# LCA of fuel cells onboard ships

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A comparative Life Cycle Assessment study, evaluating the environmental impact between a gas engine and a fuel cell

Master Thesis

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**Abstract:**

This report is a comparative life cycle assessment (LCA) of a fuel cell and a gas engine. It includes emission release over a lifetime, and recommendations to which system to install in operating vessels today.

IMO and MARPOL are the main regulators of emission at sea. An increased focus on the marine environment has provided new regulations to limit the impact from ships. Emission to sea has lately been given much attention; dangerous substances have been trapped in local food chains and disturbed the eco-systems. It is assumed that regulations today are to be followed up by stricter limits in the future. Both the fuel cell and the gas engine are solutions which reduce emission to air.

The results of the study show a large impact from fuel cell materials. This is mainly harmful to the various ecosystems, and the marine ecosystem is the largest impact category. The fuel cell is a more efficient solution with lower fuel consumption. Because of the electrolyte reaction, there is no combustion process. This gives low $CO_2$ and $NO_X$ emissions and approximately zero $SO_X$ and PM emissions. This result in a 30% global warming potential reduction compared to the gas engine.

Evaluating the results we found the gas engine to be the best solution at the moment. This is based on an overall evaluation of the environmental impact. In addition to this, the capital cost is low. Fuel cell technology is not developed enough to meet today's standards. To be able to install a fuel cell delivering energy supply to a whole ship, the volume per kW output has to decrease and the lifetime has to be increased. Increased lifetime does not only reduce the environmental impact, it reduces the capital cost as well. The fuel cell has better operational qualities, especially when it comes to global warming impact. In the future the use of fuel cells can be an important tool to reduce the $CO_2$ emission and other emissions to air.

**Keyword:**

| |
|---|
| LCA |
| Fuel Cell |
| Ship |

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# TMR 4905 – Master Thesis Marine Systems - spring 2010

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## Life cycle assessment of Fuel Cells onboard ships

Livssyklusanalyse av bruk av brenselsceller om bord i skip

## Background

It is expected that the maritime community of the future will be challenged regarding the development and verification of environmental friendly concepts. Fuel cells are introduced as an alternative and more environmental friendly source for energy production on board ships. A relevant question is to ask whether fuel cells used on board ships are effective means of reducing the environmental impacts from sea transportation systems.

## Goal

The main intention of the thesis is to perform a comparative Life cycle Assessment (LCA) study comparing environmental consequences of switching from traditional engines to fuel cells.

Further, by implementing a cost and reliability discussion to the environment analysis, it is the intention to be able to recommend the implementing of fuel cells onboard a ship or not based on criteria defined by the students.

Norges teknisk-naturvitenskapelige universitet

## Work description

In the first part of the thesis, the students will collect data from Fuel Cells onboard ships, define goal and scope for the environmental analysis including definition of system boundaries, functional unit and allocation procedure. A model for LCA in Simapro shall be established. Basic criteria for evaluation of fuel cells versus conventional power systems shall further be defined.

In the second part the analysis will be run, and the information will be evaluated. The advantages and disadvantages regarding environmental issues, costs and reliability will be discussed and compared to an existing ship with traditional machinery.

A final evaluation shall be performed aiming at identifying whether use of fuel cells are recommendable as power supply sources onboard a ship or not.

## General

The work shall be carried out in accordance with guidelines, rules and regulations pertaining to the completion of a Master Thesis in engineering at NTNU.

The work shall be completed and delivered by: June 14th, 2010 in one electronic and three printed copies.

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*We do not inherit the earth from our ancestors,*
*we borrow it from our children.*
*~Native American Proverb*

# PREFACE

This master thesis is the final report ending five years at the Norwegian University of Science and Technology, Department of Marin Technology. It is written in its entirety by Kjersti Hestad Strand and Kaja Jonsvik Aarskog, spring 2010.

The goal for this student work was to perform a comparative Life Cycle Assessment study, evaluating the environmental impact between a gas engine and a fuel cell. We have looked at the environmental impact, changing from gas engine to fuel cell technology. To calculate the impact, the LCA software tool SimaPro was used.

During the project we have worked well together, but discovered the problems collecting quality data for the study. The efficiency test was finished late April, delaying the life cycle assessment interpretation. This made the workload larger the last period of time.

We would like to thank our contacts, giving us vital information, working in Eidesvik, Rolls-Royce, MTU and Wärtsilla. Without this information the study would not have been successful. A special thanks to Harald Ellingsen for guidance during the whole project.

This project has been interesting and valuable for our knowledge in the field of environmental technology in the ship industry, as well as life cycle assessment techniques. This is a field of innovative technology, and we hope that shipping will be more environmentally friendly in the future.

Trondheim 11. June. 2010

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# EXECUTIVE SUMMARY


Shipping is an effective distribution method, making it the choice of transportation for 90% of international trade. Transportation by sea is the most cost efficient and environmental friendly alternative today. The question is how the ship industry can contribute to a reduction in the emissions leading to global warming and hazards to the environment and population.

Current regulations are given by IMO and MARPOL. Today there are limits regarding emission to air, including PM, $NO_X$ and $SO_X$. There are no regulations with respect on $CO_2$ today, but if regulations are introduced, methods to reduce emission to air have to be implemented.

The goal of the study is to evaluate the environmental impact of a fuel cell and a gas engine and compare these solutions. Eidesvik has installed a MCFC (molten carbonate fuel cell) as a test project on the supply vessel Viking Lady. In a fuel cell chemical energy is converted directly into electrical energy. The fuel (anode) and the oxidant (cathode) react making an electron flow. Various fuels can be used, in this study LNG is the choice of fuel for both solutions.

A life cycle assessment (LCA) is a technique to establish emission impact from a given product. The main objective is to point out the emission release over a life time. By using the LCA software SimaPro, the impact can be calculated. SimaPro uses the ecoinvent database, which provides the software with input data. By implementing data from the manufacturers and operators into SimaPro, a life cycle assessment was established. The assembly of the assessment was divided in a construction and an operation phase. The construction phase includes the use of materials and end of life scenarios, where 75% of the material were reused or recycled. The operating phase was calculated based on the operating profile from Viking Lady and two supply vessels from Teekay, and includes fuel consumption and emission release.

The results show a large impact from fuel cell materials. This is mainly harmful for the various ecosystems, and the marine ecosystem is found to be the largest impact category. The environmental impact with respect on global warming shows a 30% reduction switching from gas engine to fuel cell. By implementing a second characteristic model, a single score value made it possible to compare the two systems directly. This resulted in a 50 % higher impact from the fuel cell compared to the gas engine. This is mainly due to the large construction impact of the fuel cell. It is important to notice that the second approach is weighted; this means that the result is evaluated with respect on total damage. The categories are weighted after the severity, to get a final comparison score.

By evaluating the results we found the gas engine to be the best solution at the moment. This is based on an overall evaluation of the environmental impact. In addition to this, the capital cost is low. The fuel cell technology is not developed enough to meet today's standards. To be able to install a fuel cell delivering energy to a large ship, the volume per kW output has to decline and the life time has to be improved. Increasing the lifetime does not only decrease the environmental impact, it reduces the capital cost. The fuel cell has better operational qualities, especially to lower the impact of global warming. In the future this can be an important tool to reduce $CO_2$ emission and other emissions to air.

# SAMMENDRAG


Nesten alle varer som skal fraktes over store avstander blir i dag fraktet med skip. Et økt fokus på miljø har krevd flere restriksjoner og de fleste er i dag enige om at flere tiltak må innføres. Skipsindustrien er intet unntak. Strengere utslippsrestriksjoner har blitt innført de siste årene og industrien må iverksette tiltak for å redusere utslippet.

Den regulerende enhet i maritim sammenheng er IMO, og den underliggende avdelingen MARAPOL har hovedfokuset på miljø. Fokuset er ikke bare på utslipp til luft, men også på utslipp til sjø. Foreløpig er ikke $CO_2$-utslipp regulert, hvis dette kommer inn i reglementet må tiltak igangsettes av skipsrederne for å redusere utslippet, for å unngå skatter og avgifter.

Dersom det innføres $CO_2$ begrensinger i fremtiden, er det interessant å se på løsninger som kan redusere $CO_2$ og andre utslipp fra skip. Målet med denne oppgaven er å gjøre en evaluering på hvilken teknologi som er best egnet til å redusere miljøbelastningen av en gassmotor og en brenselcelle, slik teknologistatusen er i dag. Eidesvik har installert en brenselcelle av typen MCFC (karbonatsmelte brenselcelle) på forsyningsskipet Viking Lady for å teste teknologien. Brenselcellen konverterer kjemisk energi direkte til elektrisk energi, og kan drives av ulike typer brensel. I denne oppgave har vi fokusert på naturgass som brensel for begge maskineriløsningene.

En livsløpsanalyse (LCA) er en teknikk som brukes for å klargjøre hva som slipper ut miljøskadelige stoffer i et livsløp og hvor skadevirkningen oppstår. For å finne miljøkonsekvensen av systemene brukte vi SimaPro, en programvare for LCA analyser, som innhenter nødvendige data fra databasen ecoinvent. I denne analysen er konstruksjons- og operasjonsfasen implementert. Konstruksjonsfasen inneholder materialer som er innhentet fra forskjellige produsenter, og ved slutten av levetiden har vi antatt at 75 % av alle materialene er resirkulert. I operasjonsfasen inngår drivstofforbruk og utslipp i de ulike driftsfasene. Driftsprofilen er basert på driftsprofilene til Viking Lady og to av forsyningsskipene eid av Teekay.

Resultatene viser store utslag av miljøgifter som følge av materialene brukt i brenselcellen. Dette skader økosystemene, hovedsaklig de maritime økosystemene. Når det kommer til global oppvarming gir brenselcellen en forbedring på 30% i forhold til gassmotoren. Ved å implementere en karakteristisk modell som gir ut resultatet i en felles evaluering, kan de to produktene sammenlignes direkte. Dette resultatet viser en 50% forbedringspotensial for brenselcellen i forhold til gassmotoren. Dette er i hovedsak grunnet den materielle påvirkningen fra brenselcellen. Det er viktig å legge merke til at denne modellen selv vekter viktigheten av de forskjellige kategoriene.

Evaluering av resultatene viser at gassmotoren er det beste alternativet i dag. Resultatene viser at gassmotoren gjenomgående har mindre miljøpåvirkning og lavere total kostnad enn brenselcellen. Teknologien til brenselcellen er per dags dato ikke utviklet nok til å kunne forsyne et helt forsyningsskip med energi. For å kunne gjøre dette må brenselcelle bli mer effektiv per volum samtidig som levetiden må forlenges. Forlenget levetid reduserer investeringskostnadene og miljøpåvirkning fra materialene. De operasjonelle kvalitetene er bedre enn hos gassmotoren, blant annet på grunn av lavere brenselsforbruk. I fremtiden kan brenselcellen bli en god løsning for å redusere $CO_2$-utslippet og andre utslipp til luften.

# TABLE OF CONTENT

Preface ... i
Executive summary ... ii
Sammendrag ... iii
Table of content ... iv
List of illustrations ... viii
List of tables ... ix
Abbreviations ... x
1. Introduction ... 11
2. Background ... 12
2.1 Emission ... 12
2.2 Rules and regulations ... 12
2.3 Engine options ... 13
2.4 FellowShip ... 15
2.5 Natural gas as fuel onboard ships ... 15
3. Methodology ... 16
3.1 Goal and scope definition ... 16
3.1.1 Allocations ... 16
3.2 Life cycle inventory analysis (LCI) ... 18
3.3 Life cycle impact assessment (LCIA) ... 18
3.4 Life cycle interpretation ... 19
3.5 Life cycle assessment software ... 20
3.6 Basic mathematics of LCA ... 21
3.7 Life cycle phases ... 23
4. Goal, scope and boundaries ... 25
4.1 Goal and scope ... 25
4.2 Boundaries ... 25
4.2.1 Choice of engine ... 26
5. Life Cycle Inventory analysis (LCI) ... 27
5.1 MTU fuel cell system ... 28
5.2 Rolls-Royce Marine gas engine ... 28
5.3 Construction ... 29
5.4 Operation ... 30

5.5 End of life ........ 30
5.6 Operation profile ........ 31
5.7 Implementing data in SimaPro ........ 32
5.7.1 Materials ........ 32
5.7.2 Operation ........ 33
5.8 Data collection and assumption ........ 34
5.8.1 Fuel cell system ........ 34
5.8.2 Gas engine ........ 34
5.8.3 Operational profile ........ 34
6. Life cycle impact assessment (LCIA) ........ 35
6.1 CML 2001 ........ 35
6.1.1 ADP (Abiotic depletion potential) ........ 35
6.1.2 AP (Acidification potential) ........ 35
6.1.3 EP (Eutrophication) ........ 35
7.1.4 GWP (Global warming potential) ........ 35
6.1.5 HTP (Human Toxicity Potential) ........ 36
6.1.6 Eco-toxicity ........ 36
6.1.7 Photochemical oxidation ........ 36
6.2 Eco-indicator 99 ........ 37
7. Life cycle interpretation (LCI) ........ 38
7.1 Results fuel cell system ........ 39
7.1.1 Materials ........ 39
7.1.2 Operation ........ 40
7.1.3 Total ........ 42
7.2 Results gas engine ........ 43
7.2.1 Materials ........ 43
7.2.2 Operation ........ 44
7.2.3 Total ........ 46
7.3 Gas engine compared to fuel cell ........ 47
7.3.1 Materials ........ 47
7.3.2 Operation ........ 48
7.3.3 Total ........ 49
7.4 Comparison between eco-indicator and CML categorization ........ 51
7.5 Gas engine and fuel cell compared to diesel engine ........ 55
8. Evaluation of the study ........ 57
8.1 Evaluation of data ........ 57

8.2 Evaluation of characterization models ........ 57
8.3 Evaluation of results ........ 58
9. Advantages and disadvantages of the engine systems ........ 60
9.1 Fuel cell system ........ 60
9.2 Gas engine ........ 61
9.3 Reliability ........ 61
9.4 Economical impact ........ 62
9.4.1 Capital cost ........ 62
9.4.2 Operational cost ........ 63
9.4.3 Life cycle cost ........ 63
10. Fuel cell development ........ 64
10.1 Environmental impact of increased lifetime ........ 64
10.2 Economical impact of increased lifetime ........ 65
10.3 Future development and improvements ........ 66
11. Recommendations and conclusion ........ 68
12. Further work ........ 69
13. References ........ 70
14. Appendix ........ I
14.1 Assignment text ........ I
14.2 Material, fuel cell ........ III
14.3 Fuel consumption and operation information, fuel cell ........ III
14.4 Operational information, gas engine ........ IV
14.5 Operational information, diesel engine ........ V
14.6 Operation profile ........ VI
14.6.1 Operation profile Viking Lady ........ VI
14.6.2 Operation profile, Petroatlantic ........ VII
14.6.3 Operation profile Petronordic ........ VIII
14.7 Flow chart, implementing in SimaPro ........ IX
14.7.1 Fuel cell materials ........ X
14.7.2 Fuel cell operation ........ XI
14.7.3 Fuel cell ........ XII
14.7.4 Gas engine materials ........ XIII
14.7.5 Gas engine operation ........ XIV
14.7.6 Gas engine ........ XV
14.8 Result figures ........ XVI

14.8.1 Fuel cell materials, CML characterized ..... XVII
14.8.2 Fuel cell materials, CML normalized ..... XVIII
14.8.3 Fuel cell materials, CML normalized ..... XIX
14.8.4 Fuel cell operation, CML normalized ..... XX
14.8.5 Fuel cell operation, CML distributed ..... XXI
14.8.6 Total result fuel cell, CML characterized ..... XXII
14.8.7 Total result fuel cell, CML normalized ..... XXIII
14.8.8 Gas engine material, CML characterized ..... XXIV
14.8.9 Gas engine material, CML normalized ..... XXV
14.8.10 Gas engine material, CML distributed ..... XXVI
14.8.11 Gas engine operation, CML normalized ..... XXVII
14.8.12 Gas engine operation, CML distributed ..... XXVIII
14.8.13 Total result gas engine, CML characterized ..... XXIX
14.8.14 Total result gas engine, CML normalized ..... XXX
14.8.15 Gas engine compared to fuel cell, materials, CML characterized ..... XXXI
14.8.16 Gas engine compared to fuel cell, materials, CML normalized ..... XXXII
14.8.17 Gas engine compared to fuel cell, operation, CML characterized ..... XXXIII
14.8.18 Gas engine compared to fuel cell, operation, CML normalized ..... XXXIV
14.8.19 Gas engine compared to fuel cell, total, CML characterized ..... XXXV
14.8.20 Gas engine compared to fuel cell, total, CML normalized ..... XXXVI
14.8.21 Gas engine compared to fuel cell, materials and operation, CML characterized ..... XXXVII
14.8.22 Gas engine compared to fuel cell, materials and operation, CML normalized ..... XXXVIII
14.8.23 Gas engine compared to fuel cell, Eco-indicator damage assessment ..... XXXIX
14.8.24 Gas engine compared to fuel cell, Eco-indicator damage assessment ..... XL
14.8.25 Gas engine compared to fuel cell, Eco-indicator normalized ..... XLI
14.8.26 Gas engine compared to fuel cell, Eco-indicator normalized ..... XLII
14.8.27 Gas engine compared to fuel cell, Eco-indicator weighted ..... XLIII
14.8.28 Gas engine compared to fuel cell, Eco-indicator weighted ..... XLIV
14.8.29 Gas engine compared to fuel cell, Eco-indicator single score ..... XLV
14.8.30 Gas engine compared to fuel cell, Eco-indicator single score ..... XLVI
14.8.31 Gas engine and fuel cell compared to diesel engine, CML characterized ..... XLVII
14.8.32 Gas engine and fuel cell compared to diesel engine, CML normalized ..... XLVIII
14.8.33 Gas engine and fuel cell compared to diesel engine, Eco-indicator single score ..... XLIX
14.8.34 Gas engine and fuel cell compared to diesel engine , Eco-indicator single score ..... L

