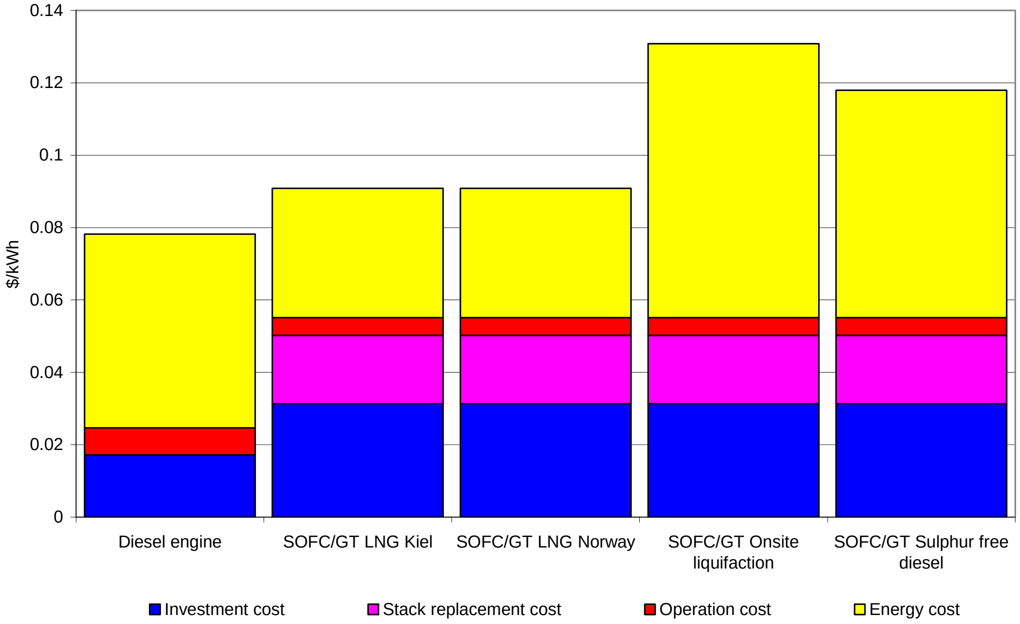

Figure 11-2: LCC results for Diesel engine and SOFC/GT for higher purchasing price Diesel engine

Table 11-2: LCC higher purchasing price Diesel engine

Cost [$/kWh]	Diesel engine	SOFC/GT LNG Kiel	SOFC/GT LNG Norway	SOFC/GT Onsite liquifaction	SOFC/GT Sulphur free diesel
Investment cost	0.0172	0.0313	0.0313	0.0313	0.0313
Stack replacement cost	-	0.0189	0.0189	0.0189	0.0189
Operation cost	0.0075	0.0049	0.0049	0.0049	0.0049
Energy cost	0.0535	0.0357	0.0357	0.0757	0.0629
Total cost	0.0782	0.0908	0.0908	0.1308	0.1180

The original chosen values for the diesel engine costs makes the diesel engine 25% cheaper than the SOFC/GT system. The higher diesel engine cost alternative increases the life cycle cost of the diesel engine to 0.0782$/kWh, only 14% lower than the two cheapest SOFC/GT alternatives (LNG Norway and import), which has a LCC cost of 0.0908$/kWh.

11.3 Other fuel cost scenario

Uncertainty are connected with the fuel prices, this scenario is using the fuel supply cost calculated by Altman et al /30/.
The fuel costs are presented in the table under, for details please refer to /30/.

Table 11-3: Alternative fuel costs

Fuel supply	Cost
Import Kiel	0.021 $/kWh
Norway	0.018 $/kWh
Onsite liquifaction	0.039 $/kWh
Sulphurfree diesel	0.025 $/kWh

The largest fuel price difference is the sulphur free diesel price, which is only 0.025$/kWh in this scenario compared with 0.044$/kWh.

The over all life cycle cost analysis with the alternative fuel supply is showed in the figure below.

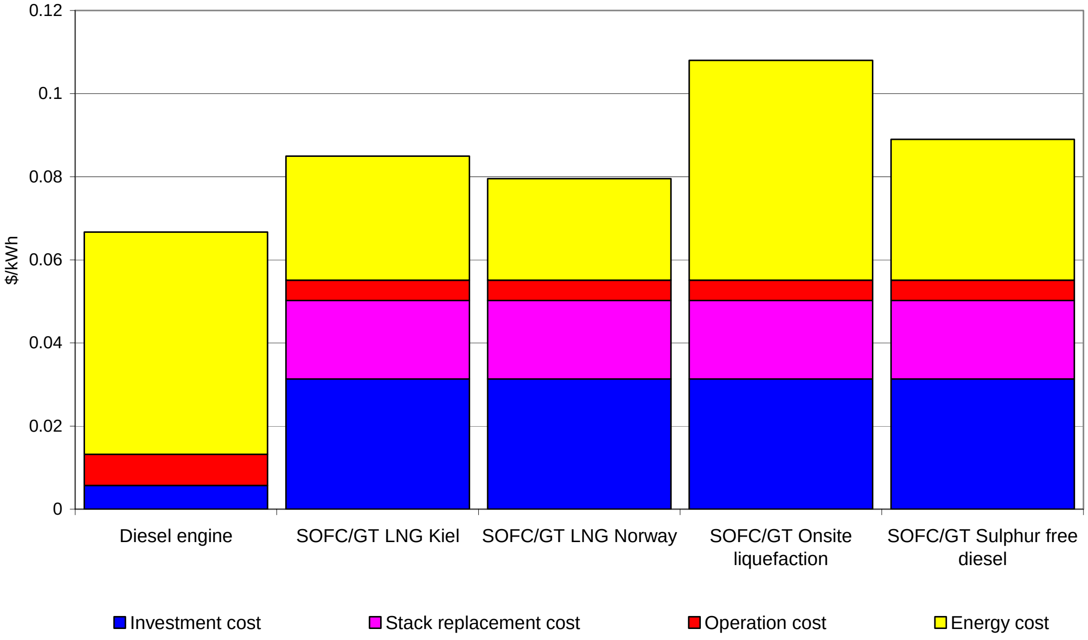

Figure 11-3: LCC results $/kWh for Diesel engine and SOFC/GT, alternative fuel cost

Table 11-4: LCC alternative fuel costs

Cost [$/kWh]	Diesel engine	SOFC/GT LNG Kiel	SOFC/GT LNG Norway	SOFC/GT Onsite liquefaction	SOFC/GT Sulphur free diesel
Investment cost	0.0057	0.0313	0.0313	0.0313	0.0313
Stack replacement cost	-	0.0189	0.0189	0.0189	0.0189
Operation cost	0.0075	0.0049	0.0049	0.0049	0.0049
Energy cost	0.0726	0.0426	0.0244	0.0529	0.0339
Total cost	0.0858	0.0977	0.0795	0.1080	0.0890

All fuel cell systems have higher life cycle costs than the diesel engine, but the differences are smaller than in the original LCC performed, for onsite liquefaction and sulphur free diesel specially. However there is an approximately 20% higher cost on the cheapest SOFC/GT alternative, Norwegian LNG tanked in Oslo.

11.4 High operating cost Diesel engine

A sensitivity analysis for higher maintenance cost for the diesel engine was performed. A maintenance price of 18$/h or 0.013$/kWh were assumed for the diesel engine. The results are presented in the figure and table below.