# LIST OF ILLUSTRATIONS


FIGURE 1: Fuel cell reaction ........ 14
FIGURE 2: Allocations (ISO 2006) ........ 17
FIGURE 3: Simplified procedures for inventory analysis (ISO 2006) ........ 18
FIGURE 4: Life cycle assessment framework (ISO 2006) ........ 19
FIGURE 5: Basic foreground/ background system, (Strømman 2008) ........ 21
FIGURE 6: Life cycle phases (Strømman 2008) ........ 23
FIGURE 7: MCFC flow diagram (He 1998) ........ 26
FIGURE 8: Foreground and background process ........ 27
FIGURE 9: Assembly foreground process ........ 27
FIGURE 10: Life cycle model fuel cell ........ 32
FIGURE 11: Life cycle model materials ........ 32
FIGURE 12: Life cycle model operation ........ 33
FIGURE 13: Fuel cell material, CML characterized ........ 39
FIGURE 14: Fuel cell material, CML normalized ........ 40
FIGURE 15: Fuel cell material, CML distributed ........ 40
FIGURE 16: Fuel cell operation, CML normalized ........ 41
FIGURE 17: Fuel cell operation, CML distributed ........ 41
FIGURE 18: Total result fuel cell, CML characterized ........ 42
FIGURE 19: Total result fuel cell, CML normalized ........ 42
FIGURE 21: Gas engine material, CML normalized ........ 44
FIGURE 22: Gas engine material, CML distributed ........ 44
FIGURE 20: Gas engine material, CML characterized ........ 44
FIGURE 23: Gas engine operation, CML normalized ........ 45
FIGURE 24: Gas engine operation, CML distributed ........ 45
FIGURE 25: Total result gas engine, CML characterized ........ 46
FIGURE 26: Total result gas engine, CML normalized ........ 46
FIGURE 28: Gas engine compared to fuel cell, material, CML normalized ........ 47
FIGURE 27: Gas engine compared to fuel cell, material, CML characterized ........ 47
FIGURE 30: Gas engine compared to fuel cell, operation, CML normalized ........ 48
FIGURE 29: Gas engine compared to fuel cell, operation, CML characterized ........ 48
FIGURE 31: Gas engine compared to fuel cell, total, CML characterized ........ 49
FIGURE 32: Gas engine compared to fuel cell, total, CML normalized ........ 49
FIGURE 33: Gas engine compared to fuel cell, material and operation, CML characterized ........ 50
FIGURE 34: Gas engine compared to fuel cell, material and operation, CML normalized ........ 50
FIGURE 35: Gas engine compared to fuel cell, Eco-indicator damage assessment ........ 51
FIGURE 36: Gas engine compared to fuel cell, Eco-indicator damage assessment ........ 51
FIGURE 37: Gas engine compared to fuel cell, Eco-indicator normalized ........ 52
FIGURE 38: Gas engine compared to fuel cell, Eco-indicator normalized ........ 52
FIGURE 39: Gas engine compared to fuel cell, Eco indicator weighted ........ 53
FIGURE 40: Gas engine compared to fuel cell,Eco-indicator weighted ........ 53
FIGURE 41: Gas engine compared to fuel cell, Eco-indicator single score ........ 54
FIGURE 42: Gas engine compared to fuel cell, Eco-indicator single score ........ 54

FIGURE 43: Gas engine and fuel cell compared to diesel engine, CML charecterized .......................... 55
FIGURE 44: Gas engine and fuel cell compared to diesel engine, CML normalized ............................. 55
FIGURE 45: Gas engine and fuel cell compared to diesel engine, Eco-indicator single score ............... 56
FIGURE 46: Gas engine and fuel cell compared to diesel engine, Eco-indicator single score ............... 56
FIGURE 47: Impact reduction by increasing fuel cell lifetime ............................................................ 64
FIGURE 48: Single score comparison, increased lifetime fuel cell ...................................................... 64
FIGURE 49: Distribution life cycle cost ............................................................................................. 65
FIGURE 50: Increased lifetime, fuel cell ............................................................................................ 65
FIGURE 51: Equivalent life cycle cost ................................................................................................ 66

## LIST OF TABLES

Table 1: Materials fuel cell ................................................................................................................ 29
Table 2: Fuel consumption and emission ............................................................................................ 30
Table 3: Operation profile .................................................................................................................. 31
Table 4: Categories with units ............................................................................................................ 38
Table 5: Capital cost .......................................................................................................................... 62
Table 6: Operational cost ................................................................................................................... 63
Table 7: Life cycle cost ....................................................................................................................... 63

# ABBREVIATIONS

CH - Switzerland

$CO_2$ – Carbon dioxide

ECA- Emission Control Areas

FC- Fuel Cell

GLO - Global

HFO – Heavy Fuel Oil

IMO – International Maritime Organization

IO – Input-Output (input-output table)

IOA – Input-Output Analysis

ISO – International Standards Organization

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA- Life Cycle Inventory Assessment

LNG – Liquefied Natural Gas

MARPOL – The International Convention for the Preventing of Pollution from Ships

MCFC - Molten Carbonate Fuel Cell

MCR – Maximum Continuous Rating

MDO- Marin Diesel Oil

NG- Natural Gas

$NO_X$ – Nitrogen oxide

PM – Particle Matters

RER - Europe

SECA- Sulfur Emission Control Area

$SO_X$ – Sulfur oxide

U – Unit process

# 1. INTRODUCTION

The ongoing global climate discussions are widespread and the need for change seems inevitable. Today, shipping contributes with 1 billon ton $CO_2$ yearly, this is a result of 350 million ton burned heavy fuel oil (HFO).(Madsen 2009) Calculating with a sulfur level of 4,5% this equals 32 million ton $SO_X$ emissions every year. (Sustainable_shipping.com 2010) Shipping also contributes to a large $NO_X$ release, depending on the engine a ship can emit approximately 100 kg $NO_X$ per ton burned HFO. This give a total of 35 million ton $NO_X$ released to air. (Stapersma 2009) Total emission release for the world shipping fleet is overwhelming, but compared to rail and road transport seaborne cargo is still more environmental friendly.

By introducing more efficient machinery solutions the fuel consumption will decrease, and the emission levels will thereby be reduced. Lower fuel consumption reduces especially $CO_2$ which is difficult to reduce using other methods. By switching from HFO and diesel oil to gas, $NO_X$ and $SO_X$ is minimized and $CO_2$ is reduced. The challenge is how to use the fuel efficiently. Natural gas can be used as an energy source by using alternative technologies. Gas turbines and gas engines are becoming more standard, but also fuel cells have risen in popularity. In a fuel cell the chemical energy in the natural gas is transferred directly into electric energy. Fuel cell technology has been introduced onboard ships in recent years. Fuel cells are said to have higher efficiency than traditional engines. They operate at high temperatures which make it possible to use the waste heat in combined cycle operations with for example a gas turbine, to increase the efficiency furthermore. (Vielstich, Gasteiger et al. 2003) In this article we will evaluate the effect that use of fuel cell systems onboard ships has on the level of emissions compared to gas engines.

As a tool to evaluate the effect of a fuel cell and the gas engine a life cycle assessment (LCA) approach is used. LCA is a technique for assessing the environmental aspects and potential impacts associated with a product. The main objective of the LCA is to minimize the energy consumption, environmental impact and the amount of materials (Strømman 2008). The ship industry is one of the main contributors to global anthropogenic emissions. By reducing the environmental impact a ship-owner can reduce environmental tax cost. Sustainable ship design and operation management are to be two leading core areas.

# 2. BACKGROUND

## 2.1 Emission

Shipping has always been a big contributor to global warming. $CO_2$ is considered the largest contributor to greenhouse gases. $CO_2$ emission from ships is depending on the carbon content of the fuel and the fuel consumption. Therefore the solution to reduce $CO_2$ emission is to switch to more efficient machinery solutions or to use alternative fuel. Today there are no good solutions to reduce $CO_2$ from the exhaust gas, but the industry is currently seeking improvements in this area.

$NO_X$ and $SO_X$ are the main contributors to acid rain. Acid rain leads to a decrease in the pH-value of rainwater and fog from 5.6 to 4 and below, this damage the ecosystems. $NO_X$ and $SO_X$ influence the human health. Exposure to high $NO_X$ concentration may cause short term changes in airways responsiveness and lung function, but the main problem is long term exposure that can cause larger damage to the lungs. $SO_X$ and particular matters (PM) are dangerous for the human health as $SO_X$ has a negative effect on the lung volume and PM damage the flagellum.

Emission from ship engines is not only related to emission to air. The manufacturing of the engine and the material selection influences the environment as well. Heavy metals and metal production has a negative influence on different ecosystems, and energy is consumed in the manufacturing process. (Stapersma 2009)

## 2.2 Rules and regulations

In recent years the rules and regulations for emission have become stricter due to more focus on global warming and the damaging impact on the environment and human health. The International Maritime Organization (IMO) was established in Geneva 1948. The main focus of the convention is to regulate the shipping industry. (IMO 2009) In 1973 IMO adopted The International Convention for the Preventing of Pollution from Ships (MARPOL), and is now the main regulator for marine pollution. MARPOL regulates pollution by oil, chemicals, harmful substances in packaged form, sewage and garbage. Today the convention regulates the following topics, where especially the last three are of relevance for this assignment. (MARPOL 2009)

| | |
|---|---|
| Annex I | Regulations for the Prevention of Pollution by Oil |
| Annex II | Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk |
| Annex III | Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form |
| Annex IV | Prevention of Pollution by Sewage from Ships |
| Annex V | Prevention of Pollution by Garbage from Ships |
| Annex VI | Prevention of Air Pollution from Ships (entry into force 19 May 2005) |

The MARPOL Annex IV (MARPOL 2009) is the main regulator for emission to air. Until now the focus in IMO has been on emission to air of $NO_X$ and $SO_X$. In March/April 2008 new regulations for emission were announced.

The $NO_X$ emissions shall, from January 1 2011, be reduced by 20 % out of today's requirements of new build vessels. By the beginning of 2016 the emissions shall be reduced by 80 %. The last requirement is known as Tier III, and this applies to all ships built after January 1 2016, sailing in Emission Control Areas (ECA). Maximum emission of $NO_2$ is 3,4 g/kWh for engines speed of less than 130 rpm, and 2 g/kWh for engines speed of 2000 rpm or more. For ships operation outside ECA the limit is set to Tier II. This requires maximum $NO_2$ emission of 14.4 g/kWh for engine speed less than 130 rpm and 7,7 g/kWh for engine speed of 2000 rpm or above.

Today the maximum amount of sulfur in heavy crude oil is 4,5 %. From January 1 2012 the maximum limit is 3,5 %, and from year 2020 the limit will be 0,5 %. Sulfur emission control areas (SECA) implements the global official requirements. There are two main SECA areas, the Baltic Sea and the shore outside California. Here the limit of sulfur content in the fuel will be 0,1 % within year 2015. Ships passing the SECA border have to carry a written procedure showing how the fuel change-over is done.

Particles are to be removed from the exhaust. By reducing $NO_X$ and $SO_X$, PM is reduced. Emission of $CO_2$ is not yet regulated, even though the impacts from $CO_2$ are recognized as severe. If restrictions are made on pollution of greenhouse gases, more efficient machinery solutions may be required. (MARPOL 2009)

## 2.3 Engine options

A fuel cell is an electrochemical cell that produces electricity from different fuels like hydrogen or liquid natural gas (LNG). The power is not generated by regular combustion, but from a chemical reaction between the fuel (anode) and the oxidant (cathode). There are different types of fuel cells, but one of the most applicable onboard ships with high power demand is the Molten Carbonate fuel cell (MCFC). This fuel cell can use LNG as fuel source. The electrolyte in a MCFC is a mixture of lithium carbonate and potassium carbonate, which forms a highly conductive molten salt. The carbonate ions $CO_3^{2-}$ provides for the ionic conduction through the electrolyte. The fuel cell requires supply of carbon dioxide to the cathode to form the carbonate ions, and the same amount of carbon dioxide will be formed at the anode, which can be recycled and fed back into the cathode. (Larminie and Dicks 2003) Figure 1 below shows the principle and structure of a MCFC using hydrogen fuel. When LNG is used as fuel, mainly consisting of methane, the fuel goes through steam reformation, either in a separate reformer or at the anode. Carbon monoxide and water are the products of this reaction. The carbon monoxide is then oxidized into carbon dioxide in a water-gas shift reaction. (Li 2006)

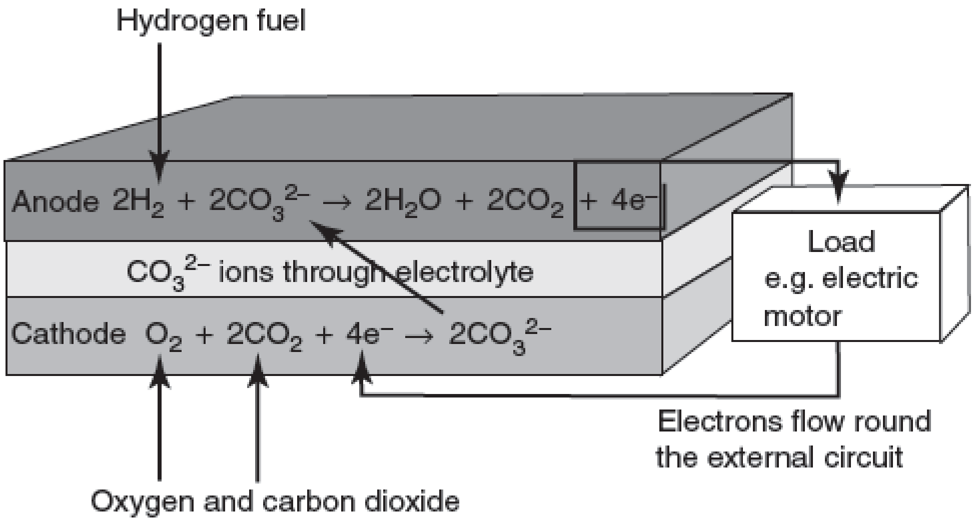


FIGURE 1: FUEL CELL REACTION

The MCFC is a high temperature fuel cell. The high temperature increases the activation process at the electrodes, which gives the advantage of not needing a noble catalyst. An advantage of this is that it can run on fuels with carbon content. The high temperature makes it possible to use the waste heat in combined cycle operations, for example with a gas turbine. The high operating temperature results in long startup time, which limits the potential for mobile applications. The fuel cell operating temperature is around 650°C, and it can achieve efficiencies of 40-50%. In a combined cycle with reuse of waste heat, the efficiency can be above 70%.

Gas engines are combustion engines operating according to the Otto-process. The difference from diesel engines is that they have a spark plug for ignition of the fuel. The lean burn technology, meaning adding more air than necessary to the combustion, allows the peak burn temperature to be reduced. By lower temperatures the $NO_X$ emission is reduced. Gas engines run on LNG have less emission of carbon dioxide than diesel engines, even though the efficiency of the engines is about the same. This is due to due to lower contents of carbon in LNG compared to MDO, and the high heating value of LNG. (Wärtsilä 2009)

Both gas engines and fuel cells are assumed to be more environmentally friendly than the cheaper regular engines, using MDO and HFO as fuel. Due to regulations regarding $NO_X$, $SO_X$ and PM reduction there are several methods available today to reduce these emissions. It is expected that regulations to reduce $CO_2$ will be implemented in MARPOL in the future. When this happens the ship industry has to be ready to follow these rules. Both fuel cells and gas engines reduce $NO_X$, $SO_X$ and $CO_2$ emissions. In this report we want to consider the differences between these two machinery solutions, and what there is to gain on using one instead of the other.

## 2.4 FellowShip

This choice of fuel cell is based on the FellowShip project. FellowShip is a joint industry R&D project performed by DNV, Wärtsilä, MTU onsite energy and Eidesvik Offshore ASA. The vessel was designed by Wärtsilä Ship design, and the fuel cell system by the German company MTU Onsite Energy GmbH. The goal with this project is to develop and demonstrate the use of high temperature fuel cells onboard ships, and thereby reduce $CO_2$ emissions and improve energy efficiency. The project is divided into two parts: Phase 1 of the project started in 2003 and ended in 2007, and consisted of development, research and initial design. The fuel cell system chosen for installation is a 320 kW MCFC (molten carbonate fuel cell) system prototype running on LNG as fuel. The main machinery onboard the ship is also run on LNG. The second phase of the project, which will be finished in 2010 according to the plan, involves the integration of the system, testing and evaluation. (FellowShip 2010)

The fuel cell system was installed in the supply vessel Viking Lady, owned by Eidesvik Offshore, during the fall of 2009. The testing is being performed at the time of writing (spring 2010). The efficiency results of the fuel cell without heat reuse were ready and provided to us in May 2010. The testing with heat recovery has not been performed. (Haugen 2010)

## 2.5 Natural gas as fuel onboard ships

Natural gas was first introduced as fuel onboard ships in Norway in the year 2000, on the ferry Glutra. This project was funded by the Norwegian Government. The background of this project was that the Norwegian transportation authority's wanted to make use of the available natural gas resources that Norway has. The machinery system onboard this ferry consists of four gas engine generator sets of 675 kW each. (Einang 2000) It has not been registered any severe problems caused by the choice of fuel and machinery. (Storting 2010)

The Viking Energy, a support vessel owned by Eidesvik and designed by Vik Sandvik, was the first ship of its type run on LNG. It is powered by four Wärtsilä dual fuel engines with an output of 2010kW each. The vessel was put into operation in the year 2003, and has been in operation since. This vessel has shown an emission reduction of 20% $CO_2$ and 89% $NO_X$ when switching from diesel to LNG as fuel. (Fr.Meling 2006) During the first 5 years of operation the engines have been run on LNG 97% of the time. There has not been reported any down time of the vessel due to the gas system onboard. (Skrede 2008)

The use of LNG as fuel on ships has gained a status mature technology, and there are many brands and sizes of gas engines available. Since the testing of the fuel cell system run on LNG onboard the Viking Lady shows promising results, this technology is believed to be seen in use in the future. The question we want to answer is whether the use of fuel cell technology is competitive with gas engines when it comes to emissions, cost and reliability when both are run on LNG. This is only realistic if the volume and cost of the fuel cell is reduced.