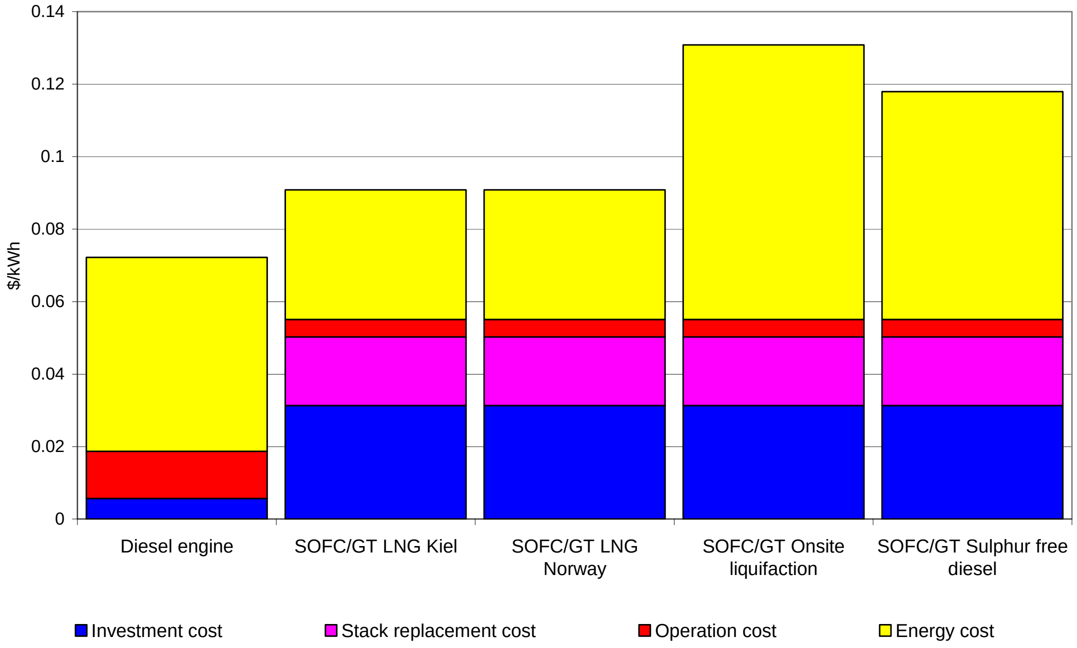

Figure 11-4: LCC results $/kWh for Diesel engine and SOFC/GT, higher operating cost Diesel engine

Table 11-5: LCC higher operating cost Diesel engine

Cost [$/kWh]	Diesel engine	SOFC/GT LNG Kiel	SOFC/GT LNG Norway	SOFC/GT Onsite liquifaction	SOFC/GT Sulphur free diesel
Investment cost	0.0057	0.0313	0.0313	0.0313	0.0313
Stack replacement cost	-	0.0189	0.0189	0.0189	0.0189
Operation cost	0.0130	0.0049	0.0049	0.0049	0.0049
Energy cost	0.0535	0.0357	0.0357	0.0757	0.0629
Total cost	0.0722	0.0908	0.0908	0.1308	0.1180

As a result of the higher maintenance costs the life cycle cost of the diesel engines has increased some. The cost is however, still 20% lower than the SOFC/GT Norway and Kiel systems and the diesel engine is still significant cheaper. The performance is only 5% worse for a maintenance cost increase of nearly 50%.

11.5 Alternative scenarios

All the alternative scenarios are presented together in the figure and table below to illustrate the differences in the results changing the different parameters.

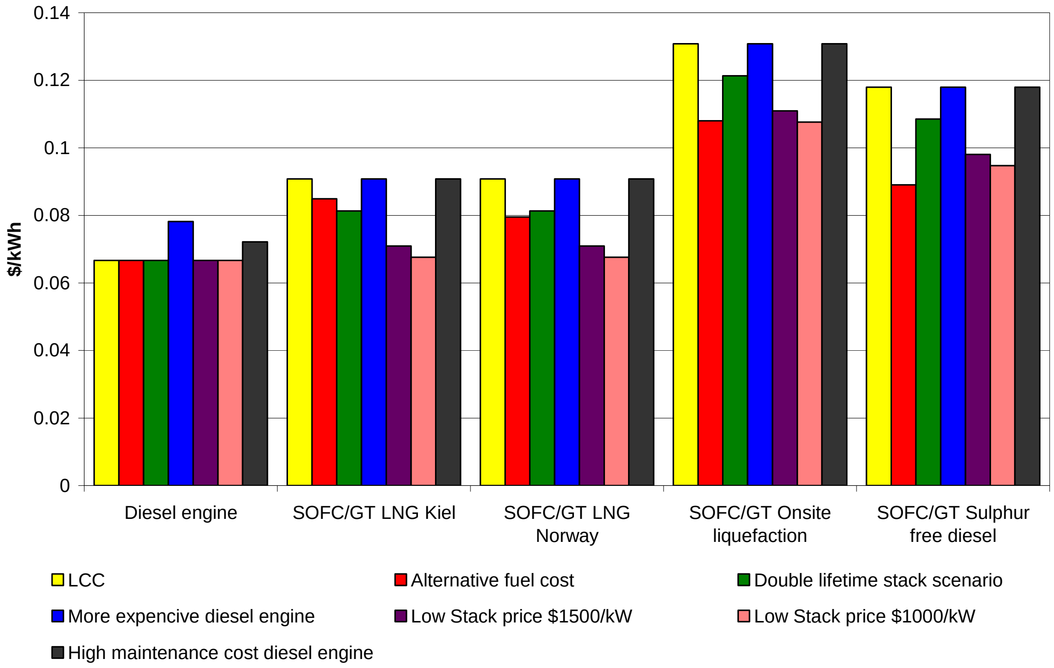

Figure 11-5: Comparison LCC scenarios

Table 11-6: LCC scenarios

Cost [$/kWh]	Diesel engine	SOFC/GT LNG Kiel	SOFC/GT LNG Norway	SOFC/GT Onsite liquefaction	SOFC/GT Sulphur free diesel
LCC	0.0667	0.0908	0.0908	0.1308	0.1180
Alternative fuel cost	0.0667	0.0850	0.0795	0.1080	0.0890
Double lifetime stack scenario	0.0667	0.0814	0.0814	0.1214	0.1085
More expencive diesel engine	0.0782	0.0908	0.0908	0.1308	0.1180
Low Stack price $1500/kW	0.0667	0.0709	0.0709	0.1109	0.0981
Low Stack price $1000/kW	0.0667	0.0676	0.0676	0.1076	0.0948
High maintenance cost diesel engine	0.0722	0.0908	0.0908	0.1308	0.1180

Low stack prices makes the SOFC/GT system most compatible with the diesel engine. All the other scenarios also makes the SOFC/GT systems better off compared with the conventional system.

In general all scenarios indicate that to make the SOFC/GT system compatible the next decade the purchasing price has to fall. The fuel prices also plays an important role, and the LNG price is another important factor, with a much higher efficiency, the prices can however exceed the LSFO prices some.

12 LCC/LCA integration

Life cycle assessment (LCA) evaluates the environmental performance through the whole life cycle of a product or service. The comparative nature of LCA makes it suitable for comparison, and can, from an environmental sustainable point of view, be an important part of decision-making processes. However, neither internal nor external economic aspects are taken into account in the LCA methodology and this traditional separation of LCA and economic analysis may have limited the influence and relevance of LCA for decision making. /26/
The lack of economical aspect omits the important relationships and trade offs between economic and life cycle environmental performance of alternative product design decision scenarios.

Life Cycle Cost analysis (LCC) compares the cost effectiveness of alternatives investments or business decisions through the whole economical life cycle, from acquisition, through use to disposal. Purchasing price is often well known and easy to compare but is usually just a little fraction of the cost through the whole life cycle. LCC gives a holistic picture of the economical performance of a product or system but lack the environmental perspective.

Integration of LCA and LCC may be a good tool for sustainable economical decisions taking also the environmental aspects into account.