# 3. METHODOLOGY

Life cycle assessment (LCA) is an environmental management technique. The purpose is to develop an analysis that calculates the environmental impacts throughout the lifetime. The International Organization for Standardization (ISO) has developed standards for the LCA model. ISO 14040 and 14044 consist of principles, framework, requirements and guidelines. (ISO 1999) (ISO 2006) The layout in this study is based on this method.
A LCA consist of four phases:

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

The goal and scope phase defines the system boundaries and level of details, also called the framework of the assessment. Based on the framework an inventory analysis (LCI) is implemented. The purpose with the LCI is to find superior input-output data. The next phase provides additional information to implement in the analysis; this phase is the lifecycle impact assessment (LCIA). The last phase, the interpretation, contains a conclusion and a summary to present the information. The end result is the solution of the assessment, and a recommendation is made. (Strømman 2008)

## 3.1 Goal and scope definition

The goal and scope of an LCA study should be clearly defined and consistent with the intended applications. It should include the product to be studied and the reason for performing the study. The boundaries of the study shall limit and clarify which processes that are taken into account. This is to be consistent with the goal and scope of the study. In a comparative study, the equivalence of the two systems is to be evaluated before the interpretation of the results. The systems are to be consequent, using the same functional unit and equivalent methodological evaluation.

The functional unit is to be consistent with the goal and scope of the study. It is important that the unit is measurable. The purpose of the functional unit is to provide a reference that normalizes the input and output data.

### 3.1.1 ALLOCATIONS

In an input output model different processes are gathered to see the final result. In this procedure it is vital that the same process is not taken into account several times. Double counting can mislead the result and give an uncorrected comparative base. The ISO 14044 standard has provided three Allocation procedure steps. The first step states that allocations should be avoided by either dividing the process to be allocated into sub-processes or expand the product system to include additional functions. Step two and three establishes methods to use when allocations cannot be avoided. Step two is a method to divide the input output data directly under the products in the system. Step three is a result of the conserves of non physical relationship. In this case the input data should allocate between the products. In addition to this, there are specific regulations regarding allocations in the reuse and recycling phase. In this phase it is important to take into count the inherent properties of the materials. The same methods to prevent allocations are used in this case. Dividing the input and output data at the subsystems prevents that the correct data is reused or recycled. Figure 2 describes the distinction between a technical description of a product system and allocation procedures for recycling. There are four different ways to look at the problem, the easiest is to recycle the product in the same closed loop, more difficult is it to recycle products in a different product, a transaction in an open loop. (ISO 2006)

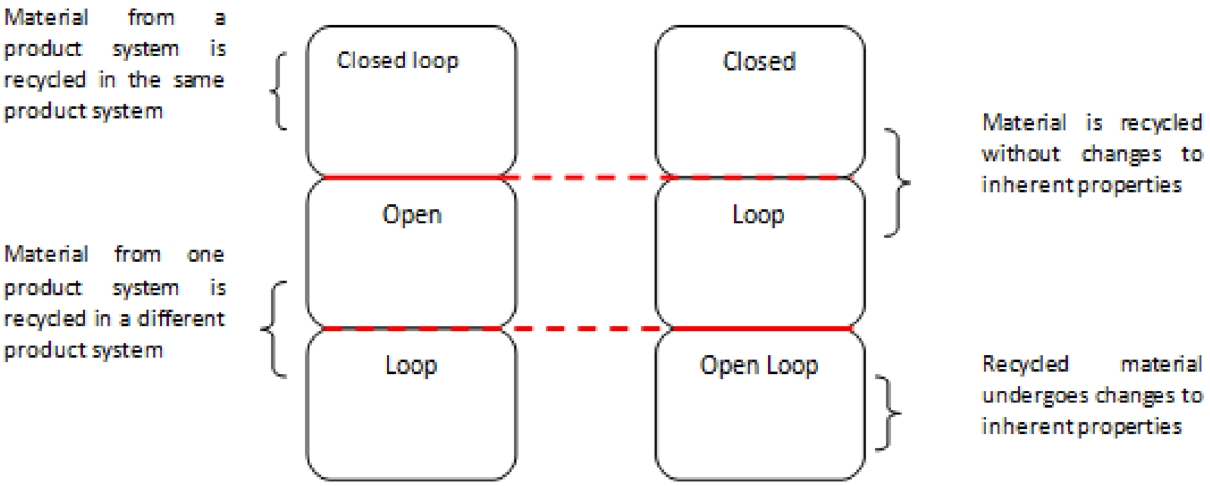


FIGURE 2: Allocations (ISO 2006)

## 3.2 Life cycle inventory analysis (LCI)

The inventory analysis is the second step of the study. The definition of goal and scope provides the initial plan for the inventory. Figure 3 displays the steps that should be performed in an inventory analysis. This includes collection, preparation and validation of data. It is important that the data is well documented and that assumptions are clearly stated and explained. A validity check shall be done during collection of data. This is done to provide evidence that the data quality meet the required standards. To relate the data to the functional unit it is essential that the output input data can be related to an appropriate flow for each unit process. (ISO 2006)

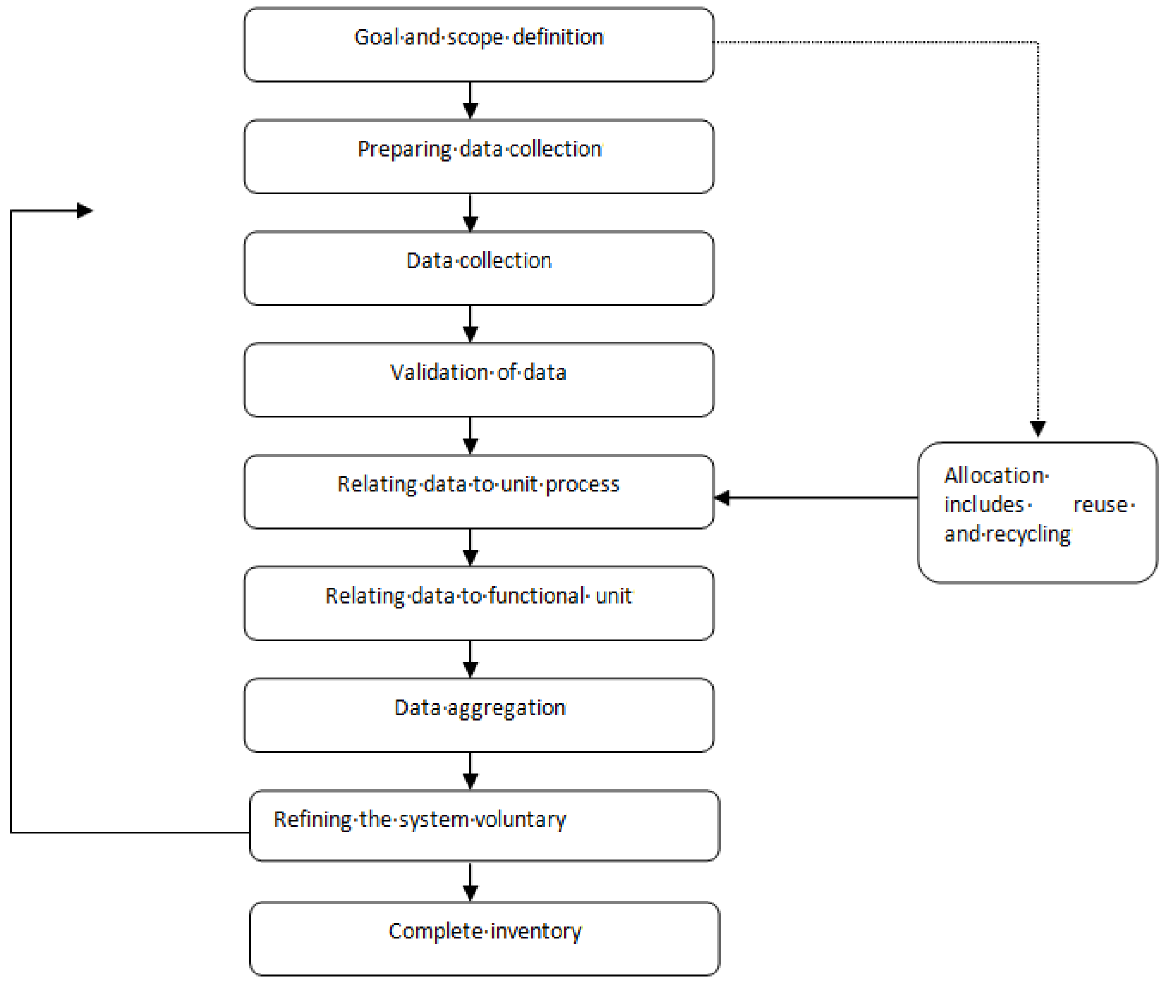


FIGURE 3: SIMPLIFIED PROCEDURES FOR INVENTORY ANALYSIS (ISO 2006)

## 3.3 Life cycle impact assessment (LCIA)

Life cycle impact assessment (LCIA) is a relative approach based on the functional unit. It shall include selection of impact categories, categories indication and characterization models. The impact categories shall be both justified and consistence with the goal of the study. (ISO 2006) Special models are developed by different institutions, too make secure results. The CML 2 Baseline uses a midpoint, problem orientated approach. This method shows the result in ten sub categories, with different values. This includes inter alia global warming potential, human toxicity and marine aquatic ecotoxicity. These ten sub categories give a normalized and characterized score. This means that the result is given with respect on the individual categorize, and not as a total score. Another method, the Eco-indicator, is damage-orientated. This approach uses in addition to the normalization and characterization a weighting procedure evaluating the different categories against each other. Because of this weighting procedure a single score result can be established. A single score display the total impact from the product in one impact score. This score is divided into three main ending damage groups, recourses, ecosystems and human health. The result gives a total value of the environmental damage. (PRè-Consultants 2008)

## 3.4 Life cycle interpretation

The interpretation of the life cycle is a four step evaluation. It includes the results, the assumptions and limitations associated with the results and the methodology and the data collection, the data quality assessment and the terms of value choices and expert judgments. The figure below gives an overview of the relationship of the interpretation phase and other phases of the LCA. As displayed the interpretation is dependent on the previous LCA phases and gives input to the direct applications. Interpretations are results of identifications of significant issues and evaluation checks. These two lead to the conclusions, limitations and recommendations. (ISO 2006)

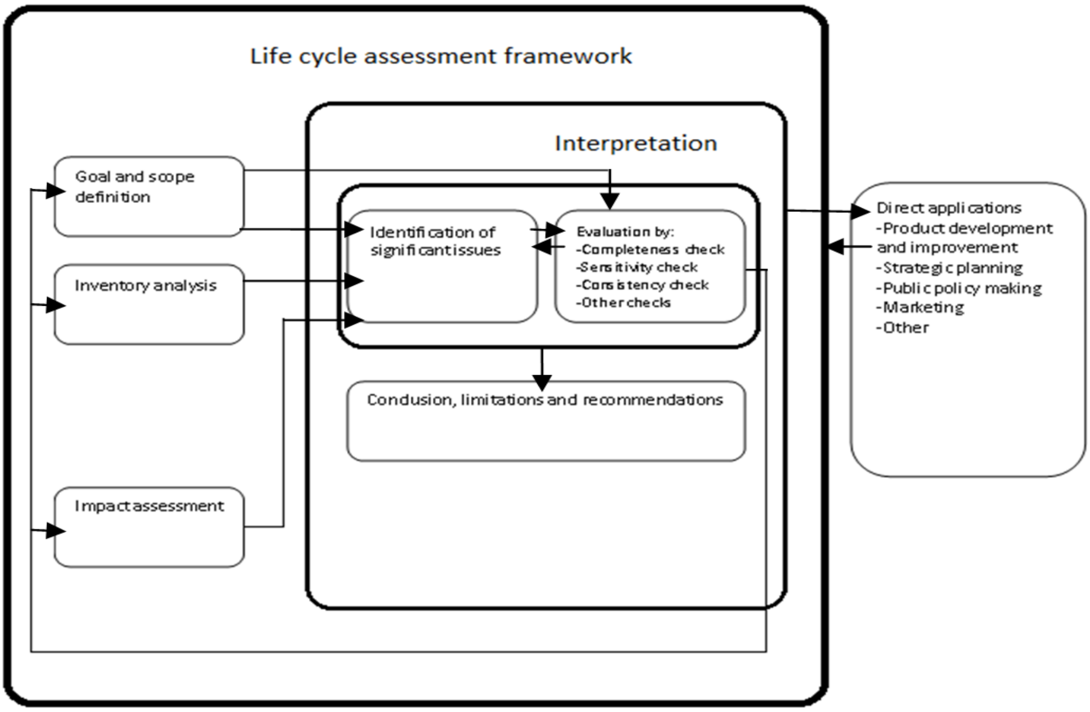


FIGURE 4: LIFE CYCLE ASSESSMENT FRAMEWORK (ISO 2006)

The results of the Life cycle interpretation (LCI) and life cycle impact assessment (LCIA) shall be interpreted according to the goal and scope of the assessment. The LCI results should be interpreted with caution because they refer to input and output data and not to the environmental impact. In addition to this the uncertainty of the data has to be considered to evaluate the results. (ISO 2006)

## 3.5 Life cycle assessment software

To calculate the LCA a software program named SimaPro is used. SimaPro is a professional software tool which collects, analyzes and monitors the environmental performance of products and services. It was first developed in 1990, and has since developed to be one of the most used LCA software worldwide. It is based on the ecoinvent database providing over 4000 processes. In addition to the ecoinvent database it is possible to add own processes. (SimaPro7 2008) While the ecoinvent database provides SimaPro with possesses, the study needs a method to calculate the result. There are several categorization methods to implement to get an overview of the consequences in the impact assessment phase.

SimaPro is modeled after the ISO 14040 and ISO 14044 standards. The version used in this study is the SimaPro 7.1.8 Multi user.(SimaPro7 2008) The main menu contains goal and scope, inventory, impact assessment, interpretation and general data. The program displays a process tree which gives an overview of the modeled processes. In the inventory processes and products are defined, they are collected from the ecoinvent database or added manually. Especially in the operating phase, different operating levels occur and this needs to be added manually. Parameters connected to waste are included at the end. In the impact assessment the environmental effect is calculated. It is important to monitor and understand the processes to get an optimal result. Allocation is a huge pitfall. This means that a process is taken into account several times, giving a double counting. The program calculates the different impacts using the categorization model of choice. The result is displayed in graphs and by numeric presentation. It is possible to compare two or more products enabling an evaluation of the differences between the products.

Ecoinvent Center is an organization created in 1997, at that time called The Swiss Center for Life Cycle Inventories. Their main product is the ecoinvent database, which is based on the older ETH-ESU 96 database. (Ecoinvent 2010) ETH_ESU 96 was established in 1996 as a joint project between the university ETH and the consulting company EUS. This database was the first to be compiled with feedback loops and the main focus was on energy convention technologies. Today ecoinvent is recognized as the best quality and most complete database for European purpose. It has a wide range of process categories and includes the vital materials. The database has been developed by several institutions, including ETHZ (The Swiss Federal Institute of technology Zürich), PSI (Paul Scherrer Institute) and EMPA (Swiss Federal Laboratories for Material Testing and research). A new version was released in 2009. (Strømman 2008)

## 3.6 Basic mathematics of LCA

SimaPro is based on basic LCA mathematics. To get a better understand of the calculations done in SimaPro this chapter will give a basic overview of the mathematics implemented in the program.

A LCA problem can be displayed as a system containing different processes (nodes with numbers) each represented with input and output values. The figure below displays a foreground system ($A_{ff}$) receiving information from a background system ($A_{bb}$). This results in a final emission release ($y_1$). (Strømman 2008)

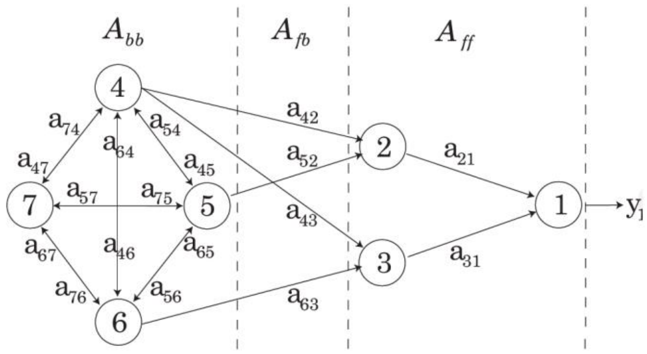


FIGURE 5: BASIC FOREGROUND/ BACKGROUND SYSTEM, (STRØMMAN 2008)

For each process, information regarding the input value is collected. A process can be manufacturing of the steel engine. This is formed into an A matrix or requirement matrix, see equation 1. $a_{12}$ represents the input required from process 2 per unit output from process 1. To produce the engine, there has to be an input of steel. The explanation for $a_{11}$ is a little different; this product has an input of something it also produces. An example of this can be construction steel used to construct the fabric that produces steel.

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} \quad (1)$$

To be able to establish a correct picture of the total demand we need to define the amount of every production that is found in the ending product. The output vector $x_i$ defines this. $y_i$ defines the external demand of the processes.

$$x = Ax + y \quad (2)$$

The x vector is the unknown and thereby the formula has to be solved with respect on x.

$$x = (I - A)^{-1} y \text{ -->} \quad \text{where } L = (I - A)^{-1} \quad (3)$$

The last expression is known as the Leontief Inverse. It is important that the matrix is invertible and self-sustaining, the Hawkins-Simon condition.

To be able to calculate the total impact or emission we have to implement a contribution analysis. The total impact for a given external demand is given as a stressor intensity matrix, S.

$$S = \begin{bmatrix} s_{11} & \cdots & s_{1,pro} \\ \vdots & \ddots & \vdots \\ s_{1,str} & \cdots & s_{str,pro} \end{bmatrix} \tag{4}$$

By multiplying this with the x vector we get a vector of stressors generated for a given demand, e. This is the total emission generated in a production network, per process.

$$e = Sx => \begin{bmatrix} e_1 \\ \vdots \\ e_{str} \end{bmatrix} = \begin{pmatrix} s_{11} & \cdots & s_{1,pro} \\ \vdots & \ddots & \vdots \\ s_{str,1} & \cdots & s_{str,pro} \end{pmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_{pro} \end{bmatrix} \tag{5}$$

In order to get a better understanding of the process the E matrix is developed. The E matrix tells us which stressor we are dealing with and the amount of emission this stressor release.

$$E = \begin{pmatrix} e_{11} & \cdots & e_{1,pro} \\ \vdots & \ddots & \vdots \\ e_{pro,1} & \cdots & e_{str,pro} \end{pmatrix} = \begin{pmatrix} s_{11} & \cdots & s_{1,pro} \\ \vdots & \ddots & \vdots \\ s_{str,1} & \cdots & s_{str,pro} \end{pmatrix} \begin{pmatrix} x_1 & 0 & a_{1n} \\ 0 & \ddots & 0 \\ a_{m1} & 0 & x_{pro} \end{pmatrix} \tag{6}$$

To be able to compare the different emissions the characterization factor(C) is added. This matrix changes with respect to which impact assessment is used.

$$C = \begin{bmatrix} c_{11} & \cdots & c_{1,str} \\ \vdots & \ddots & \vdots \\ c_{imp,1} & \cdots & c_{imp,str} \end{bmatrix} \tag{7}$$

Then the total impact can be calculated, d is the total impact for the given stressors

$$d = Ce \tag{8}$$

The different processes contribute to the various impact categories, and it is also possible to get emissions from the varying stressors. This is the final solution, which can be evaluated. This refers to the different impact categories established in chapter x.

$$D_{pro} = CE = CS\hat{x} = CS\widehat{Ly} = CS\widehat{(I-A)^{-1}y} \tag{9}$$

$$D_{str} = C\hat{e} = C\widehat{Sx} = C\widehat{SLy} = C\widehat{S(I-A)^{-1}y} \tag{10}$$

To be able to connect this mathematics into a bigger system, a background and foreground system and a link between these two has to be clarified. This is done by extending the A and S matrix

$$A = \begin{pmatrix} A_{ff} & 0 \\ A_{bf} & A_{bb} \end{pmatrix} \tag{11}$$

To include an economic aspect of the assignment a Hybrid LCA can be developed. Here the foreground system refers to units and the background system refers to economic flow (Strømman 2008).

## 3.7 Life cycle phases

To get a better LCA understanding of the system description the life cycle phase structure is a good model. In this model the transaction between construction, operational and dismantling is important. The model is as described in figure 6. This is the foreground system of the model. The red line ending in $y_{O1}$ represent the total external demands. The small arrows represent the internal demand to the different processes from the background system. An example of this is the fuel cell system divided in three parts: The stack (part 1), the HotModule (part 2) and the fuel supply (part 3). C3 represents fuel supply construction, O3 is fuel supply operation and D3 is dismantling of the fuel supply. The same notation is applicable for the other parts, and more parts may be added in the final structure

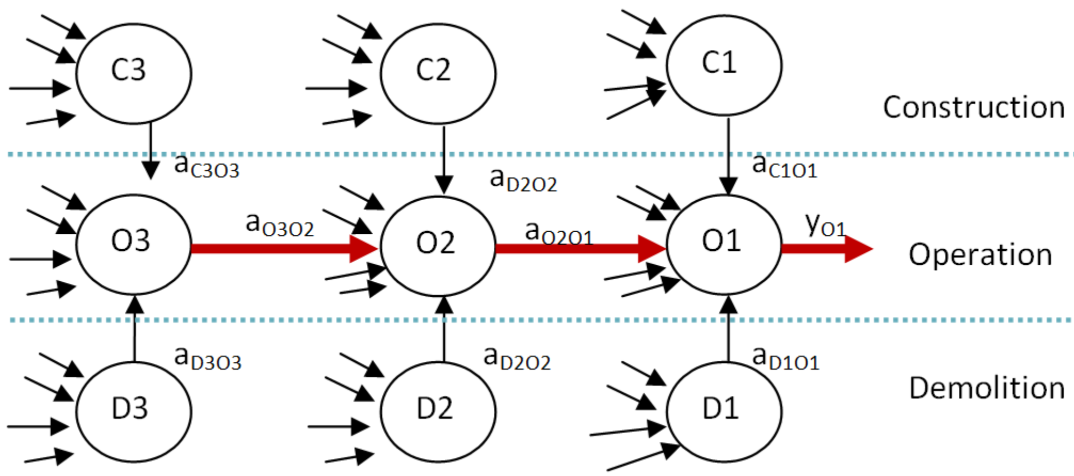


FIGURE 6: LIFE CYCLE PHASES (STRØMMAN 2008)

$a_{OiDi}$ represent the amount over a lifetime of dismantling that is to be considered in the operation phase. To get the amount over a lifetime of construction that is to be taken into count in operation $a_{OiCi}$ is used.

$$a_{CiOi} = a_{DiOi} = \frac{1}{total\_production\_over\_lifetime} = \frac{1}{m_{year}\tau_{life}} \qquad (12)$$

To be able to evaluate the final stressor and the impact an A-matrix has to be established. I-Aff describes the difference between the processes in the foreground system. $A_{nf}$ describes the transaction between the background system $A_{bb}$ and the foreground system $A_{ff}$. $A_{bf,I}$ describes the transaction from the background system to foreground system for the different sub-system. The resulting matrix is as shown in equation 13 (Strømman 2008).

$$\begin{bmatrix} I - A_{ff} \\ -A_{nf} \end{bmatrix} = \begin{bmatrix}
 & \vdots & O1 & O2 & O3 & \vdots & C1 & C2 & C3 & \vdots & D1 & D2 & D3 \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
O1 & \vdots & 1 & & & \vdots & & & & \vdots & & & \\
O2 & \vdots & -a_{O2O1} & 1 & & \vdots & & 0 & & \vdots & & 0 & \\
O3 & \vdots & & -a_{O3O2} & 1 & \vdots & & & & \vdots & & & \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
C1 & \vdots & -a_{C1O1} & & & \vdots & 1 & & & \vdots & & & \\
C2 & \vdots & & -a_{C2O2} & & \vdots & & 1 & & \vdots & & 0 & \\
C3 & \vdots & & & -a_{C3O3} & \vdots & & & 1 & \vdots & & & \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
D1 & \vdots & -a_{D1O1} & & & \vdots & & & & \vdots & 1 & & \\
D2 & \vdots & & -a_{D2O2} & & \vdots & & 0 & & \vdots & & 1 & \\
D3 & \vdots & & & -a_{D3O3} & \vdots & & & & \vdots & & & 1 \\
\cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\
b & \vdots & & -A_{bf,O} & & \vdots & & -A_{bf,C} & & \vdots & & -A_{bf,D} &
\end{bmatrix} \qquad (13)$$

The two methods above give a quick introduction to the basic mathematics that is used to develop a LCA. SimaPro is an advanced software making it possible to calculate the environmental impact in a larger scale and at the same time provide the assessment with proper data from various databases. These chapters are provided to give an understanding of the processes done in SimaPro. It is not proven that SimaPro uses this exact method to calculate the impact, but it is possible to calculate this study based on basic LCA mathematics and other mathematics. Because of the complexity of the matrix Matlab can be used as a calculation tool.

# 4. GOAL, SCOPE AND BOUNDARIES

## 4.1 Goal and scope

The main intention of the thesis is to perform a comparative Life cycle Assessment (LCA) study comparing environmental consequences of switching from traditional engines to fuel cells. Further, by implementing a cost and reliability discussion to the environment analysis, it is the intention to be able to recommend the implementation of fuel cells onboard a ship. A final evaluation shall be performed aiming at identifying whether the use of fuel cells is recommendable for power supply onboard ships or not.

As a baseline for our project we will look into the FellowShip project, since this is one of very few projects going on in the industry regarding the use of high temperature fuel cells onboard ships. FellowShip is a joint industry R&D (research and development) project performed by DNV, Wärtsila, Eidesvik Offshore ASA and MTU.(F.C.Bulletin 2009) The purpose with this pilot project is to develop and demonstrate use of fuel cells on ships, and thereby reduce $CO_2$ emissions and improve energy efficiency.

## 4.2 Boundaries

The boundaries of the study are based on information given from manufacturer and operators. We have narrowed it down to functional unit, time horizon, allocations and choice of engines.

In this case study the functional unit has to be able to compare a fuel cell and an electrical gas engine. 1kWh represent the amount of energy transformed from the system over a time period of one hour. By using this unit the chance for allocations is low, the results are measurable and in accordance with the goal.

The lifetime of the compared components is put to 20 years. This is done to have an equal time horizon, due to short lifetime of the fuel cell. The environmental impact and operational cost will be influenced by this time scale. A 20 year timeline will include all life cycle phases.

In this study the probability for allocations is low. The system is simple and the functional unit is easy to track. Because of the chosen comparative system the fuel supply is equal; this makes the probability for allocations lower. Because of the complexity of estimating the energy consumption of processing the materials into products, this is not evaluated in this study. This eliminates the allocations problems with respect to energy use.

The largest probability for allocations is in the reuse and recycling phase. By using SimaPros reuse/recycle function it is difficult to see what is reused and what is recycled. In this study 75% of the materials are recycled, but we have little control on what is reused and what effect this has. By using a closed loop, more control is gained. A closed loop prevents other materials than those used in the product to be recycled.

### 4.2.1 CHOICE OF ENGINE

In this case study a gas engine from Rolls-Royce is compared with a fuel cell from MTU. The choice of fuel cell was based on the installation at the Viking Lady. Since we want to compare the results from the life cycle analysis of a fuel cell with the results from a gas engine, it has been important to find a gas engine of the right size. There are very few gas engines installed in marine vessel of this size. To be able to compare the two solutions an upscale of the fuel cell system was used for this comparison. The study is limited to the engine systems, this involves the material used in construction, fuel production and emission release in the operation phase.

The fuel cell installed onboard the Viking Lady is of the type molten carbonate fuel cell, MCFC, with an output of 320kW. This fuel cell has been upscaled with factor of 10, the same size as the gas engine. This fuel cell has to be replaced two times in a 20 year lifetime. Below a schematic flow diagram of a MCFC is displayed. This shows the components needed in a fuel cell system.

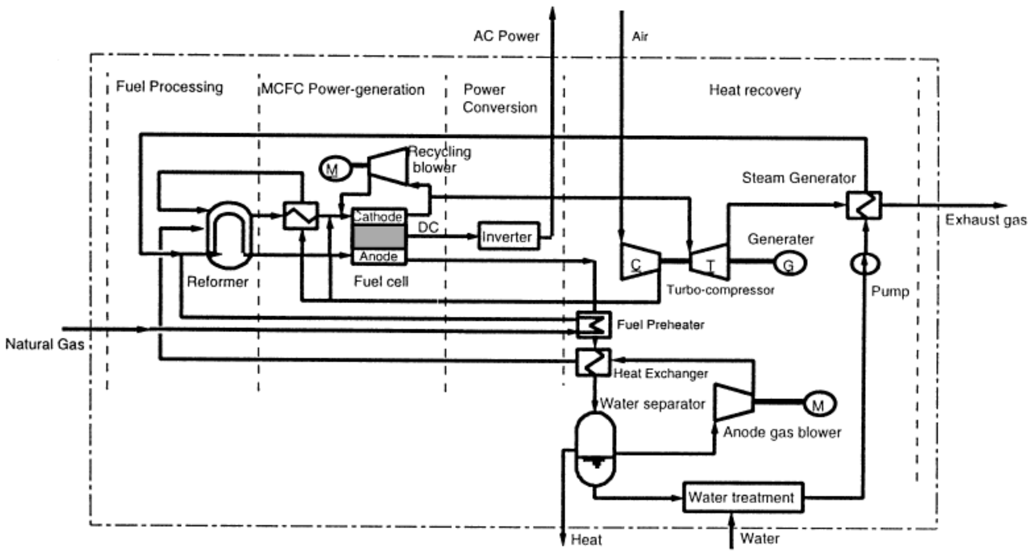


FIGURE 7: MCFC FLOW DIAGRAM (HE 1998)

The gas engine is a Bergen C26:33, with a capacity of 3550kW. It is designed for long service and is simple to maintain. This makes the life cycle costs of the engine low. Some of the characteristics for the engine is that it is compact and powerful, have low emission and low energy consumption. (Rolls-Royce 2010)

This fuel cell uses LNG as fuel supply. By comparing the fuel cell with a gas engine the case study has less complexity because of the similar fuel system. This makes the study more precise and gives a better understanding of the emission release. There will be no difference in emission because of different fuel. The use of LNG as a fuel source has increased lately, mostly due to stricter emission regulations. Some countries now induct tax incentives for low emission. LNG is set to become an important marine fuel of the future.

# 5. LIFE CYCLE INVENTORY ANALYSIS (LCI)

In this case the data is based on different sources from the marine business. Some of the data is based on assumptions because the technology is new and not fully tested. The study is modeled as displayed in figure 8 and 9 below. Two separate foreground systems are compared. The foreground systems are dependent on the processes in the background system. The main processes interfering with the background system are raw materials, waste and energy. The background system represents the elements needed to establish the emission release of the foreground system.

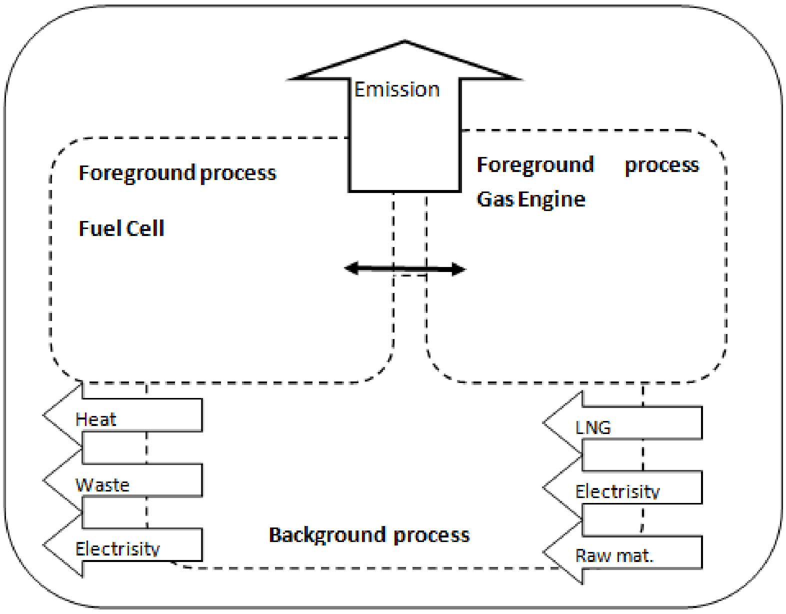


FIGURE 8: FOREGROUND AND BACKGROUND PROCESS

To get a clearer view of the involved systems figure 9 describes the assembly of the foreground process. Both foreground systems can be divided in a manufacturing phase, operation phase and a demolition phase. The manufacturing phase consists of the material, transport and energy needed to produce the product. The operation phase is based on fuel production and emission related to the combustion and the decomposition process of the fuel. The demolition phase is waste and reuse of materials. The engines were analyzed according to this model.

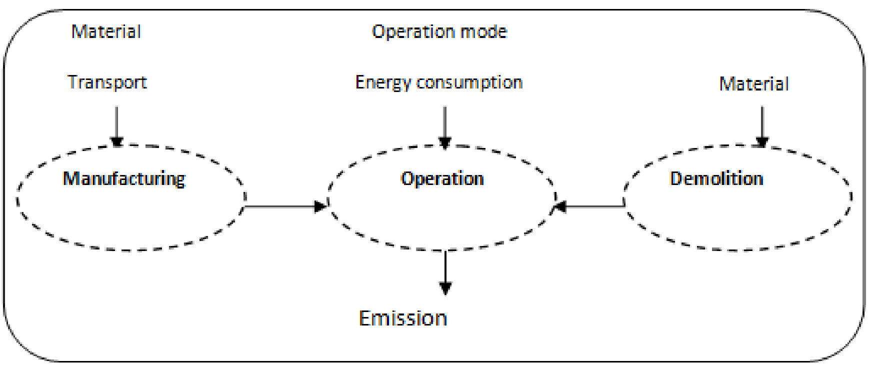


FIGURE 9: ASSEMBLY FOREGROUND PROCESS

## 5.1 MTU fuel cell system

The fuel cell installed onboard the Viking Lady has an output of 320kW. The testing shows an efficiency of 42% at 50% load, and an efficiency of 44% at 100% load. Testing with reuse of heat has not yet been performed. (Haugen 2010) The total fuel cell system efficiency with heat recovery is expected to be 70%. (Huber 2010) The LNG consumption at 363kW stack power is 73,4 Nm3/h. With a lower heating value of 10,325 kWh/Nm3 it is estimated to have a input of 758,9 kW fuel power, which correspond to 100% output. (Haugen 2010)

Measures of emission from the installed fuel cell have not been performed. From the input of fuel we have calculated the emissions to be 181 g/kWh $CO_2$, 0.06 g/kWh CO and 0.14 g/kWh $NO_X$.