12.1 Reasons for integration

There are several reasons why to integrate LCA and LCA some are listed underneath/46/:

- Quantification of processes, material- and energy- flows for LCA and LCC, related to environmental emissions and costs respectively, are performed in a similar way.
- The environmental parameters in an LCA may have direct internal costs, i.e. CO_2 taxes. This can be included in an LCC.
- The environmental stress quantified in an LCA will give external costs, which can be included in an LCC:
- Function unit are used for comparison between systems in both LCA and LCC.
- If both LCA and LCC are used early in the planning process the chance increases to obtain cost effectiveness and low environmental stress at the same time.
- Synergy effect in cost and benefit by using both LCA and LCC.

An LCA and LCC are based on the same basic system. The LCC mostly has a business economic focus, including those processes imposing direct economic costs or benefits upon a given organisation, i.e. procurement cost, use and maintenance costs and disposal costs. An LCA includes all this steps, but has a social approach and includes the processes before procurement, often called cradle to gate, i.e. resource use, intermediate materials and products. Environmental stress is connected with the cradle to gate steps, but no economical costs not included in the initial cost.

An LCA identifies which steps in the service or products life cycle that have the largest potential for improvement, i.e. which parts of the life cycle that have the larger environmental impact. In general emissions can be seen as recourses in the wrong place. The more effective the energy and resources are utilized the less emissions and the lower energy and material costs. There are direct economical costs that can be seen as environmental impacts. These direct costs are represented as resource use, waste and emission in LCA and as monetary costs in LCC, i.e. material use ($/t), energy use ($/kWh), waste and special waste ($/t) and in some cases greenhouse gas emission (environmental taxes).

By integrating LCA and LCC both the economy in and environmental influence from a product/project will be considered. There is no accepted well known practice for how to carry out this integration at present and it is therefore not frequently done. There is, however, research on the topic but this has not yet led to a common agreement of how to do it. One of the questions is; fully integration or LCC as “just another flow” in LCA? One of the main problems is that while LCA measures its results in physical units LCC results are presented in monetary units. In the case of direct integration, environmental harm will have to be translated into monetary units. There are several methods of how to this, but they are all rather uncertain. Is it possible to put a price on the environment?
Another crucial difference between LCA and LCC is the time scope. While LCA includes emissions that may first harm in 100 years, long after final disposal of a product, the LCC only includes costs that occur in the lifetime of the product. An LCC does not account for potentially future problems, while these costs usually not are reflected in future direct costs. The long time horizon of the LCA may influence companies to take more environmental sustainable choices in their decision making processes. This in turn may lead to public good will, the public usually like products to be environmental, something which may give the company a higher market share if the prices are nearly the same.
Table 12-1: LCA and LCC /26/ describes the differences between LCA and LCC.

Table 12-1: LCA and LCC /26/

Tool/Method	LCA	LCC
Purpose	Compare environmental performance of alternative product systems or different life stages within the system. Give a holistic picture of the environmental performance of a product or system.	Determine cost effectiveness of alternative investment and business decisions, from the perspective of an economical decision maker such as manufacturing firm or consumer.
Activities included in the Life Cycle.	All processes casually connected to the physical life cycle. Including the entire pre-usage supply chain; use and processes supplying use; end of life and the processes supplying end of life steps.	Activities causing direct costs or benefits to the decision maker during the economic life of the investment, as a result of the investment.
Flows considered	Pollutants, resources, and inter-process flow of materials and energy.	Costs and benefit monetary flows directly impacting decision maker.
Units for tracking flows	Primarily mass and energy; occasionally volume, other physical units.	Monetary units.
Time treatment and scope	The timing of processes and their release or consumption flows is traditionally ignored; impact assessment may address a fixed time window of impact. (e.g. 100 year time horizon for global warming potential) but future impacts are generally not discounted.	Timing is critical. Present value (discounting) of costs and benefits. Specific time horizon scope is adopted, and any costs or benefits occurring outside that scope are ignored.

Translating the physical units into monetary units, aggregating all categories into one environmental category may seem a good solution for integration. However there are a lot of uncertainties connected with translating amounts of emissions into monetary units. Transforming different categories into environmental units a price has to be set on the different environmental aspects, in this study this would mean to price global warming potential, acidification and photochemical oxidation, i.e. an economical weighting. Weighting of different environmental categories will always be subjective and the environmental aspect may be better illustrated in physical units of category equivalents (Like g CO_2, for global warming potential)

In this study a "LCC as just another flow in LCA" approach is chosen to integrate LCA and LCC. The decision making process are based on trade offs between the LCA and LCC results.

13 Hybrid LCA-LCC results

The hybrid model can be used to choose the best environmental and economical alternative. In this model just three environmental categories are accounted for and potentially economical profit as a result of choosing the best environmental alternative is not included, neither potential emission fees are considered. Even if the diesel engine are the cheapest alternative when costs are considered there may indeed be market advantages connected with the choice of a more environmental SOFC/GT solution.

The LCC part is presented as one economic category, while the same three environmental categories used in the LCA represent the LCA part of this project. The graphs are presented below, and the heights of the bars are given in % relative to the highest contribution to the four categories.

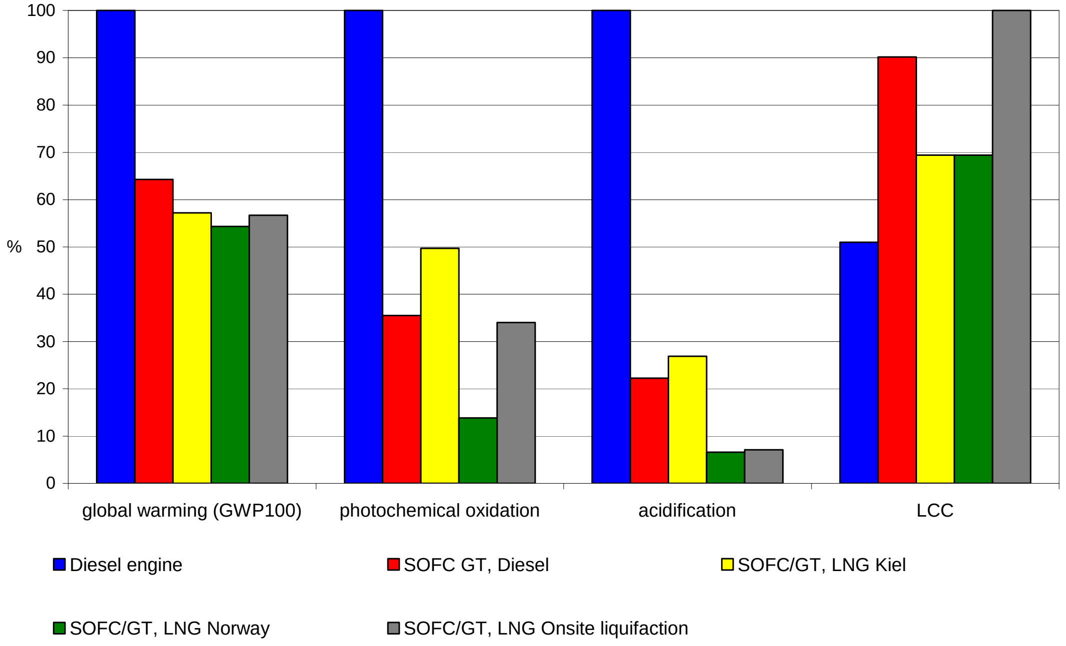

Figure 13-1: Hybrid LCA/LCC results

Table 13-1: Hybrid LCA/LCC results

Impact category	Unit	Diesel engine	SOFC GT, Diesel	SOFC/GT, LNG Kiel	SOFC/GT, LNG Norway	SOFC/GT, LNG Onsite liquifaction
Global warming (GWP100)	kg CO_2 eq./kWh	0.725	0.466	0.415	0.394	0.411
Photochemical oxidation	kg C_2H_4/kWh	3.38E-05	1.20E-05	1.68E-05	4.68E-06	1.15E-05
Acidification	kg SO_2 eq./kWh	0.00124	0.000276	0.000333	8.15E-05	8.83E-05
LCC	$/kWh	0.066676	0.117961	0.090818	0.090818	0.130818