The fuel cell system is divided into three units: The HotModule, the stack and the media supply. The hot module refers to the unit containing the fuel cell stack. It serves as an insulation surrounding the fuel cell stack to keep the temperature constant, to avoid unwanted temperature changes and thermal stress which can affect the operation. The stack refers to the sandwich of individual cells containing the electrolyte, anode and cathode. The media supply unit is located upstream the hot module. This is where the fuel gas is purified and heated before entering the system. (MTU 2010)

Wärtsila is responsible for the inverter. The fuel cell system contains the following materials: High-alloy steel, nickel, structural steel, ceramic, lithium potassium carbonate, rock wool, copper and plastic. For percentage of the materials in the three units, see appendix 14.2. (Huber 2010)

## 5.2 Rolls-Royce Marine gas engine

The Rolls-Royce gas engine has a power of 3550 kW and a fuel consumption of 48,068 MJ/kg. At 100 % speed and power the engine releases 1,34 g/kWh $NO_X$, 432,64 g/kWh $CO_2$, 1,77 g/kWh CO and 5,51 g/kWh hydrocarbons (HC). At 100% MCR operating state the engine efficiency is 42,9%, with a specific fuel consumption of 174,4 g/kWh. The engine is based on the modern lean burn technology, which Rolls-Royce was a pioneer in developing. This method improves the ignition phase giving a cleaner combustion. This makes the engine more efficient and reduces emissions. This technology is now found in several engines from different manufacturers.(Valde 2010)

The 6 cylinder gas engine from Rolls-Royce which we are considering for this project is not yet manufactured. The 9 cylinder test engine was tested onshore for the first time April 15, 2010. The material data received is based on the 9 cylinder engine and down scaled based on information on the diesel engines in the same engine series. The 6 cylinder gas engine has a material distribution of 95% cast iron, 3,5% aluminum, and 1,5 % tin and rubber. (Gudmunset 2010)

## 5.3 Construction

The construction involves the production of the materials from raw materials and the energy used to process these. The materials were selected from the ecoinvent database, with the assumption that the product is produced in European countries. This eliminates the risk that different standards affect the end result of the analysis. European production allows us to eliminate the transportation of materials and finished products in the analysis without affecting the result considerably. When material data is not provided for the European situation in the database, the closest possible production site is selected. The energy use for processing the materials has not been added, since these numbers were hard to find. The error in the calculations from ignoring this use of energy will be minimal, since emission from this energy use is very small compared to the total emissions. (Stenersen 2010) The last column in table 1 indicates the country of production of the materials, and what type of process has been used. Unit processes have consequently been selected, since they give more detailed information than system processes, which is the other option. For explanation of the country codes, see abbreviations. As boundary and level of value chain, "at plant" is the common selection for materials in ecoinvent. It should be selected as close to end user as possible. The amount of materials is not included, since this data is confidential. See appendix 14.2.

| **Materials fuel cell** | | |
|---|---|---|
| Steel, converter, chromium steel 18/8 | at plant | RER/U |
| Steel, low alloyd | at plant | RER/U |
| Copper | at regional storage | RER/U |
| Polyethylene, HDPE, granulate | at plant | RER/U |
| Nickel, 99,5% | at plant | GLO/U |
| Potassium carbonate | at plant | GLO/U |
| Lithium carbonate | at plant | GLO/U |
| Sanitary ceramics | at regional storage | CH/U |
| Rock wool | at plant | CH/U |
| **Materials gas engine** | | |
| Cast iron | at plant | RER/U |
| Aluminum, production mix | at plant | RER/U |
| Tin | at regional storage | RER/U |
| Synthetic rubber | at plant | RER/U |

TABLE 1: MATERIALS FUEL CELL

## 5.4 Operation

To implement fuel production and fuel combustion/decomposition in SimaPro the load contribution was used as start point. Emission possesses were established manually based on test results and calculations. The fuel input was selected from the ecoinvent database. This process contains of many sub-processes, including natural gas, onshore production in Germany, Algeria, Netherlands and Russia, offshore production in Norway, Netherlands and United Kingdom, and transport processes. By using natural gas from various production countries the value of fuel production is not depended on one country and thereby more average. The fuel consumption was modeled together with the emission giving a total impact from the different load conditions.

| **Fuel** | | |
|---|---|---|
| Natural gas, high pressure | at consumer | RER/U |
| Fuel cell (100% MCR) | 17214 | MJ/h |
| Gas engine (100% MCR) | 29350 | MJ/h |
| | | |
| **Emission fuel cell (100% MCR)** | | |
| Carbon dioxide | 865,88 | Kg/h |
| Nitrogen oxides | 0,68 | Kg/h |
| Particulates | 0,05 | Kg/h |
| Carbon monoxide | 0,30 | Kg/h |
| | | |
| **Emission gas engine (100% MCR)** | | |
| Carbon dioxide | 1535,87 | Kg/h |
| Nitrogen oxides | 4,68 | Kg/h |
| Hydrocarbons, unspecified | 19,28 | Kg/h |
| Carbon monoxide | 6,20 | Kg/h |

TABLE 2: FUEL CONSUMPTION AND EMISSION

## 5.5 End of life

The end of life phase is based on the construction phase. We have made the assumption that 75% of the materials can be reused for both systems, and that 25% of the materials are scrapped. SimaPro calculates the processes, which makes it difficult to have a 100% overview of the transaction. When the materials are reused, they will be recycled in a closed loop model by SimaPro, by reducing the production needed to fill the functional unit by 75%. The remaining 25% are sent to landfill.

## 5.6 Operation profile

The operation phase is based on the operation profile of an average offshore supply vessel. Viking lady operates 28% of the time in harbor, 28% of the time in transit and 44% of the time in field operation. The ship is in dynamic position (DP) modus during field operation. (Sandaker 2010) Emissions test result from the gas engine received from Rolls-Royce divides the operation phase in five load conditions. To evaluate the time spent in each load condition, an operating profile from Teekay was analyzed. The engine log transcript from the two offshore supply vessels Petronordic and Petroatlantic together with the information from Viking Lady gave the following profile, see table 3. (Teekay 2010)

| Engine load | 100 % | 75 % | 50 % | 23 % | 13 % | |
|---|---|---|---|---|---|---|
| Harbour | | | | | 28 % | % of time |
| | | | | | 2453 | hours |
| Transit | 15 % | 65 % | 10 % | | | % of time |
| | 368 | 1594 | 245 | | | hours |
| DP in field | 15 % | 65 % | 5 % | 5 % | | % of time |
| | 578 | 2505 | 193 | 193 | | hours |
| **Total** | **946** | **4100** | **438** | **193** | **2453** | **hours** |
| **20 years** | **18922** | **81994** | **8760** | **3854** | **49060** | **hours** |

TABLE 3: OPERATION PROFILE

## 5.7 Implementing data in SimaPro

In SimaPro we defined the assemblies (product stages) and processes. The assemblies define the composition of the product. This includes construction, operation and disposal scenarios and refers to the processes in use. The processes describe the production of the assemblies, and include energy use and raw material needed to create the assemblies. For each of the machinery systems a main product stage was created: Life cycle fuel cell, life cycle gas engine and life cycle diesel engine. This is the top level of the engine system models. The input to this level is the product stages life cycle materials and life cycle operation. When the analysis is performed at this level, the result of the analysis gives the total impact on the environment from both use of materials and operation during the lifetime of 20 years. The two top levels of the fuel cell system model are shown in figure 10. The complete networks can be found in appendix 14.7.1-14.7.6.

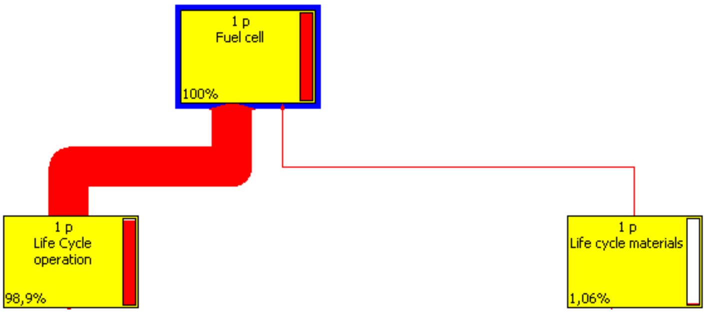


FIGURE 10: LIFE CYCLE MODEL FUEL CELL

### 5.7.1 MATERIALS

The network for life cycle materials is shown in figure 11. The life cycle materials level has the input materials and reuse/disposal of materials. When the materials are selected from the ecoinvent database, the processes needed are included. The output from this level is the environmental impact from use of materials for each engine system when the amount of reused materials after end of life is taken into consideration.

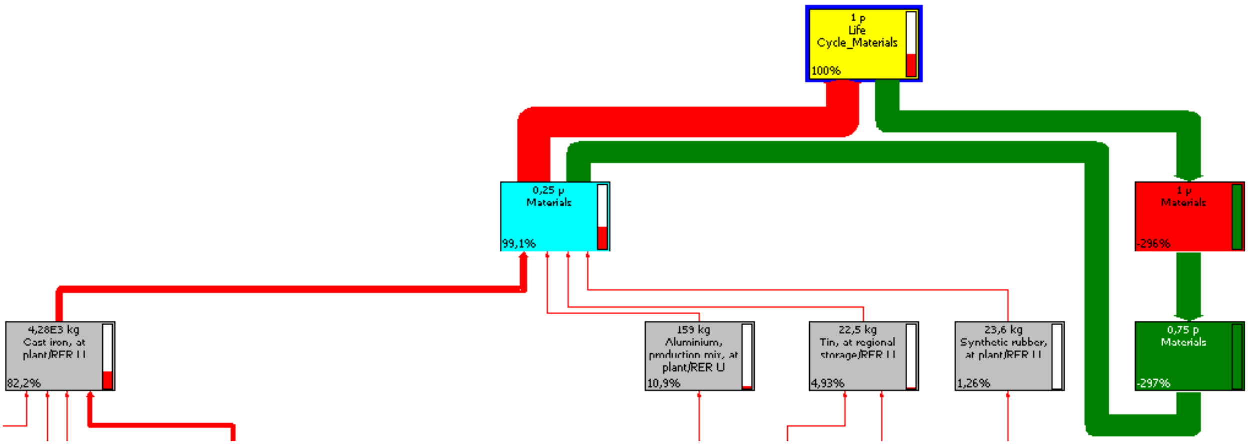


FIGURE 11: LIFE CYCLE MODEL MATERIALS

### 5.7.2 OPERATION

The network for life cycle operation is shown in figure 12. The top level is the life cycle of the operation. Here all 20 years of operation is the input, and this is where we find the total result from operation. On the second level the total emission from the different operational phases during one year of operation is collected, this is multiplied by 20 years. The third level shows the breakdown in the different operating phases. The input on this level is the amount of LNG used in each operating phase during one hour of operation, and the known emissions per hour inserted manually. The type of LNG is selected from ecoinvent. The percentage in the bottom left corner in these boxes show the weighting the impact from this phase has on the second level, and refers to the specific fuel consumption and number of hours in operation of each phase. There are numerous levels beneath, all referring to the fuel processing, added automatically when selecting LNG as input.

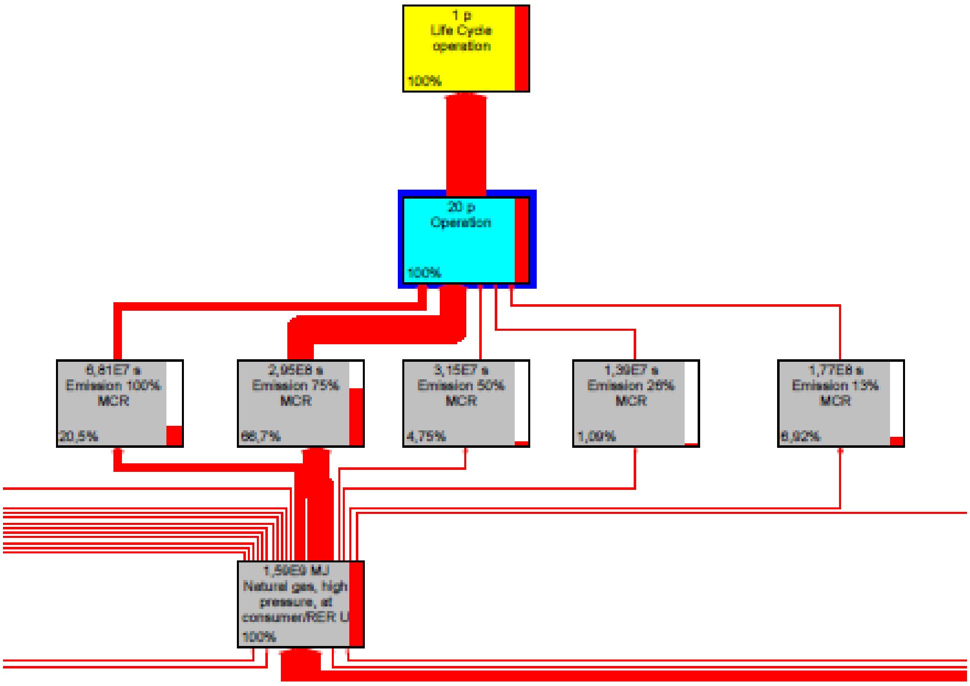


FIGURE 12: LIFE CYCLE MODEL OPERATION

## 5.8 Data collection and assumption

Data for the engine systems and operational profile has mainly been collected from different sources in the industry. When no data was available we have made assumptions based on advice from our supervisor and contacts in the industry.

### 5.8.1 FUEL CELL SYSTEM

The data on the fuel cell system has been collected from different sources. Erkko Fontell, director of Fuel Cell Product Centre Ecotech in Wärtsilä Finland (Fontell 2010), and Kristine Bruun, researcher at DNV Oslo, have provided us with contact information for people working in the companies involved in the FellowShip project. The collecting process has been long due to little testing and low experience on similar systems onboard ships, which influences the accuracy of the result of our thesis.

The information about the materials in the fuel cell has been provided by Johann Huber, team manager for system technology department construction at MTU onsite energy (Huber 2010), which is the company that has designed the fuel cell onboard Viking Lady. The material data was divided in the Hot Module, stack and media supply, and for each of these three the percentage of each material used in the unit was given. It is uncertain if the percentage was given as a percentage of volume or weight, so we have assumed weight. The total weights of the units were not given. Dag Stenersen, Senior Research Engineer at Marintek (Stenersen 2010), provided us with estimates on the weight and volume as a function of installed power. The investment cost of the fuel cell is based on information from Kjell Sandaker, working as project developer in Eidesvik. (Sandaker 2010)

The electrical efficiency of the fuel cell has been measured onboard Viking Lady. This data was provided to us by Bjørn Roger Haugen, Wärtsila (Haugen 2010). The total efficiency with reuse of heat has not been measured yet, but an estimate of 70% was given.

### 5.8.2 GAS ENGINE

The data on the gas engine has been provided by Rolls Royce. This data is more reliable than the data on the fuel cell. A price estimate was given by Kim Espen Tepstad, sales manager-offshore S&S (Tepstad 2010), and the emissions by Kurt Valde, senior development engineer, both employed in Rolls-Royce Marine, Engines Bergen. (Valde 2010) Information about the use of materials in the gas engine was provided by Steinar Gudmundset, VP engine design at Rolls-Royce Marine, Engines Bergen. (Gudmundset 2010)

### 5.8.3 OPERATIONAL PROFILE

The operational profile of Viking Lady was provided by Kjell Sandaker. The profile was not detailed enough for this purpose, and additional information about typical operational profiles for this type of vessels was collected from Teekay Petrojarl Production AS. The information was provided by Marte B. Gresset, operation assistant. (Gresset 2010)

# 6. LIFE CYCLE IMPACT ASSESSMENT (LCIA)

When investigating the emission impact, it is a key factor to group the different types of environmental impacts. This is done to be able to compare the various emissions. In this report the main environmental impacts are based on the CML 2 (Center of Environmental Science of Leiden University) method. (CML 2001) This is a problem oriented approach, giving the results with respect on the different impact categories. To be able to evaluate at the whole system in one category the damage approach can be used. In this study the Eco-indicator is used as a secondary approach to look at differences in the results.

## 6.1 CML 2001

The CML 2001 approach divides the environmental impacts into 10 different subcategories; Characterization. The categories are explained underneath. The advantages by using this model is that it gives a clear picture on what type of emissions are emitted from the various processes. It does not give a total result of the environmental damage. (PRè-Consultants 2008)

### 6.1.1 ADP (ABIOTIC DEPLETION POTENTIAL)

ADP is defined as non-renewable non-organic materials, and is determined for each extraction of minerals and fossil fuels (kg antimony equivalents/ kg extraction). The geographic scope of the indicator is at global scale. This means that the substance affect the world globally. At end of life the engine contains non renewable materials.

### 6.1.2 AP (ACIDIFICATION POTENTIAL)

AP sums the contributors that cause acid rain. This is mainly sulfuric and nitric acids. Acid rain leads to a decrease in the pH-value of rainwater and fog from 5.6 to 4 and below, this damage the ecosystems (Stapersma 2009). AP is expressed as kg $SO_2$ equivalent / kg emission. AP has a geographic range from local to continental. This means that the substance is not dangerous at a global scale. This is why $NO_X$ and $SO_2$ emissions are most dangerous when emitted in harbor or near the shore.

### 6.1.3 EP (EUTROPHICATION)

EP is increased nutrients in a specific derivation; algae's develops in eutrophication water. This leads to a decrease in photosynthesis and less oxygen production. In addition, oxygen is needed to maintain the marine ecosystem. The geographic scope varies from local to continental and is expressed in kg $PO_4$ equivalent / kg emission.

### 7.1.4 GWP (GLOBAL WARMING POTENTIAL)

GWP is a method for comparing the potential climate impact from emissions of various greenhouse gases. By comparing the environmental impact from carbon dioxide with the same amount of a different greenhouse gas a relative scale can be established. In addition to this, GWP is based on time account data, this means that a strong greenhouse gas with a short lifetime could have the same GWP impact as a weaker greenhouse gas with a longer lifetime (Strømman 2008). The intergovernmental Panel on Climate Change (IPCC 2009) has expressed the comparison factor in a time horizon of 100 years (GWP100), in kg carbon dioxide/kg emission. The geographical scope is of global scale. $CO_2$ is considered the largest contributor to greenhouse gas emissions. Reducing $CO_2$ is therefore high priority.

### 6.1.5 HTP (HUMAN TOXICITY POTENTIAL)

HTP measures human exposure to toxic substances by breathing (air), drinking (water), and ingestion (food, soil particles). For each toxic substance HTP's are expressed as 1,4-dichlorobenzene equivalents / kg emission. The geographical scope is between local and global distribution. Emissions that are toxic for humans are for instance lead (Pb) to air, and emissions of TBT and other toxic compounds. In shipping particulate matter (PM) is one of the main contributors. The exhaust gas contains small particles formed in the combustion process, they have a complex chemical composition and their size can vary. Ambient concentrations of PM lead to respiratory problems, when the particles destroy the flagellum. This cause asthma, heart attacks, hospital admissions, and premature mortality. Exposure to high $NO_X$ concentration may cause short term changes in airways responsiveness and lung function, but the main problem is long term exposure that causes larger damage to the lungs. $SO_X$ is also dangerous for the human health, $SO_X$ have a negative effect on the lung volume (Stapersma 2009).

### 6.1.6 ECO-TOXICITY

Eco-toxicity includes three impact categories: Marine eco-toxicity, fresh-water aquatic eco-toxicity and terrestrial eco-toxicity. The categories refer to the impact in ecosystems, in fresh water, marine environment and in terrestrial environment. Eco-toxicity is a result of emission of toxic substances in air, water and soil and is measured in 1,4-dichlorbenzen equivalents/kg emission. The time horizon is infinity because of the long-lasting effect of the impact. The effect is global, continental, regional and local scale.

### 6.1.7 PHOTOCHEMICAL OXIDATION

Photochemical oxidation is formation of reactive substance, mainly ozone. This is injurious to human health, ecosystems and may affect the crops. The oxidation is measured in kg ethylene equivalent / kg emission. The time span is 5 days and the geographical scale varies between local and continental.