The most environmental friendly system, when only global warming, photochemical oxidation and acidification are considered is the SOFC/GT fuelled on LNG from Norway, this system is also the cheapest SOFC/GT system. The question for the passenger ferry company is whether it is willing to pay 30% more per kWh for the SOFC/GT system than for the diesel engine, to achieve 45% lower greenhouse gas emission, and 87 and 93% lower contributions to photochemical oxidation and acidification. Maybe can a more environmental profile of the company lead to a higher market share? Maybe there will be higher and new pollution taxes, and therefore a huge potential to save money choosing the fuel cell? These questions are not easy to answer and they are extremely difficult to include in economical terms in an LCC.

If the fuel cell prices drop to 1000-1500$/kW and the stack replacement cost sink or/ the lifetime gets longer, the SOFC/GT will have equal lifetime costs if not lower. In that case the combined fuel cell/ gas turbine system will have a huge market advantage being both more environmental friendly and cheaper.

14 CONCLUSIONS

14.1 LCA conclusions

This LCA study has compared a conventional system for auxiliary power production scenario onboard a passenger ship with the four SOFC/GT scenarios in the FCShip project. The study has also corrected the impact assessment of the SOFC/GT study, by correcting and differentiating the lifetime of the SOFC/GT system and new assumptions of CO_2 emissions from the fuel cell. The scenarios compared are:

- Diesel engine, low sulphur fuel (S=0.2%)
- SOFC/GT, LNG fuel supply via Kiel.
- SOFC/GT, LNG fuel supply via Kiel and LNG produced on site (quay)
- SOFC/GT, LNG fuel supply via Norway
- SOFC/GT, sulphur free car diesel

An LCA is conducted for the diesel engine scenario and the corrected SOFC/GT via Kiel, i.e. as a reference for all SOFC/GT scenarios, taking into account energy and material consumption, emissions and waste from each life cycle stage. The environmental performance over the whole lifetime of the conventional diesel engine is compared with all four SOFC/GT scenarios.

When interpreting the results of this study, it is important to highlight that:

- Equal weighting has been given to each impact category.
- The results have not been normalised to any known baseline, e.g. total contribution to these categories from sector, region or current technology.

Some simple sensitivity analyses have been conducted to check some of the system parameters in this study. Stack lifetime and efficiency, pollution from and specific materials in the diesel engine have been examined. It was found that neither increase in life-time of the SOFC nor the fuel efficiency did have any significant influence on the results of the study. 50% increased lifetime led to a maximum 3% improvement in the overall environmental performance. The change in efficiency led to 6% higher contribution to the global warming and acidification category, while 33% higher for photochemical oxidation, however it makes a rather small difference compared to the diesel engine. Increased sulphur content to a worst-case example, from 0.2 to 1.5%, changed the emission profile for the two categories photochemical oxidation and acidification with 45% and 80% respectively.

Conclusions are drawn as follows:

1. All SOFC/GT scenarios have approximately 35–90% better environmental performance in all the three chosen categories. The study shows that the scenario for LNG supply via Norway has the lowest contribution in all impacts categories considered, it has approximately 60% lower contribution to the global warming potential, 85% smaller to photochemical oxidation and 90% smaller to acidification. This is mainly due to less transportation in this scenario.

2. When looking at the different life cycle stages in more detail, the study shows that for the diesel engine system the operation stage has the greatest contribution to the global warming and acidification categories while the fuel treatment has a little bit higher contribution to the photochemical oxidation category. The manufacturing phase is nearly insignificant and has it maximum contribution in the photochemical oxidation category with 3%. This means that if the environmental performance of the system is to be optimised on greenhouse gas emissions or acidification, the operational stage is the general hot spot. For photochemical oxidation, the operation phase and the fuel supply stages are both of about the same importance. To improve the overall efficiency the most the operating phase should be improved.

3. For the SOFC/GT system, the Kiel scenario is studied in more detail as a reference for all the four scenarios. Studying the lifecycle of the SOFC/GT LNG Kiel scenario shows that the operating phase is most important for the global warming category and contributes with about 75% of the total contribution. Fuel treatment stands for more than 90% of the contribution in the photochemical oxidation category and 75% in the acidification category. The manufacturing phase contributes with nearly 25% of the acidification category and about 3% for the others in the over all contribution. This means that if the environmental performance of the system is to be optimised on greenhouse gas emissions, the operational stage is the general hot spot also for this case. In the two other impact categories, the fuel supply stages are of importance. The manufacture of the SOFC has alone 20% of the contribution to the acidification category and may be of importance if the acidification emissions are to be reduced. In the other categories manufacture is of less importance.

With the limitations and system boundaries implemented and if only the three categories, global warming, photochemical oxidation and acidification, are taken into account these conclusions results in that the SOFC/GT system can be recommended. A certain uncertainty is connected to all data used in the project, but they should be of about the same quality. The difference in performance is over 37% better for global warming, 50% better for photochemical oxidation and 73% better for acidification for all SOFC/GT solutions compared to the diesel engine. This should, despite the uncertainty in the data material, give a good enough picture of that the environmental performance in this three categories are substantially better for the SOFC/GT systems.

The lack in categories is a significant weakness of this analysis. Problem shifting may have occurred, and there is a certain danger that the wrong alternative may be chosen. The special alloys in the stack could be one reason for an eventually problem shift. Though the results gives the SOFC/GT system a significant environmental advantage in the three categories considered.

14.2 LCC conclusions

The LCC study in this report has compared rough cost estimates through the life cycle of a conventional system for auxiliary power production scenario onboard a passenger ship with the four SOFC/GT scenarios in the FCShip project. As a result of the inaccuracy of the cost data used the LCC results should be treated very carefully. Five sensitivity cost analysis were performed on the uncertain parameters in the study. The lack of cost categories included is

also a weakness but the LCC results together with the sensitivity results give a rough picture of the economical performance of the different scenarios for auxiliary energy production.
The cost numbers calculated in this LCC result in that the diesel engine is the over all cheapest alternative. This as a result of lower investment and operation/maintenance cost. The diesel engine cost is approximately 25% lower than the cheapest SOFC/GT alternatives, SOFC/GT fuelled on LNG from Norway refuelled in Oslo and on LNG from Import refuelled in Kiel. SOFC/GT fuelled on onsite liquefied LNG is the most expensive alternative, with SOFC/GT fuelled on sulphur free diesel as number three. The initial cost and stack replacement cost is the main cost is the disadvantage for the SOF/GT system relative to the diesel engine. The SOFC/GT initial cost alone is 80% higher than the diesel engine cost. Low fuel cost as a result of low fuel use pr unit electricity, because of the high efficiency, is a huge advantage for the SOFC/GT system. For fuels on approximately the same price level the SOFC/GT system is significantly cheaper, 33% cheaper for the LNG from Norway and import than for the diesel engine.

All LCC scenarios performed pointed out the fuel cell and stack replacement cost as the crucial cost disadvantage for the SOFC/GT system and low energy costs as a great advantage. This indicates that the main challenge is the Fuel cell price, but the relative accurate sizes of the economical differences are not known.

14.3 Integrated LCA/LCC conclusion

An LCA and LCC are in many ways based on the same basic system, in a LCA environmental stress through the whole life cycle are estimated and aggregated per functional unit, while the cost is treated the same way in a LCC. LCA lack economical aspect, while LCC may include some direct environmental costs, represented as resource use, waste and emission in LCA. The largest difference between LCA and LCC seams to be the differences in units and time scope. While LCA evaluates environmental emission contribution in physical units LCC uses monetary units. For the time scope LCA includes future environmental influence, environmental stress that occurs long after the product is disposed, LCC just takes the economical lifetime into account. The challenge is how to integrate the two systems.

The integration of LCA and LCC, where economy is added as another flow, were found to give the best picture of both the economical and environmental performance. The economical performance through the life cycle was added as an economical LCC category together with the environmental categories in the LCA. The results are presented as contributions in % of the highest contribution to the category and the decision making process has to be based on a trade of between the different categories.

The hybrid model presents the environmental and economical performance in the same diagram. The SOFC/GT system fuelled on LNG from Norway has the best environmental performance of all systems in all categories and is also on of the two cheapest SOFC/GT systems. The diesel engine has the over all worst environmental performance but is the cheapest auxiliary engine alternative. The trade of between environment and economy will in this case be whether the passenger ferry company is willing to pay 30% more per kWh for the SOFC/GT system than for the diesel engine, to achieve 45% lower greenhouse gas emission, and 87% and 93% lower contributions to photochemical oxidation and acidification.

15 RECOMMENDATIONS

The LCA study, taking only global warming, photochemical oxidation and acidification into account shows that the new SOFC/GT system may have a significant environmental advantage compared to the diesel engine, and it would be of interests to perform a more detailed analysis of the system.

An analysis with all categories should be performed to make an even more holistic picture of the environmental performance of the two systems. The data quality should also be improved, more detailed data should be collected and some systems and processes described in more detail.

The LCC was based on rough cost estimates and the results should be treated with extra care. The different sensitivity analysis, however all indicates the purchasing price of the fuel cell as the hot spot for making the SOFC/GT compatible as auxiliary system. The main challenge for the Fuel cell industry seams to be lowering the manufacturing cost.

A more detailed cost analysis should be performed, taking more economic categories into account. The data quality should also be improved; fuel prices, which indeed influence the results, are due to problems gathering data based on many different sources. Better fuel data will give a better picture. The technological stage of the fuel cell technology makes the cost estimates for the fuel cell difficult to estimate. Long term test results are needed to make the fuel cell costs more credible.

The hybrid analysis gives a picture of both environmental and economical performance through the life cycle of the auxiliary systems. Integration of LCA and LCC may be a useful decision making tool for companies taking both the life time environmental and economical performance into account. Good standardized practice for integration may indeed be useful for more holistic decision making in the industry.

ACRONYMS

ATS	Austrian schilling
DNV	Det Norske Veritas
DWT	Dead weight tonnes
FCShip	Fuel Cell technology in ships
GT	Gas turbine
HFO	Heavy Fuel Oil
ISO	The International Organization for Standardisation
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
LNG	Liquefied Natural Gas
MCR	Maximum Continuous Rating
MGO	Marine gas oil
NMVOC	Non-methane volatile organic compounds
NOK	Norwegian krones
NTNU	Norges Teknisk-naturvitenskapelige universitet (Norwegian University of science and technology)
Ro-ro	Roll in–roll out
Rpm	revolutions per minute
SOFC	Solid Oxide Fuel Cell
USD	US dollars
VOC	Volatile organic compounds

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APPENDIX A

Emission factors- Manufacturing

Table A-1 Materials Auxiliary diesel engine, 6L20

Data are estimated in co-operation with Marintek /22/.

Parts auxilary engine	Material (% weight)	Database	SimaPro	Weight [kg]
Engine, Wärtsilä 6L20	Cast-iron (65%)	Cast irons	GGG60	5525
	High grade steel (34%)	Steel high grade	42CrMo4[a]	2890
	Light metal + alloys (1%)		AlCuMg2	85
Steel frame	Steel (100%)	Steel construction	Steel constr.	3000
Generator	Copper alloys (50%)	Coppers	CuZn40	2750
	Steel(50%)	Steel autom	Fe520	2750
Total				*17000*

Table A-2 Emissions manufacture, Auxiliary diesel engine

Data are based on that approximately the same processes will occur in the production of engines and gas turbines. The data are imported from Pretlove and Garman /5/.

Quantity in kg/unit and emissions in g/unit

Material/Process	Quantity	CO_2	SO_2	NO_x	PM	CO
Metal finishing, steel	1p	19216248	127888,1	123686,2	16095,94	31307,64
Metal finishing, aluminium	1p	292106,5	2156,247	584,1272	204,5931	89,32949
Welding	1p	21104,41	26651,93	19625,05	5452,831	835,3557
Transport, sea	1p	5391360	74304	5875,2	3456	1036,8
Transport, land	1p	541987,2	691,2	8596,8	691,2	3438,72
Installation	1p	322963,2	414,72	5158,08	414,72	2063,232

Table A-3 Materials Ancillary system

Data are based on the assumption that the ancillary system is approximately 10% of the engines material weight.

Ancillary system	Material (% weight)	In SimaPro	Weight [kg]
	Cast-iron (65%)	GGG60	2000
	High grade steel (34%)	42CrMo4[a]	1000
	Light metal + alloys (1%)	AlCuMg2	10

Table A-4 Emissions manufacture of ancillary system

Emissions connected to the manufacturing of the ancillary system are based on estimated energy use. Energy use is given for one unit and is based on that the energy use per kW is the same for Diesel engine as SOFC. Energy from UK CCGT plant from Pretlove and Garman is chosen and shown in the next table.

Ancillary system	Quantity	Energy	Type
	1 p	36288 MJ	UK CCGT plant

Table A-5 Emissions from energy generation, UK CCGT plant /5/

Data are imported from /5/ (Pretlove and Garman)

Emissions in g/MJ

Emission	g/MJ
Particulates	0,00028
CO	0,11139
CO_2	115,806
SO_x	0,00306
NO_x	0,20278

APPENDIX B

Emission factors- Operation

B-1 Air emission factors for operation of auxiliary diesel engine

The emission factors are calculated for special fuel consumption of 187g/kWh /21/ and 0.2% Sulphur content in the fuel /17/. CO and NO_x are collected from Wärtsilä for a $LowNo_x$ engine.

Component	g/kWh
CO_2	593
SO_x	0.75
NO_x	11,5
CO	0,5
CH_4	0.0561
PM	0.224
NMVOC	0.449
N_2O	0.015

Table B-2 Maintenance materials

Data are based on the assumption that approximately 1000kg is replaced per engine and that the material composition is the same as the ancillary system.

Maintenance materials	Material (% weight)	In SimaPro	Weight [kg]
	Cast-iron (65%)	GGG60	2000
	High grade steel (34%)	42CrMo4[a]	1000
	Light metal + alloys (1%)	AlCuMg2	10

Table A-4 Emissions manufacture of maintenance materials

Emissions connected to the manufacturing of the ancillary system are based on estimated energy use. Energy use is given for one unit and is based on that the energy use per kW is the same for Diesel engine as SOFC. Energy from UK CCGT plant from Pretlove and Garman is chosen and shown in the next table.

Maintenance materials	Quantity	Energy	Type
	1 p	36288 MJ	UK CCGT plant

Table A-5 Fuel consumption for a Medium speed $LowNo_x$ engine /21/

The fuel consumption is measured for a 32LN engine by Wärtsilä /21/. In this study the future LN 6L20 is assumed to have the same fuel consumption.