## 6.2 Eco-indicator 99

The Eco-indicator is based on a damage approach. This gives the result in a more general and total display. Categorization factors are included in the end-point level, the total damage. The impact categories include Carcinogenic, respiratory organic and inorganic, climate change, radiation, ozone layer, ecotoxicity and acidifications/ eutrophication. The first 6 categories are measured in DALY/kg emission, Ecotoxicity is expressed as potentially affected fraction (PAF)*$m^2$*year/kg emission. Acidifications/ eutrophication is measured in Potential disappeared fraction (PDF)*$m^2$*year/kg emission. (PRè-Consultants 2008)

To be able to give a meaningful weighting from the sub categories into a total impact, the comity behind this approach has collected the data in three main groups; damage to resources, damage to ecosystem and damage to human health. Damage to resources [MJ surplus energy] expresses the surplus of needed energy for future extractions of minerals and fossil fuels. The Damage to ecosystems [% plants species $m^2$*yr] express the loss of plants and species over and certain areas, during a certain time. This category includes land use and land conversion. The damage to human health expresses illnesses that people can get because of emissions. This is combined as Disability Adjusted Life Years (DALYs), an index that express loss of lifetime. The index is also used by the Worldbank and the world health organization (WHO).

The result can be weighted, meaning that the severity of each category is weighted against each other. By doing this a single score can be developed, making it easy to directly compare the two solutions.

# 7. LIFE CYCLE INTERPRETATION (LCI)

To evaluate the impact a characteristic procedure is used. The CML 2001 method evaluates the impact in different impact categories; to get a single score result the Eco-indicator 99 is used. In this study the main characteristic model is the CML 2001 method. Afterwards the Eco-indicator 99 is used to display the differences between the two methods and to reduce the uncertainty of the interpretation. The CML results are displayed in characterized and normalized state. In the characterization state the highest value in each category is given a score of 100%, and the other values are given as a percentage of this. This makes it easy to compare two products within one category; be aware that the different categories cannot be compared to each other directly. In the normalization state the results are absolute and are given in the different units. The different categories with units are displayed in table 4 below; the categories in the table are listed in the same order as they appear in the figures.

| **Category** | **Unit** |
|---|---|
| Abiotic depletion | Kg Sb equivalents |
| Acidification | Kg $SO_2$ equivalents |
| Euthropication | Kg $PO_4$ equivalents |
| Global warming (GWP100) | Kg $CO_2$ equivalents |
| Ozone layer depletion | Kg CFC-11 equivalents |
| Human toxicity | Kg 1,4-DB equivalents |
| Fresh water aquatic ecotoxicity | Kg 1,4-DB equivalents |
| Marine aquatic ecotoxicity | Kg 1,4-DB equivalents |
| Terrestrial ecotoxicity | Kg 1,4-DB equivalents |
| Photochemical oxidation | Kg ethylene equivalents |

TABLE 4: CATEGORIES WITH UNITS

First the fuel cell results are displayed then the gas engine, before the two are compared. The fuel cell results are based on the fuel cell system, meaning that the fuel cell is upscaled to match the size of the gas engine. At the end an analysis with a diesel engine is shown to give a presentation of the effect of switching to LNG as a fuel source.

All figures displayed in this chapter can be seen in large format in appendix 14.8.

## 7.1 Results fuel cell system

The result from the analysis is split in contribution from materials and from operation of the vessel. The impact from the operation involves both the emission from LNG processing until it enters the fuel cell system and the emissions from the system output. Both the results from operation and materials are for a 20 years period of operation, in accordance with the time function.

### 7.1.1 MATERIALS

The largest environmental impact from materials is from the category marine aquatic eco-toxicity, with a value of 3.32 mega ton 1.4-DB equivalents. This is mainly due to the production and disposal of nickel. The same factors impact the fresh water aquatic eco-toxicity category, which has a value of 3430 ton 1.4-DB equivalents. In the human toxicity category the steel production has a considerable impact together with nickel production and disposal, with an impact of 12 mega ton 1.4-DB equivalents. The processes needed to reform the materials contribute to the global warming impact, with a total impact of 1.48 mega ton $CO_2$ equivalents. The acidification category has impact from the nickel production, but also the blasting of the materials. The total impact in this category is 105 ton $SO_2$ equivalents. The fuel cell does not contribute with a large impact in the categories abiotic depletion, eutrophication, terrestrial eco-toxicity and photochemical oxidation.

In figure 13 the characterized CML 2001 values of the impact in each cathegory are shown. The red part of the columns show the negative impact on the environment from the production of the materials. The green part of the columns represent the positive impact the reuse of the materials when the system is replaced has on the environment.

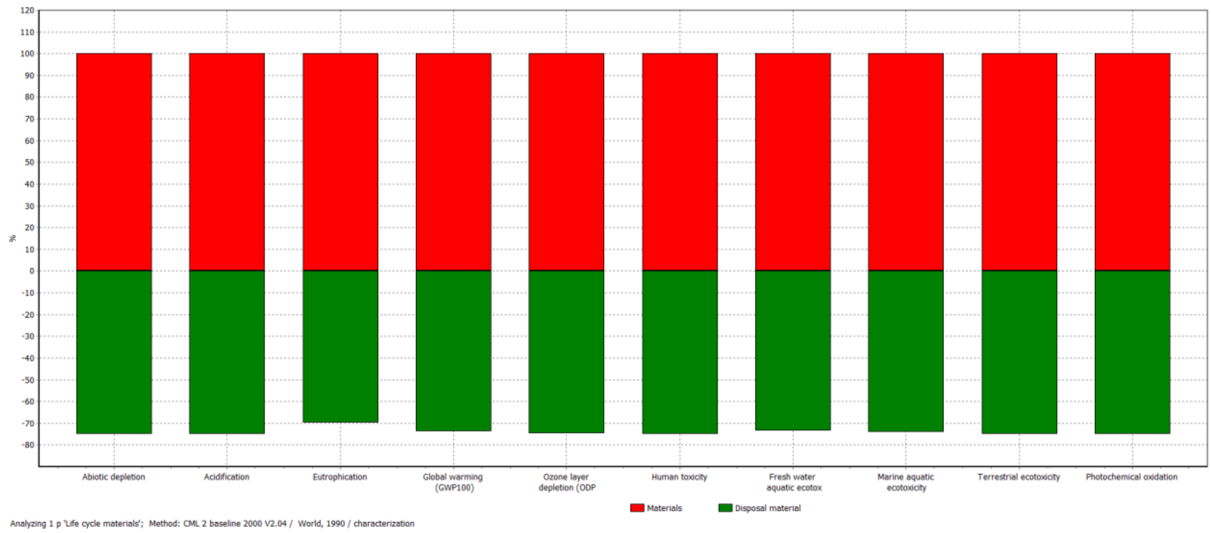


FIGURE 13: FUEL CELL MATERIAL, CML CHARACTERIZED

In figure 14 the normalized CML 2001 values are shown.

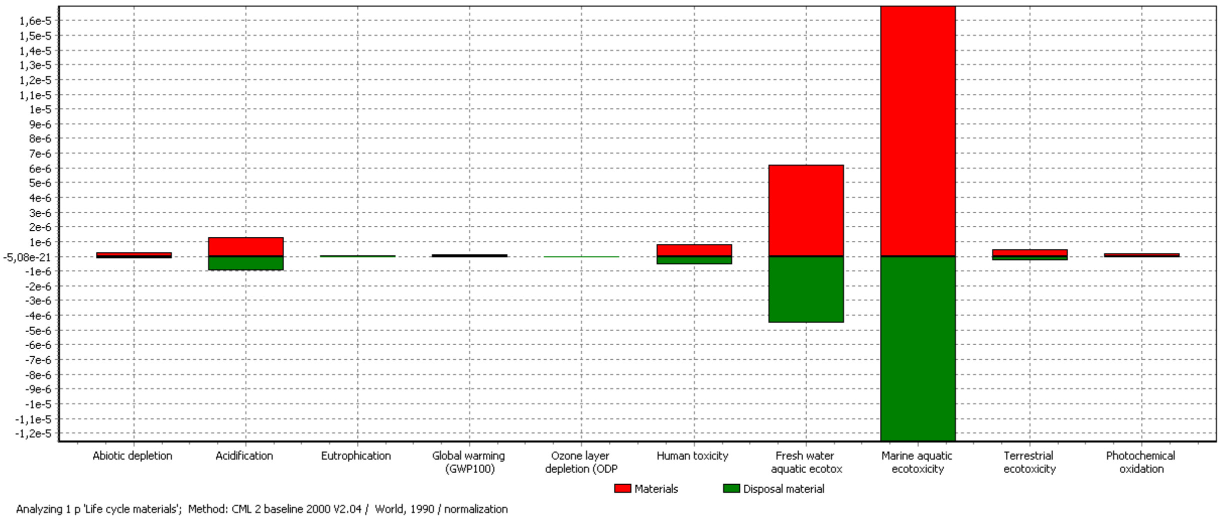


FIGURE 14: FUEL CELL MATERIAL, CML NORMALIZED

Figure 15 shows the contribution to the impact categories distributed on the different materials in the fuel cell system. Nickel and steel contribute with the main impact.

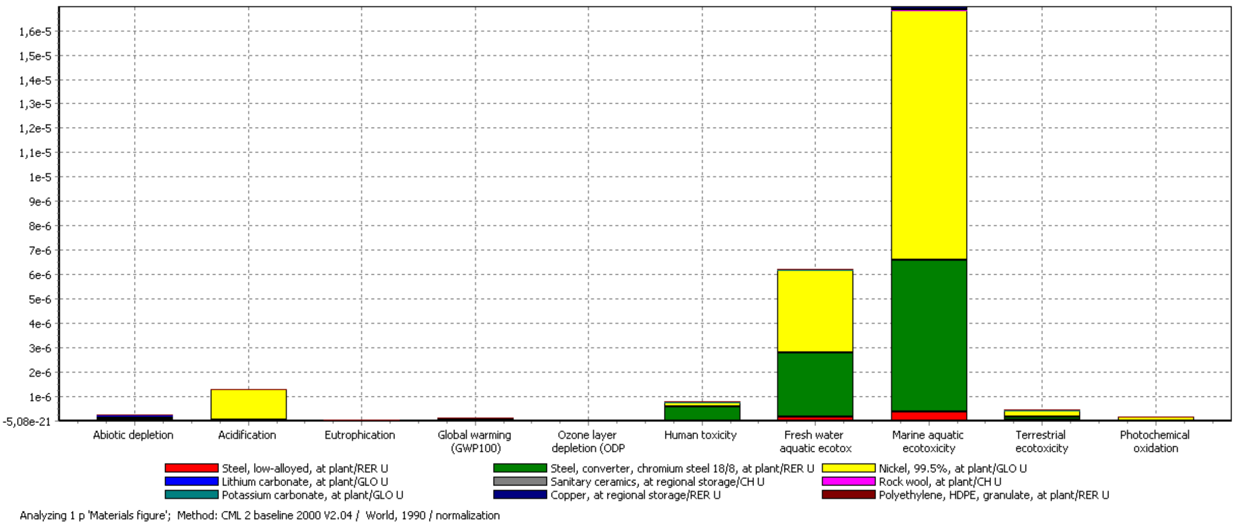


FIGURE 15: FUEL CELL MATERIAL, CML DISTRIBUTED

### 7.1.2 OPERATION

The environmental impact of the operation phase is shown in figure 16. The total emission of GWP gases is 97 600 ton $CO_2$ equivalents. This consists mainly of $CO_2$ and CO emissions from the cell reaction and emission of GWP gases from the fuel transportation and processing. The impact category contributing with the highest impact on the environment is Marine aquatic eco-toxicity, with a value of 5.14 mega ton 1,4-DB equivalents. This is emission of toxic compounds to the water during well exploration and drilling for LNG. The impact in the Fresh water aquatic eco-toxicity category, due to manufacturing of drilling equipment on land, is 281 ton 1,4-DB equivalents. The Human toxicity and Terrestrial eco-toxicity have values of 4180 and 16.2 ton 1.4-DB equivalents. The

Abiotic depletion impact, measured in ton Sb equivalents, is with 914 ton the third largest impact to the environment. This emission is mainly from the fuel processing. The Acidification category has a total impact of 92.7 ton $SO_2$ equivalents. This is due to emissions of $NO_X$ and $SO_X$ from the fuel processing and cell reaction. The ozone layer depletion impact from the operation is almost ignorable small, and the little emission of ozone depletion gases is from the transportation of LNG. The normalized values of the impact categories are shown in figure 16.

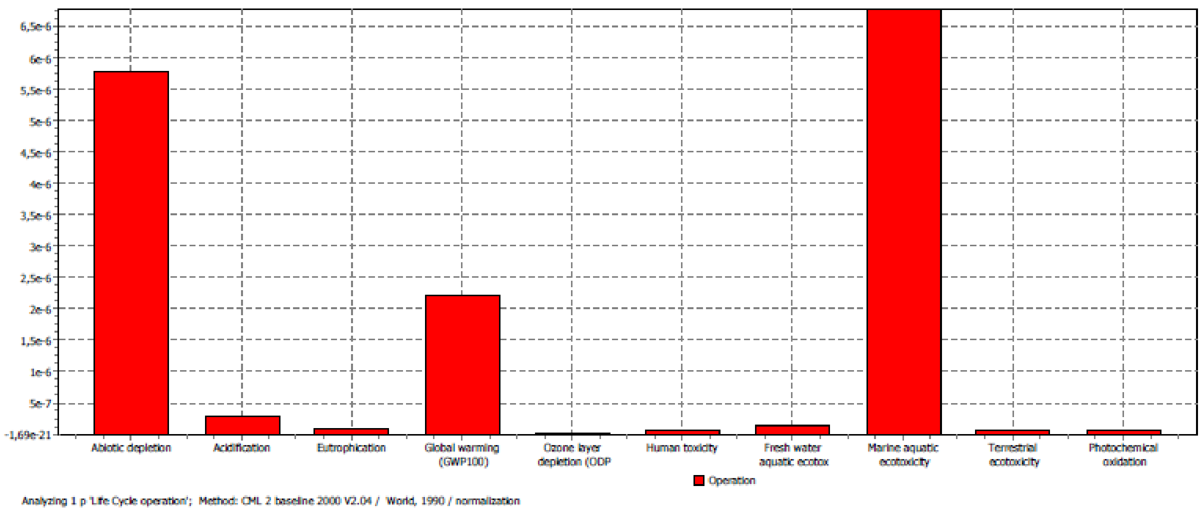

FIGURE 16: FUEL CELL OPERATION, CML NORMALIZED

In figure 17 the contribution to the impact from the different phases of operation is shown. The vessel operates at 75% MCR most of the time, making this a large contributor to the total impact. The impact per kWh output is equal for the different phases of operation.

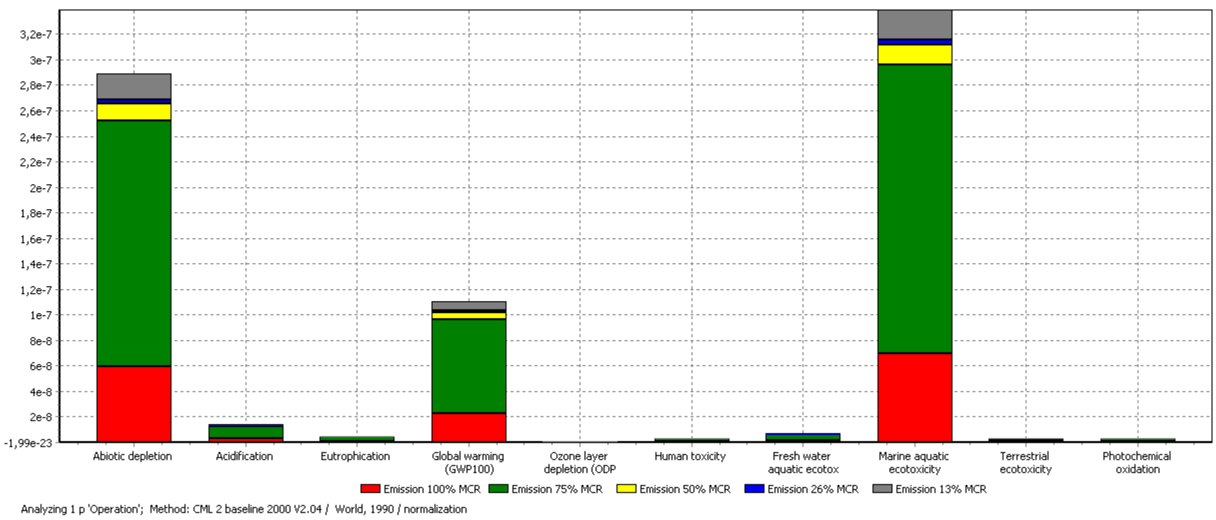

FIGURE 17: FUEL CELL OPERATION, CML DISTRIBUTED

### 7.1.3 TOTAL

The characterized values of the total impact from the fuel cell system, including use of materials (green column) and operation (red column), are shown in figure 18. The normalized values are shown in figure 19. The total global warming impact is 2.25E3 ton $CO_2$ equivalents; this is mainly impact from operation (2,21E3 ton $CO_2$ eq.). Operation is also the main contributor in abiotic depletion with a total impact of 5,84E3 ton Sb equivalents. In the marine aquatic eco-toxicity category both the materials and operation contribute with high impact, with a total of 1,12E5 ton 1.4-DB equivalents.