Effect	Fuel consumption [g/kWh]
50%	191
70%	187[a]
75%	185
100%	181

a-estimated from a linear approach between 50 and 75%

Table A-5 Electric efficiency for a Medium speed $LowNo_x$ engine /21/

El. Efficiency is calculated for fuel net caloric value of 42700kJ/kg, given for 32LN. /21/

Fuel net caloric value	42700 kJ/kg [a]
Spec fuel consumption (70% eff.)	187 g/kWh [b]
El. efficiency	45,1 % [c]

a- Wärtsila/21/

b- Calculated like table A-5 /21/

c- Calculated from a, b and table 2-1 /18/

APPENDIX C

Emission factors- Fuel supply

Table C-1: Energy requirements and emissions for fuel supply

Data are imported from /5/. The data for transport to port[a] are adjusted to ship transportation from truck transportation. This adjustment results in higher SO_2 and PM emission.

	Energy input	**Energy produc**	**Energy losses**	**GHG**	**nmVOC**	**NOx**	**SO2**	**CO**	**PM**
	kWh/ kWh	**kWh/ kWh**	**kWh/ kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**
Crude oil production	1,156	1,100	0,056	15,4	0,086	0,060	0,025	0,032	0,001
Crude oil transport	1,168	1,100	0,012	3,2	0,002	0,064	0,036	0,014	0,005
Refining	1,168	1,000	0,100	31,0	0,042	0,032	0,047	0,017	0,002
Transport to port[a]	1,171	1,000	0,003	0,8	0,000	0,003	0,010	0,002	0,001
Transport to vessel	1,171	1,000	0,000	0,1	0,000	0,000	0,000	0,000	0,000
Total	1,171	1,000	0,171	50,5	0,130	0,160	0,108	0,065	0,008

Energy input and energy produced are cumulative, energy delivered to the ship included.
All in relation to kWh delivered to vessel.

APPENDIX D

Calculations CO_2 emission factors SOFC/GT
New emission factors operation SOFC/GT

Calculation of CO_2 emissions from the SOFC/GT system, 70% overall efficiency

SOFC/GT, LNG:

Energy content LNG: 45MJ/kg /25/
Conversion MJ-kWh: 1kWh = 3.6MJ
Emission factor LNG: 2.75kg CO_2/kg LNG /25/

CO_2 Emissions LNG fuelled fuel cell, 70% efficiency ("tank to grid"):

$$\frac{2{,}75 kgCO_2 / kgLNG}{45 MJ / kgLNG} \times 3{,}6 MJ / kWh \times \frac{1}{0{,}7} = 314 gCO_2 / kWh_{el}$$

SOFC/GT, Diesel:

Energy content diesel: 43.1MJ/kg /25/
Conversion MJ-kWh: 1kWh = 3.6MJ
Emission factor diesel: 3.17kg CO_2/kg diesel

CO_2 Emissions Diesel fuelled fuel cell, 70% efficiency ("tank to grid"):

$$\frac{3{,}17 kgCO_2 / kgLNG}{43{,}1 MJ / kgLNG} \times 3{,}6 MJ / kWh \times \frac{1}{0{,}7} = 378 gCO_2 / kWh_{el}$$

Diesel engine (Diesel fuelled), 42% efficiency:

Energy content diesel: 43.1MJ/kg /25/
Conversion MJ-kWh: 1kWh = 3.6 MJ
Emission factor diesel: 3.17 kg CO_2/kg diesel /25/

CO_2 emissions Diesel engine, 43% efficiency ("tank to grid"):

$$\frac{3{,}17 kgCO_2 / kgLNG}{43{,}1 MJ / kgLNG} \times 3{,}6 MJ / kWh \times \frac{1}{0{,}42} = 616 gCO_2 / kWh_{el}$$

Energy content and emission factor for LNG and Diesel

Fuel	Energy content	Emission factor
LNG	45 MJ/kg	2,75 kg CO_2 / kg
Diesel	43,1 MJ/kg	3,17 kg CO_2 / kg

CO_2 emission SOFC/GT

System/ Fuel	CO_2 emission
SOFC/GT / LNG	314 gCO_2/kWh_{el}
SOFC/GT / Diesel	378 gCO_2/kWh_{el}
Diesel engine/ Diesel	616 gCO_2/kWh_{el}

New emission factors operation SOFC/GT

Emission operation SOFC/GT /5/

Emission to air	Operation, Diesel g/kWh	Operation, LNG g/kWh	Comment
CO2	378	314	1)
NOx	0,04	0,04	
CO	0,0144	0,0065	
SOx (as SO2)	0	0	LNG or sulphur free diesel
NMVOC	0,0025	0,0022	
CH4	0,0703	0,0598	
HC	0,0202	0,0202	

1) Calculated from energy content and emission factor for the two fuels

APPENDIX E

Inventory data

Life cycle assessment of maritime fuel cell applications

For more details:
Pretlove B., Garmann C., report no.2003-1544, Det Norske Veritas, Oslo, N, 2004

E-1 Manufacture

Table E1: Energy requirements and emissions for materials production for PEN and Interconnect

Data are imported from Imperial College, 2001

Main material	**Sum**	**ZrO2(Y2O3)**	**PVB**	**Ethanol**	**Trichloroethylene**	**Polyethylene glycol**	**Dibutyl phtalate**	**Doped LaMnO3**	**Ni-ZrO2 (Y2O3)**	**CrY alloy**
Quantity required (kg/kW)	20.576	4.031	0.211	0.748	1.567	0.194	0.167	0.117	0.128	13.413
Energy required (MJ/kW)	3756.913	55.969	10.548	38.365	71.088	11.634	21.846	2.448	1.771	3543.244
Air emissions (mg/kW)										
Particulates	305168.6739	15.55	2.9301	1628.79	5796.064		1618.852	0.6799	0.4919	296105.3
CO	88242.5175	6234.28	1174.986	626.7678	3289.658	85.3163	417.23	272.6531	197.2384	75944.39
CO2	185664205.3	6481475	1221576	2025136	3602958	414372.2	1018041	283464	205059.1	1.70E+08
SOx	1088472.78	171.02	32.2315	30203.39	18798.04		11014.87	7.4793	5.4105	1028240
NOx	383907.2368	11349.19	2139.003	9784.414	17231.54	680.9793	5173.653	496.351	359.0624	336693
H2S	308.8955			0.0045	1.5665		0.1669			307.1576
HCl	19844.3577			54.209	250.6406		60.0811			19479.43
HF	7688.3305			3.1926	9.399		3.5047			7672.234
Metals	9336.8202			20.0095	9.399		6.0081			9301.404
VOC	2223.3715			0.0001	1057.39	160.2783	0.1669			1005.536
Water emissions (mg/kW)										
COD	2632.3113			32.56	120.6208		56.7433			2422.387
BOD	242.1838			29.171	23.4976		9.5128			180.0024
Acid (H+)	47.3034			0.13	39.1626		8.0108			0
Dissolved solids	70267.4914			0.0157	43862.1		317.0948			26088.28
NH4	1154.6554			0.1185	12.532	0.0582	0.5007			1141.446
Suspended solids	96018.065			37.3506	13001.98		166.892			82811.84
NO3-	1737.1699			0.0001	18.798		0.1669			1718.205
Other nitrogen	1231.494			0.0022	14.0985		0.8345			1216.559
ClO3-	722.4281			0.0006	720.5917		1.8358			0
P2O5	3696.5657			0	4.6995		0.1669			3691.699
Detergent/oil	25064.0725			0.0067	134.7193		10.6811			24918.67
Dissolved organics	361.9373			0.0012	68.9262	0.8377	50.0676			242.1046
Other organics	285.0268			0.0004	17.2315		0.5007			267.2942
Cl-, F- ions	1132973.745			0.0786	147251.3		3504.732			982217.6
SO4--	407221.1235			0.205	12688.68		216.9596			394315.3
Soil emissions (mg/kW)										
Mineral	574112.5132			18136.39	532611.2		23364.88			
Mixed industrial	10898.62684			2921.213	6892.616		1084.798			
Slags/ash	131193.9384			5463.98	119054.3		6675.681			
Regulated chemical	9223.038511			0.009627	8772.42		450.6085			
Inert chemical	94557.93222			0.280434	93990.22		567.4329			

Table E-2: Energy requirements and emissions for materials production for Balance of Plant

Data are imported from Imperial College, 2001

Component	Sum	Casing	Air supply system	Fuel supply system	Pre/reformer/gas burner		Heat exchangers			Power conditioning system			Convent gas heat
Main material		Steel	Steel	Steel	Steel	Ni	Incaloy	Steel	Alu. alloy	Purified silica	Copper	Plastics	Steel
Quantity required (kg/kW)		10	10	10	5	0,5	2	2	0,3	0,004	0,002	0,006	50
Energy required (MJ/kW)	2230,43824	224	224	224	112	145,7	49,28	44,8	84,5253	0,556	1,202	0,37494	1120
Air emissions (mg/kW)													
Particulates	341712.1	37000	37000	37000	18500	5066.5	8140	7400	6390	104	95.4	16.2	185000
CO	270562.44	22000	22000	22000	11000	4267.5	48400	4400	18450	8000	27.54	17.4	110000
CO2	179085940.6	19000000	19000000	19000000	9500000	7194000	4180000	3800000	2292000	28000	79340.56	12600	95000000
SOx	1879739.26	68000	68000	68000	34000	1255155	14960	13600	16380	332	1253.46	58.8	340000
NOx	328709.04	35000	35000	35000	17500	15447.45	7700	7000	480	136	379.59	66	175000
H2S	2953.612	330	330	330	165	10	72.6	66		0	0	0.012	1650
HCl	12193.42	1200	1200	1200	600	1271.5	264	240	209.7	4	3.62	0.6	6000
HF	379.1778	40	40	40	20	0.1038	8.8	8	21.81	0.236	0.21	0.018	200
Metals	1323.2511	10	10	10	5	1165	2.2	2	66.3411	0.02	2.66	0.03	50
VOC	43.889	0	0	0	0	27.083	0	0	16.62	0	0	0.186	0
Water emissions (mg/kW)													
COD	8950.886676	1000	1000	1000	500		220	200	24.96	0.304	0.8226758	4.8	5000
BOD	278.831643	30	30	30	15	9.12	6.6	6	1.011	0.032	0.732643	0.336	150
Acid (H+)	1622.056894	180	180	180	90		39.6	36	3.81429	0.4	12.008604	0.234	900
Dissolved solids	1199.848626	10	10	10	5	1104	2.2	2		0.048	0.0006258	6.6	50
NH4	3814.865751	420	420	420	210	50.85	92.4	84	17.19199	0.356	0.0077605	0.06	2100
Suspended solids	7064116.804	790000	790000	790000	395000	2952	173800	158000	14340	7.2	2.6041086	15	3950000
NO3-	91.59400258	0	0	0	0	64	0	0	27.57	0	2.58E-06	0.024	0
Other nitrogen	1234.999086	130	130	130	65	56.555	28.6	26	18.75	0.088	8.629E-05	0.006	650
ClO3-	0.02202288	0	0	0	0		0	0		0.004	2.288E-05	0.018	0
P2O5	169.3607405	0	0	0	0	155.13	0	0	14.19474	0	4.98E-07	0.036	0
Detergent/oil	2689.938267	130	130	130	65	1032.05	28.6	26	498	0	0.0002671	0.288	650
Dissolved organics	11.46004768	0	0	0	0	6.66	0	0		0	4.768E-05	4.8	0
Other organics	64.15550332	0	0	0	0	39.7685	0	0	24.225	0	3.316E-06	0.162	0
Cl-, F- ions	55372.59914	50	50	50	25	39367.64	11	10	15390.81	0.148	0.00314	168	250
SO4--	24031.55282	10	10	10	5	18678.5	2.2	2	5250	0.052	0.0008183	13.8	50
Soil emissions (mg/kW)													
Mineral	80371796.1	9000000	9000000	9000000	4500000		1980000	1800000	351.3	30003.2	61207.637	234	45000000
Mixed industrial	981717.468	110000	110000	110000	55000		24200	22000	10.44	400	73.42797	33.6	550000
Slags/ash	26764414.71	3000000	3000000	3000000	1500000		660000	600000		0.008	4363.6989	51	15000000
Regulated chemical	18.2843837	0	0	0	0		0	0	0.324	0.56	0.0003837	17.4	0
Inert chemical	677.211175	70	70	70	35		15.4	14			0.011175	52.8	350

Table E-3: Energy requirements and emissions for the manufacturing process, fuel cell stack

Data are imported from Imperial College, 2001

Energy in MJ/kW and emissions in g/kW

Process	MJ/kW	Particul	CO	CO_2	SOx	NOx
Triple roll milling (Prep. cathode ink)	0,14	3,92E-05	0,015595	16,21284	0,000428	0,028389
Triple roll milling (Prep. anode ink)	0,15	0,000042	0,016709	17,3709	0,000459	0,030417
Tape casting	0,07	1,96E-05	0,007797	8,10642	0,000214	0,014195
Sintering (electrolyte)	10,53	0,002948	1,172937	1219,437	0,032222	2,135273
Sintering (electrolyte + cathode)	8,6	0,002408	0,957954	995,9316	0,026316	1,743908
Sintering (electrolyte + cathode + anode)	8,6	0,002408	0,957954	995,9316	0,026316	1,743908
Screen printing (electrolyte + cathode)	0,13	3,64E-05	0,014481	15,05478	0,000398	0,026361
Screen print (electrolyte + cathode + anode)	0,13	3,64E-05	0,014481	15,05478	0,000398	0,026361
Metal forming interconnect	0,43	0,00012	0,047898	49,79658	0,001316	0,087195
Drying (electrolyte)	1,71	0,000479	0,190477	198,0283	0,005233	0,346754
Drying (electrolyte + cathode)	1,71	0,000479	0,190477	198,0283	0,005233	0,346754
Drying (electrolyte + cathode + anode)	1,71	0,000479	0,190477	198,0283	0,005233	0,346754
Ball milling	0,95	0,000266	0,105821	110,0157	0,002907	0,192641
SUM	34,86	0,009761	3,883055	4036,997	0,106672	7,068911

Table E-4: Energy use and emissions for manufacture of Balance of Plant

Data are imported from Imperial College, 2001

Energy in MJ/kW is taken as 5% of energy requirements for materials production. Emissions in g/kW.