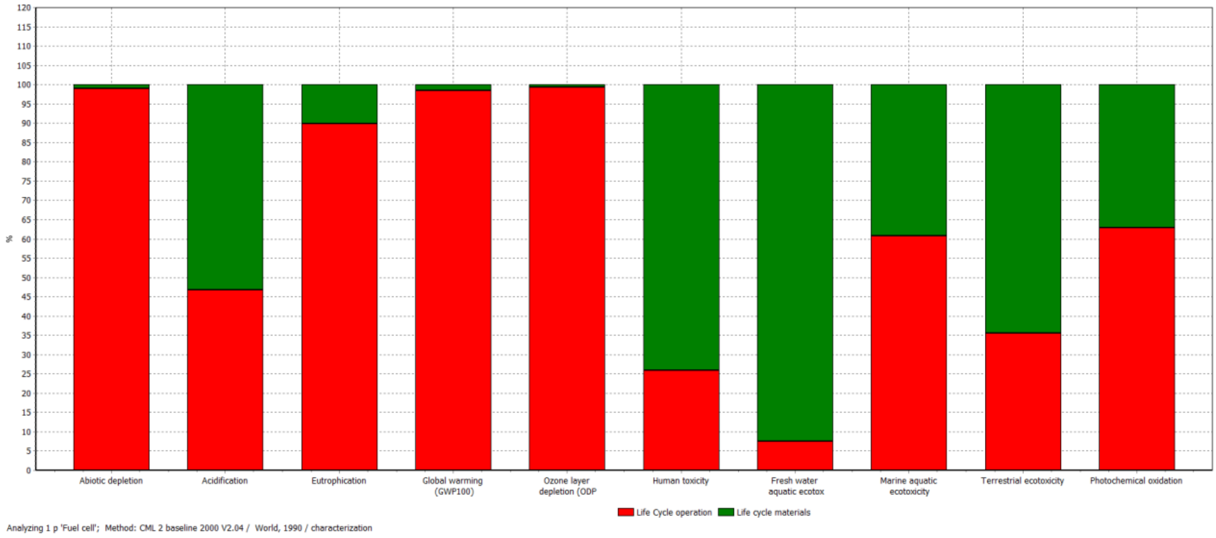


FIGURE 18: TOTAL RESULT FUEL CELL, CML CHARACTERIZED

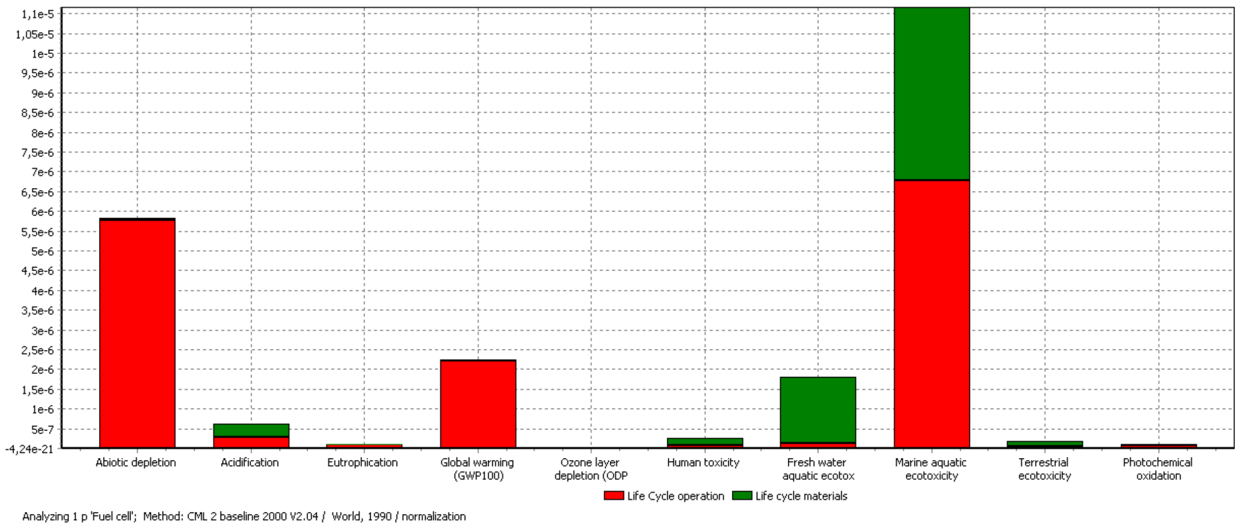


FIGURE 19: TOTAL RESULT FUEL CELL, CML NORMALIZED

## 7.2 Results gas engine

The result of the gas engine is considered to be as predicted. The use of material from the gas engine gives a lower impact on the environment compared to the operation phase. By looking at the different categories, impact from material production contributes in different categories than operation. The operation impact is especially large at global warming potential.

### 7.2.1 MATERIALS

The characterized values of the impacts from the materials are displayed in figure 20 and the normalized values in figure 21. The largest impact is at the Marin aquatic eco-toxicity, this category represents the damage in ecosystem in a marine environment. The total impact is 7.64E6 kg 1,4-DB eq, this is a result of a total negative impact (red column) of 1.84E7 and a positive impact (green column) of 1.07E7. The main substance linked to this impact category is vanadium-, nickel- and copper ion emitted to water. Other metals that impact the categories are Barium, Beryllium Barite Zink and Cobalt. The two next large impact categories are also related to damage of ecosystems, hence fresh water and territorial eco-toxicity. The total release of fresh water eco-toxicity 1,3E4 kg 1,4-DB eq and the total of terrestrial eco-toxicity is 313 kg 1,4-DB eq.

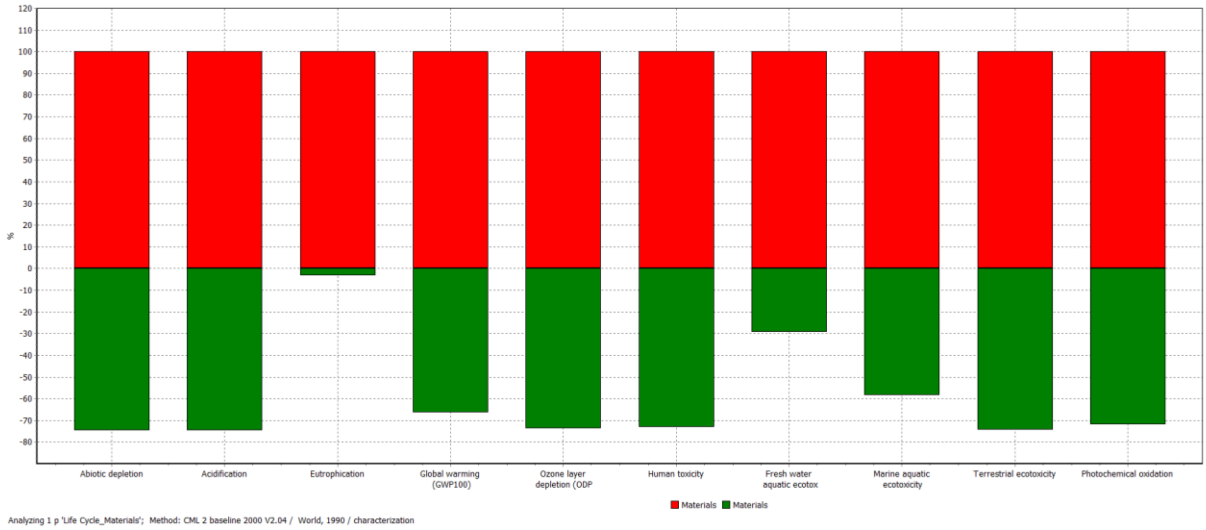

FIGURE 20: GAS ENGINE MATERIAL, CML CHARACTERIZED

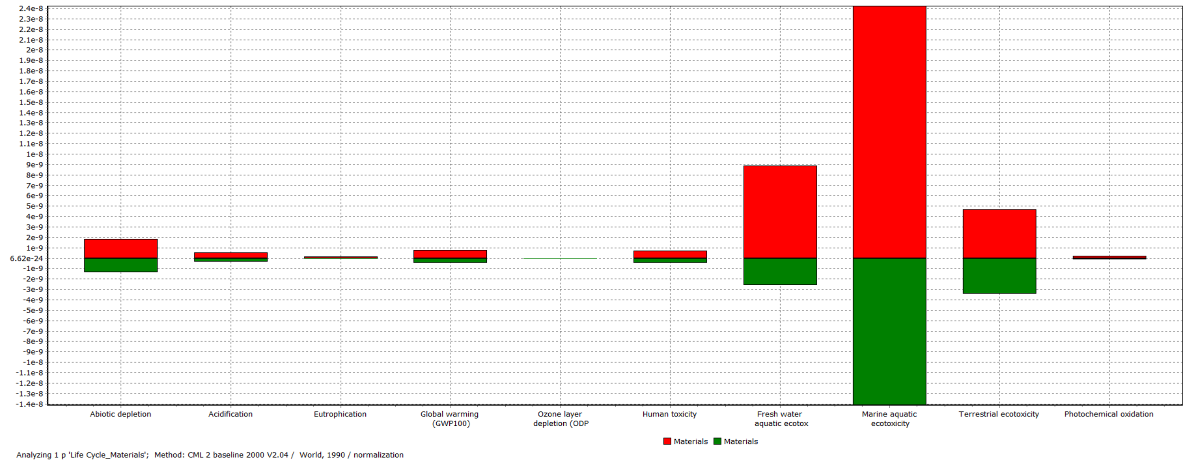


FIGURE 21: GAS ENGINE MATERIAL, CML NORMALIZED

Dividing the total impact with respect to the different materials added in the gas engine, the result displays cast iron as the main material impact. This reflects the large fraction of cast iron in the engine.

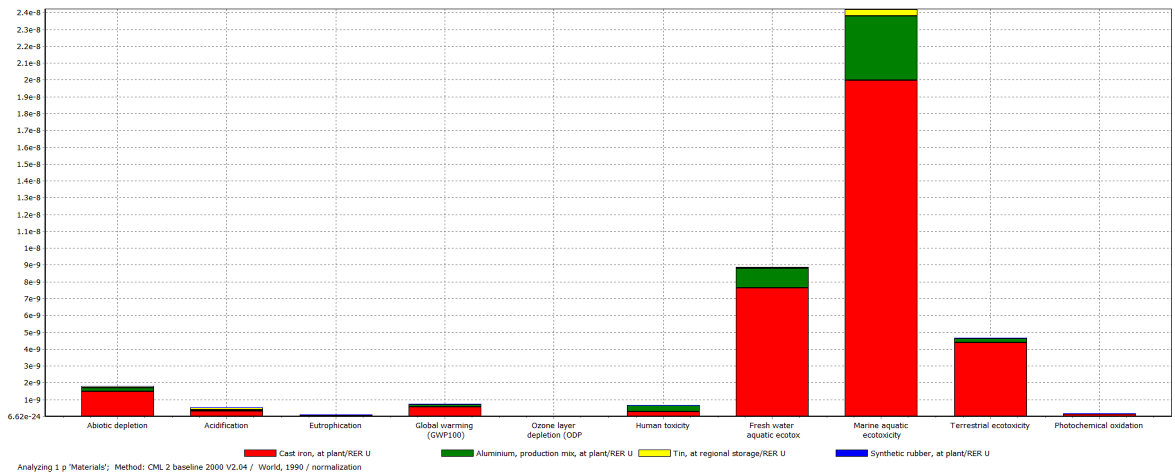


FIGURE 22: GAS ENGINE MATERIAL, CML DISTRIBUTED

### 7.2.2 OPERATION

The direct operation impact is mainly dominated by Global Warming Potential (GWP) which is a joint denomination of different greenhouse gasses. The total amount of GWP release is 2,79E8 kg $CO_2$ equivalent or 0,279 mega ton $CO_2$ eq. This is mainly $CO_2$ (2,6E8) and CO (1,41E6) emitted to air. By adding the fuel production stage two different groups stand out. The first is Abiotic depletion with a total impact of 2,61E6 kg Sb eq from non-renewable non-organic materials. This is coal (1,3E4), natural gas (2,59E6) and oil (1,1e4) in ground. The largest impact is from Marine aquatic eco-toxicity, with a total impact of 1.47E10 kg 1,4-DB eq. This category represents toxic substances on marine ecosystems. Acidification (AP) and Eutrophication (EP) are the next largest impact categories. AP is emission leading to acid rain. AP is mainly $NO_X$ (1,92E5) and some $SO_2$ (40,6) giving a total of 1,92E5 kg $SO_2$ eq emitted to the air. $NO_2$ (4,98E4 kg PO4 eq) is also the underlying factor of the Eutrophication (EP). This is an impact category that influences the water quality, since acid water leads to more algae. In figure 23 the normalized values of the gas engine operational impact are shown.

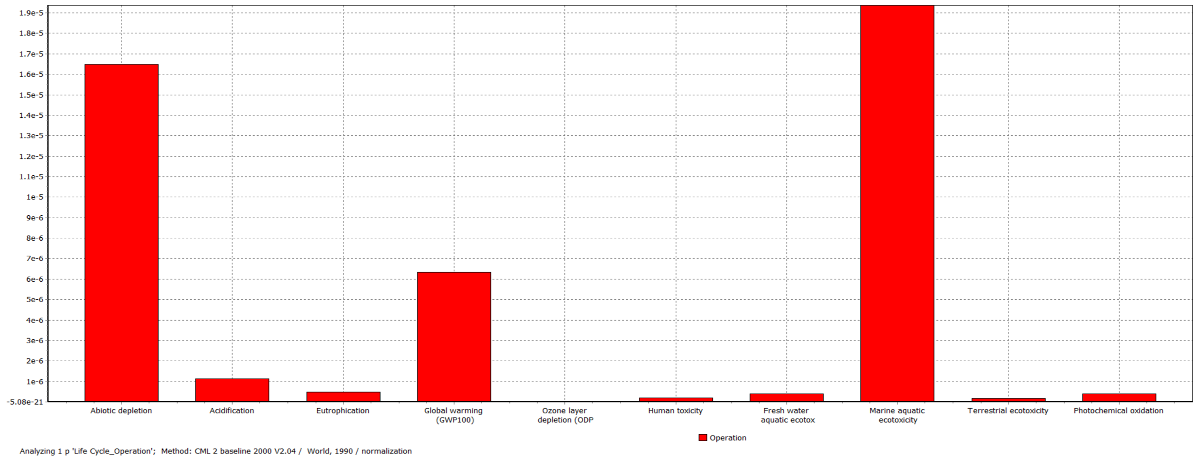


FIGURE 23: GAS ENGINE OPERATION, CML NORMALIZED

Figure 24 displays the impact divided in the different operational phases. It is important to clarify that some time spent in the different phases gives more emission. The green color represents 75% MCR which is the most effective operating phase and thereby also the phase that is used the most.

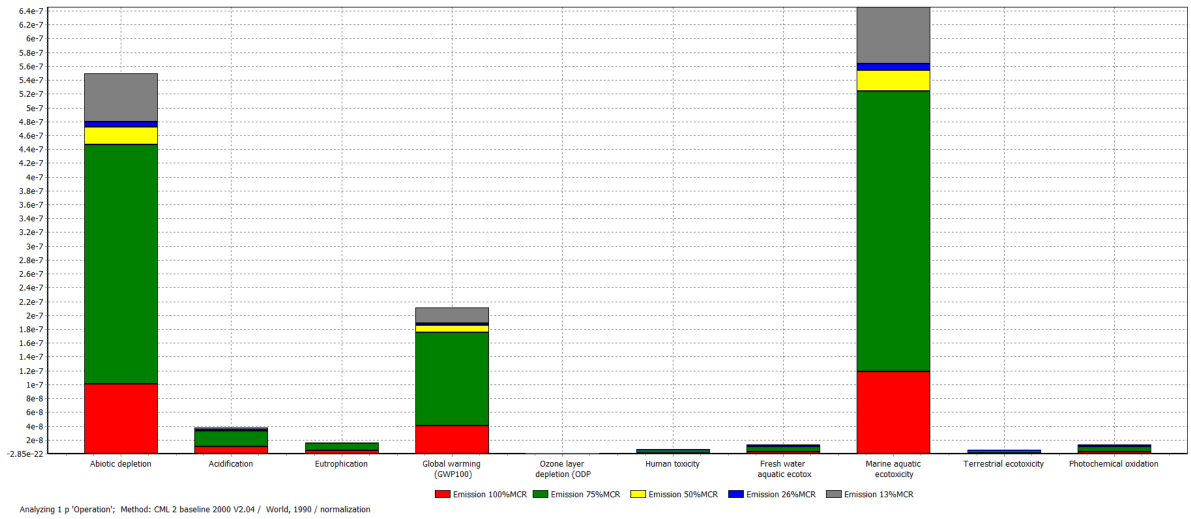


FIGURE 24: GAS ENGINE OPERATION, CML DISTRIBUTED

### 7.2.3 TOTAL

The total impact of the gas engine is dominated by the operation phase, as displayed in figure 25. The material impact is hardly visible because of the low impact compared to operation.

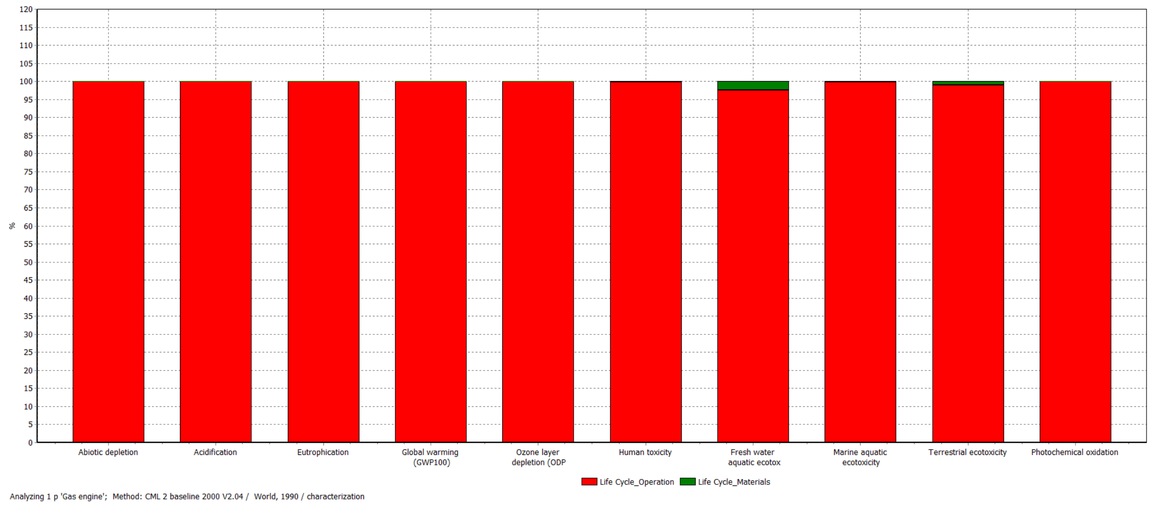


FIGURE 25: TOTAL RESULT GAS ENGINE, CML CHARACTERIZED

The normalized values of the total gas engine impact are shown in figure 26.