System	MJ/kW	Particulates	CO	CO_2	SOx	NOx
Pre-reformer / gas burner	12,884975	0,003608	1,435257	1492,157	0,039428	2,612815
Power conditioning system	4,332898	0,001213	0,482642	501,7756	0,013259	0,878625
Heat exchangers	4,704	0,001317	0,523979	544,7514	0,014394	0,953877
Fuel supply system	11,2	0,003136	1,247568	1297,027	0,034272	2,271136
Conventional gas hearing unit	56	0,01568	6,23784	6485,136	0,17136	11,35568
Casing	11,2	0,003136	1,247568	1297,027	0,034272	2,271136
Air supply system	11,2	0,003136	1,247568	1297,027	0,034272	2,271136
SUM	111,521873	0,031226	12,42242	12914,9	0,341257	22,61441

Table E-5: Emissions from energy generation, UK CCGT plant

Data are imported from/47/ Imperial College, 2001

Emissions in g/MJ

Emission	g/MJ
Particulates	0,00028
CO	0,11139
CO2	115,806
SOx	0,00306
NOx	0,20278

Table E-6: Emissions from materials and manufacture, radial gas turbine 250 kW

Data are imported from Nadal, 1997

Quantity in kg/unit and emissions in g/unit

Material/Process	Quantity	CO_2	SO_2	NOx	PM	CO
Iron	3090,00	5809200	19776	6396,3	5253	10969,5
Carbon steel	5090,00	13284900	28300,4	21276,2	6922,4	79913
Stainless steel	1110,00	4913492,69	14914,2001	9717,11163	3561,50855	18236,492
Nickel alloy	90,00	792714,075	1062,04833	1739,60253	909,354594	181,264859
Copper	300,00	2453757,41	12584,2916	4132,28974	1225,22545	838,092371
Aluminium	170,00	991100	7021	2074	2720	7837
Plastic	150,00	291000	1950	2400	585	405
Metal finishing, steel	1 p	4448205,64	29603,7281	28631,0628	3725,91148	7247,13924
Metal finishing, aluminium	1 p	67617,2405	499,131318	135,214632	47,3595187	20,6781236
Welding	1 p	4885,27967	6169,42894	4542,83546	1262,22929	193,369369
Transport, sea	1 p	1248000	17200	1360	800	240
Transport, land	1 p	125460	160	1990	160	796
Installation	1 p	74760	96	1194	96	477,6

E-2 Operation

Table E-7: Emission factors – operation of SOFC-GT

Data are imported from /24, 35, 49/. Emissions in g/kWh

Emission to air	Operation, Diesel g/kWh	Operation, LNG g/kWh	Comment
CO2	218,5	218,5	
NOx	0,04	0,04	Adsjusted for GT
CO	0,0144	0,0065	
SOx (as SO2)	0	0	LNG or sulphur free diesel
NMVOC	0,0025	0,0022	
CH4	0,0703	0,0598	
HC	0,0202	0,0202	

E-3 Fuel supply

Table E-8: Energy requirements and emissions for fuel supply – LNG via Kiel

Data are imported from /47/

	Energy input kWh/ kWh	Energy produc kWh/ kWh	Energy losses kWh/ kWh	GHG g/kWh	nmVOC g/kWh	NOx g/kWh	SO_2 g/kWh	CO g/kWh	PM g/kWh
NG prod/processing	1,108	1,082	0,026	11,9	0,000	0,018	0,005	0,004	0,001
NG liquefaction	1,182	1,068	0,087	21,1	0,001	0,024	0,001	0,028	0,001
LNG export terminal	1,183	1,058	0,012	2,5	0,000	0,001	0,000	0,001	0,000
Maritime LNG trans	1,219	1,020	0,073	17,6	0,001	0,031	0,112	0,014	0,009
LNG import terminal	1,221	1,010	0,013	2,4	0,000	0,001	0,001	0,000	0,000
Transport to port	1,248	1,005	0,031	15,5	0,003	0,029	0,000	0,015	0,000
Transport to vessel	1,248	1,000	0,005	8,3	0,000	0,000	0,000	0,000	0,000
Total	1,248	1,000	0,248	79,3	0,006	0,104	0,120	0,062	0,011

Energy input and energy produced are cumulative, energy delivered to the ship included.
All in relation to kWh delivered to vessel.

Table E-9: Energy requirements and emissions for fuel supply – LNG onsite liquefaction

Data are imported from /47/

	Energy input	**Energy produc**	**Energy losses**	**GHG**	**nmVOC**	**NOx**	**SO_2**	**CO**	**PM**
	kWh/ kWh	**kWh/ kWh**	**kWh/ kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**
NG extr/process	1,150	1,123	0,027	12,4	0,000	0,018	0,005	0,005	0,001
Transp pipe 1000 km	1,151	1,100	0,024	7,5	0,001	0,023	0,000	0,010	0,001
Distr pipe 500 km	1,150	1,088	0,011	2,4	0,000	0,012	0,000	0,005	0,000
Local dist 10 km	1,150	1,088	0,000	0,0	0,012	0,000	0,000	0,000	0,000
Liquefact at port	1,144	1,005	0,077	20,1	0,029	0,082	0,000	0,127	0,000
Transport to vessel	1,144	1,000	0,005	8,3	0,000	0,000	0,000	0,000	0,000
Total	1,144	1,000	0,144	50,6	0,043	0,135	0,006	0,147	0,002

Energy input and energy produced are cumulative, energy delivered to the ship included.
All in relation to kWh delivered to vessel.

Table E-10: Energy requirements and emissions for fuel supply – LNG via Norway

Data are imported from /47/

	Energy input	**Energy produc**	**Energy losses**	**GHG**	**nmVOC**	**NOx**	**SO_2**	**CO**	**PM**
	kWh/ kWh	**kWh/ kWh**	**kWh/ kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**
NG extrt in Norway	1,016	1,010	0,006	3,8	0,000	0,004	0,001	0,005	0,000
NG proc & liquefac	1,088	1,010	0,071	2,7	0,000	0,006	0,002	0,016	0,002
Transport to port	1,097	1,005	0,014	10,8	0,001	0,010	0,000	0,005	0,000
Transport to ferry	1,097	1,000	0,005	8,3	0,000	0,000	0,000	0,000	0,000
Total	1,097	1,000	0,097	25,7	0,001	0,020	0,003	0,026	0,002

Energy input and energy produced are cumulative, energy delivered to the ship included.
All in relation to kWh delivered to vessel.

Table E-11: Energy requirements and emissions for fuel supply – Sulphur free diesel

Data are imported from /47/

	Energy input	**Energy produc**	**Energy losses**	**GHG**	**nmVOC**	**NOx**	**SO_2**	**CO**	**PM**
	kWh/ kWh	**kWh/ kWh**	**kWh/ kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**
Crude oil production	1,156	1,100	0,056	15,4	0,086	0,060	0,025	0,032	0,001
Crude oil transport	1,168	1,100	0,012	3,2	0,002	0,064	0,036	0,014	0,005
Refining	1,168	1,000	0,100	31,0	0,042	0,032	0,047	0,017	0,002
Transport to port	1,171	1,000	0,003	0,8	0,000	0,003	0,000	0,002	0,000
Transport to vessel	1,171	1,000	0,000	0,1	0,000	0,000	0,000	0,000	0,000
Total	1,171	1,000	0,171	50,5	0,130	0,160	0,108	0,065	0,008

Energy input and energy produced are cumulative, energy delivered to the ship included.
All in relation to kWh delivered to vessel.

Program for industriell økologi (IndEcol) er et tverrfaglig universitetsprogram etablert i 1998 for en periode på minst ti år ved Norges teknisk-naturvitenskapelige universitet (NTNU). Programmet omfatter et studieprogram opprettet i 1999 og et stort antall doktorgradsprosjekter og forskningsprosjekter rettet mot vareproduserende industri, energi- og byggesektoren. Tverrfaglig forskning og undervisning står sentralt ved IndEcol, og målet er å knytte sammen teknologiske, naturvitenskapelige og samfunnsvitenskapelige bidrag i letingen etter bærekraftige løsninger på produksjon og forbruk av energi og ressurser.

The Industrial Ecology Programme (IndEcol) is a multidisciplinary university programme established at the Norwegian University of Science and Technology (NTNU) in 1998 for a period of minimum ten years. It includes a comprehensive educational curriculum launched in 1999 and a significant number of doctoral students as well as research projects geared towards Norwegian manufacturing, energy and building industries. The activities at IndEcol have a strong attention to interdisciplinary research and teaching, bridging technology, natural and social sciences in the search for sustainable solutions for production and consumption of energy and resources.

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