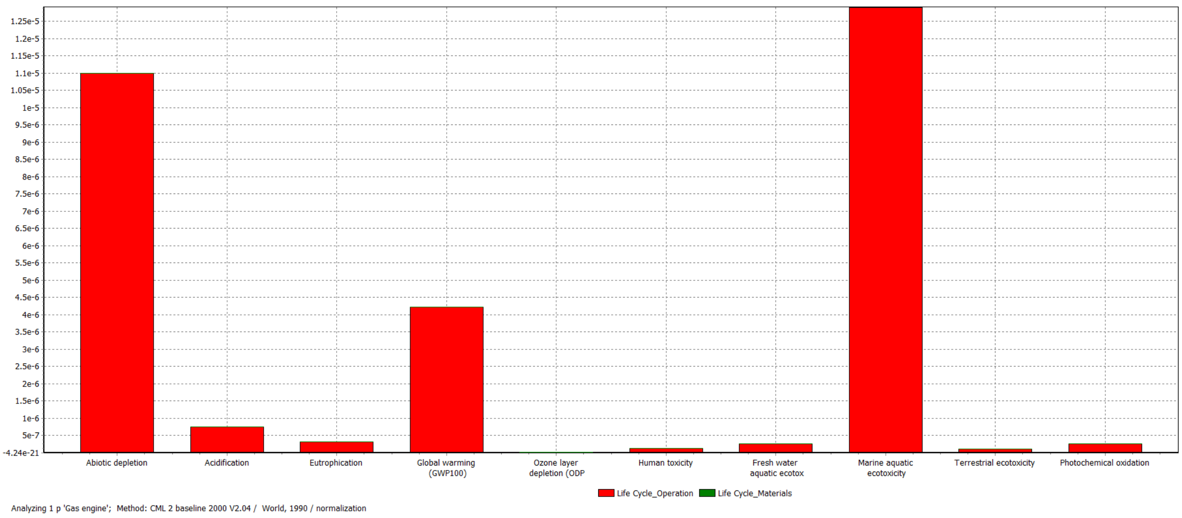


FIGURE 26: TOTAL RESULT GAS ENGINE, CML NORMALIZED

## 7.3 Gas engine compared to fuel cell

### 7.3.1 MATERIALS

Figure 27 displays the green fuel cell material column and the invisible red gas engine material column in characterized values. The main reason why the fuel cell has a much larger impact is the difference in material choice and size.

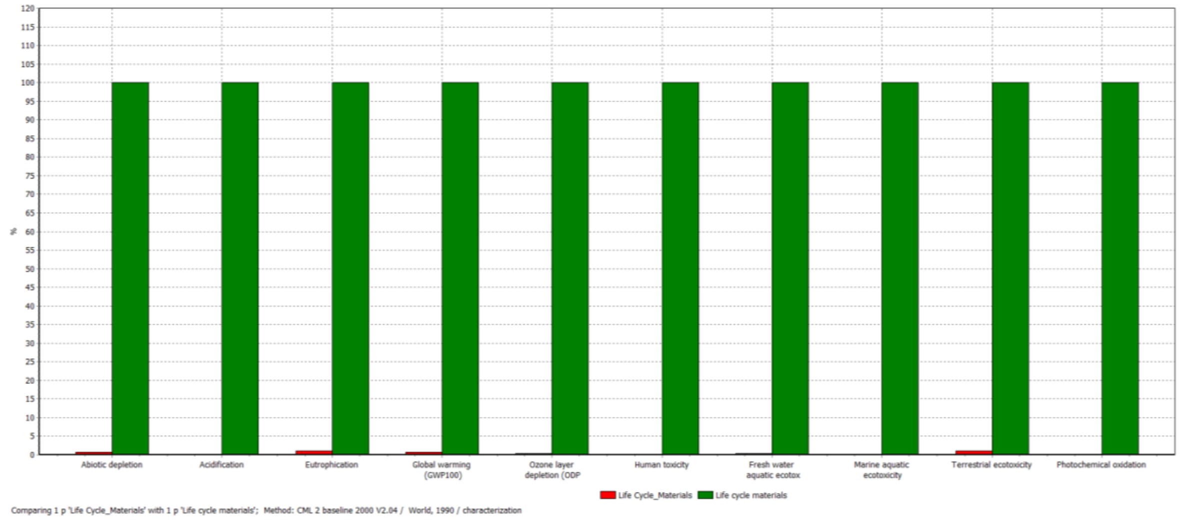


FIGURE 27: GAS ENGINE COMPARED TO FUEL CELL, MATERIAL, CML CHARACTERIZED

Figure 28 displays the normalized values of the compared material impact.

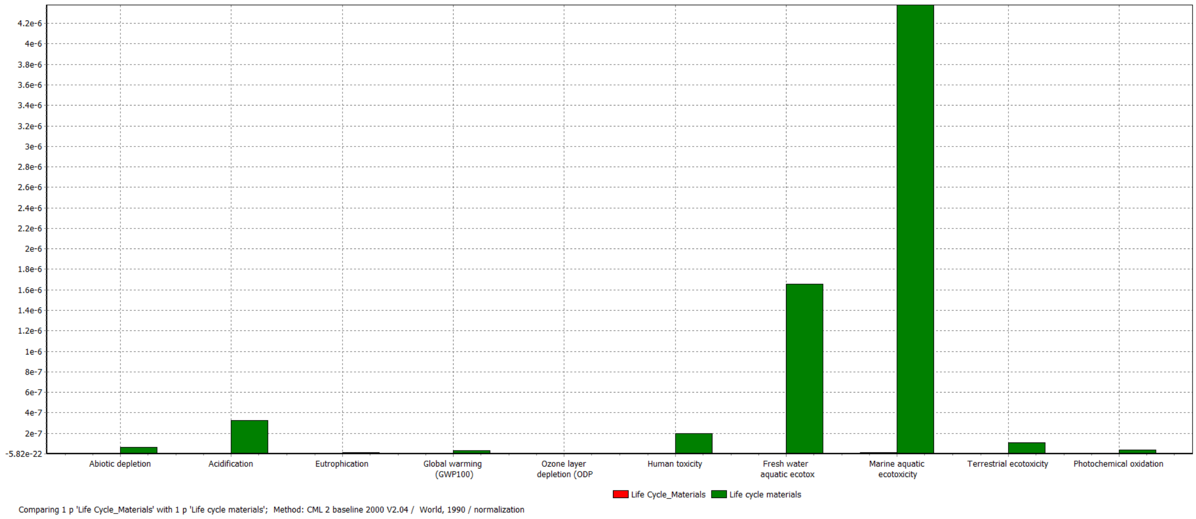


FIGURE 28: GAS ENGINE COMPARED TO FUEL CELL, MATERIAL, CML NORMALIZED

## 7.3.2 OPERATION

Looking at the difference in the operation phase there is a clear change in the result. The characterized values of the compared operational impact are shown in figure 29. The gas engine in red has an overall higher operational impact. This is a result of higher fuel consumption and higher emission release from the combustion.

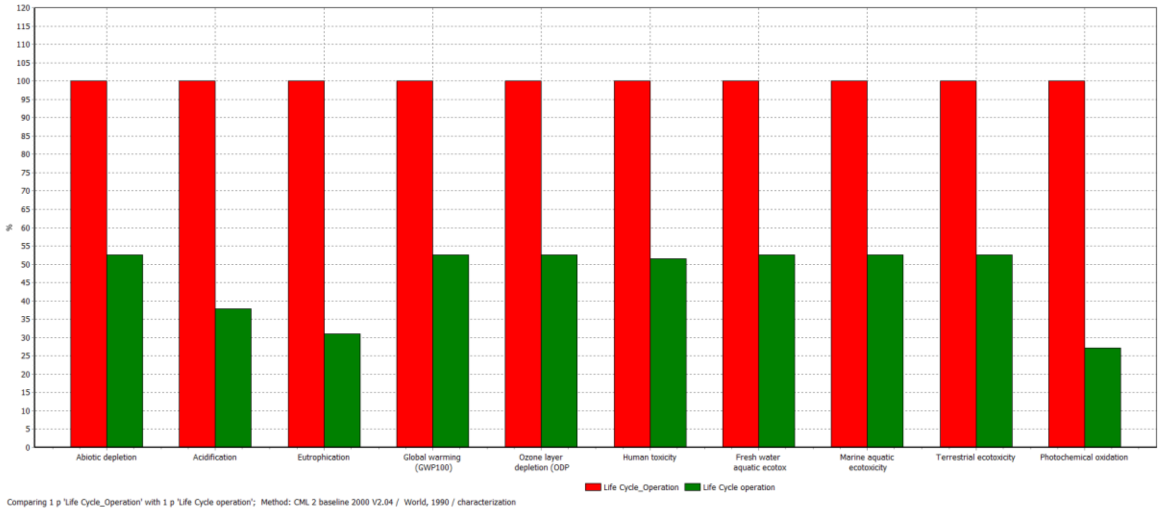


FIGURE 29: GAS ENGINE COMPARED TO FUEL CELL, OPERATION, CML CHARACTERIZED

The normalized values of the operation comparison are shown in figure 30.

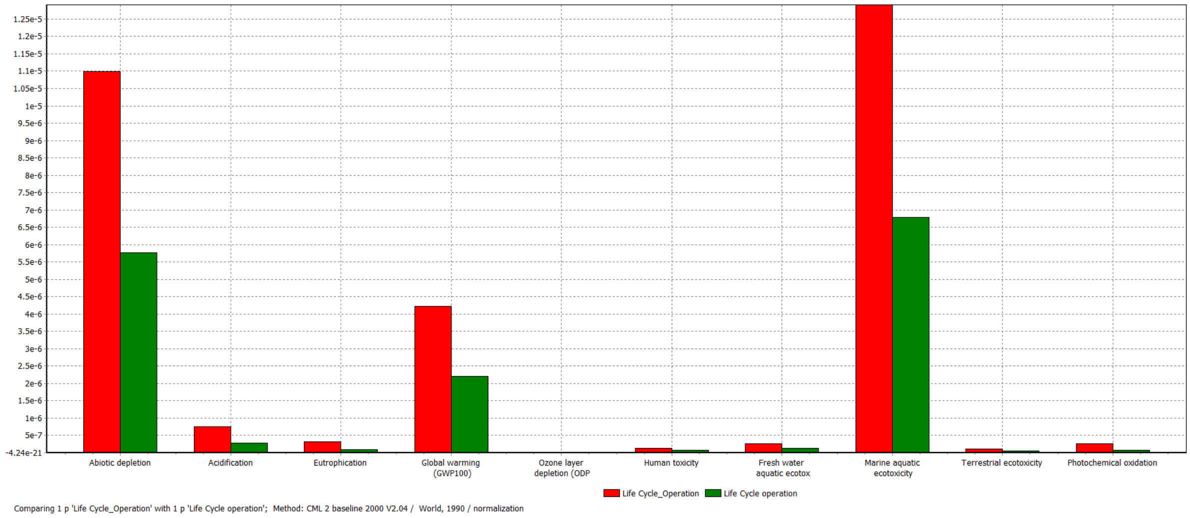


FIGURE 30: GAS ENGINE COMPARED TO FUEL CELL, OPERATION, CML NORMALIZED

### 7.3.3 TOTAL

The total result shows a large total impact on Abiotic depletion, Global warming potential and marine aquatic eco/toxicity. The gas engine has the largest impact in these three categories. The final seven categories have a minor impact. Human toxicity is relative low, both from the fuel cell and the gas engine; this is related with low $NO_X$, $SO_X$ and PM (particulate matter). Low $NO_X$ and $SO_X$ emission also interferes with the low Acidification. The fuel cell emits almost zero $NO_X$ and $SO_X$ resulting in low release in the operation phase. This makes the gas engine the main contributor in the operational phase. With respect on global warming potential figure 31 shows a 50% reduction switching from gas engine to fuel cell. The same difference appears in the difference in Abiotic depletion. The largest impact is the Marine aquatic eco-toxicity; the gas engine has a 15% higher impact compared to the fuel cell. While the gas engine impact on Marine aquatic eco-toxicity mostly is represented by the operation phase, the fuel cell has a 40%/60% impact split between material and operation phase.

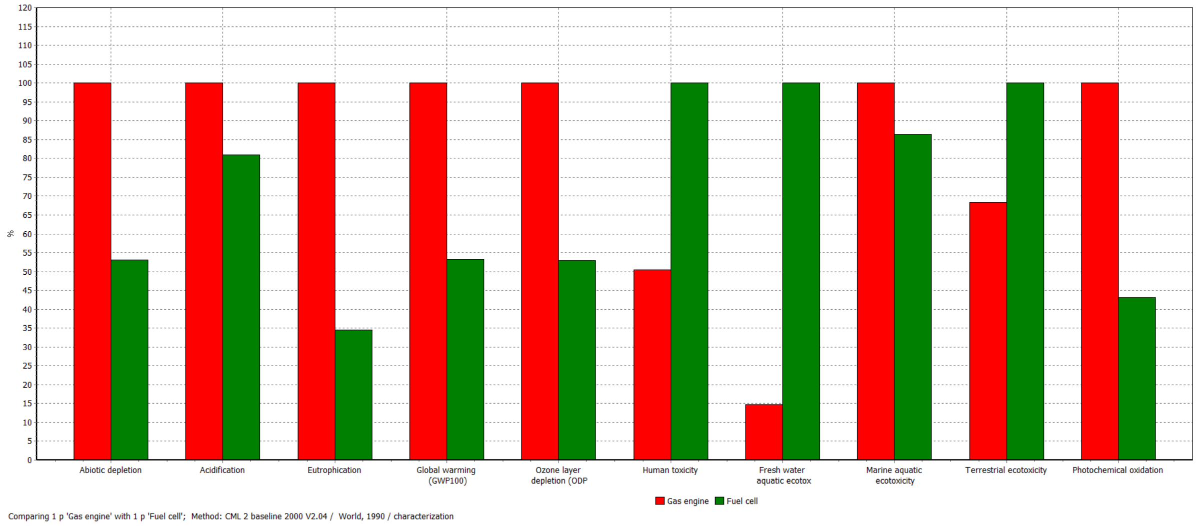


FIGURE 31: GAS ENGINE COMPARED TO FUEL CELL, TOTAL, CML CHARACTERIZED

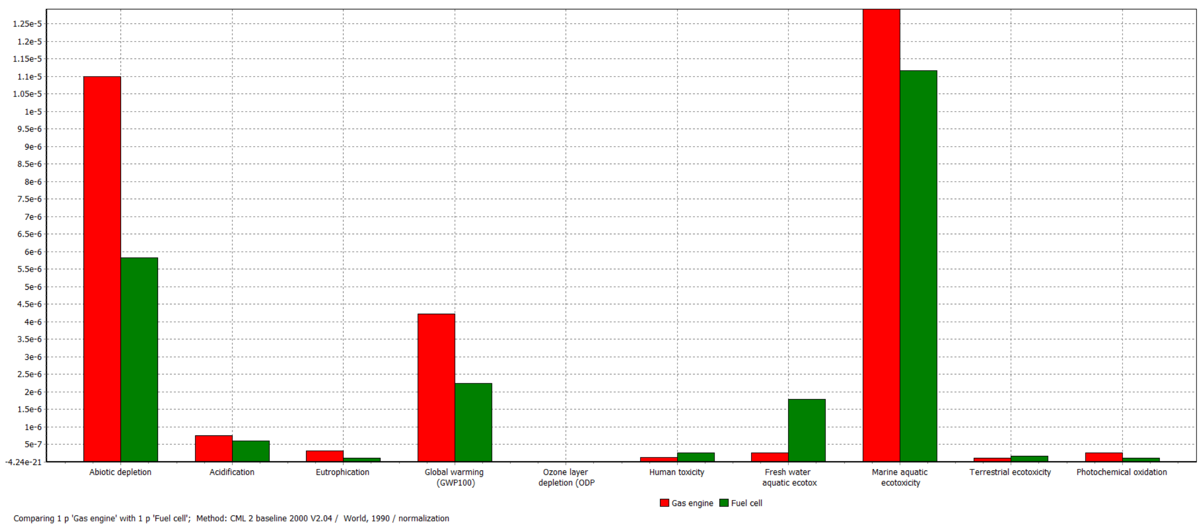


FIGURE 32: GAS ENGINE COMPARED TO FUEL CELL, TOTAL, CML NORMALIZED

The total impact is dominated by the operational impact, as displayed in figure 33, where the characterized impact from operation and material of both the fuel cell and the gas engine is shown. The red column represents the operation of the gas engine, while the green column represents the gas engine materials. The yellow column is the operation of the fuel cell and the blue column is the fuel cell materials. Due to the high material impact, the fuel cell contributes more in the total picture. The red gas engine operation column has the largest impact of the four categories in eight of ten categories, this give an indication of where to reduce the emission impact.

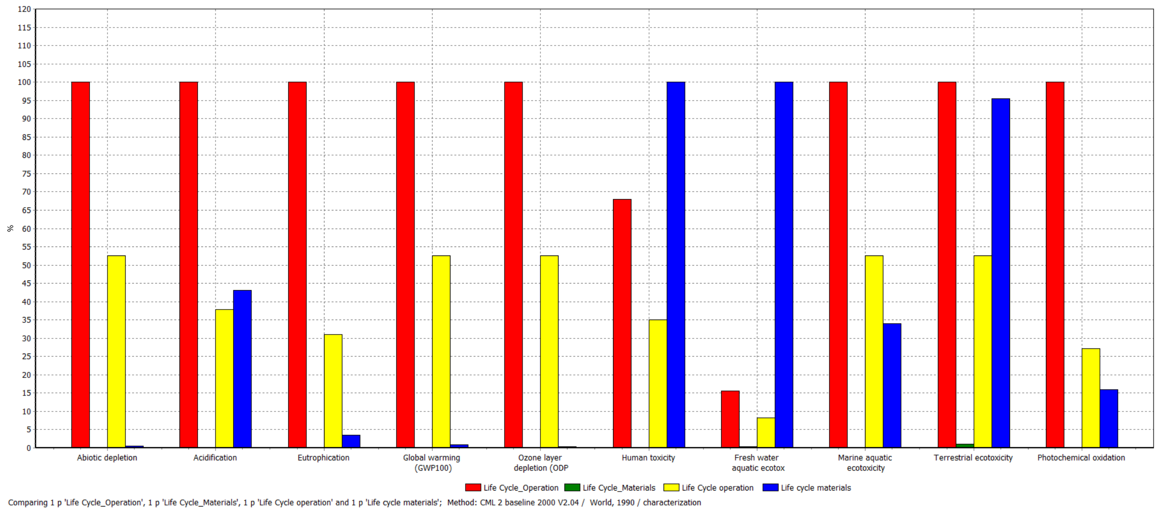


FIGURE 33: GAS ENGINE COMPARED TO FUEL CELL, MATERIAL AND OPERATION, CML CHARACTERIZED

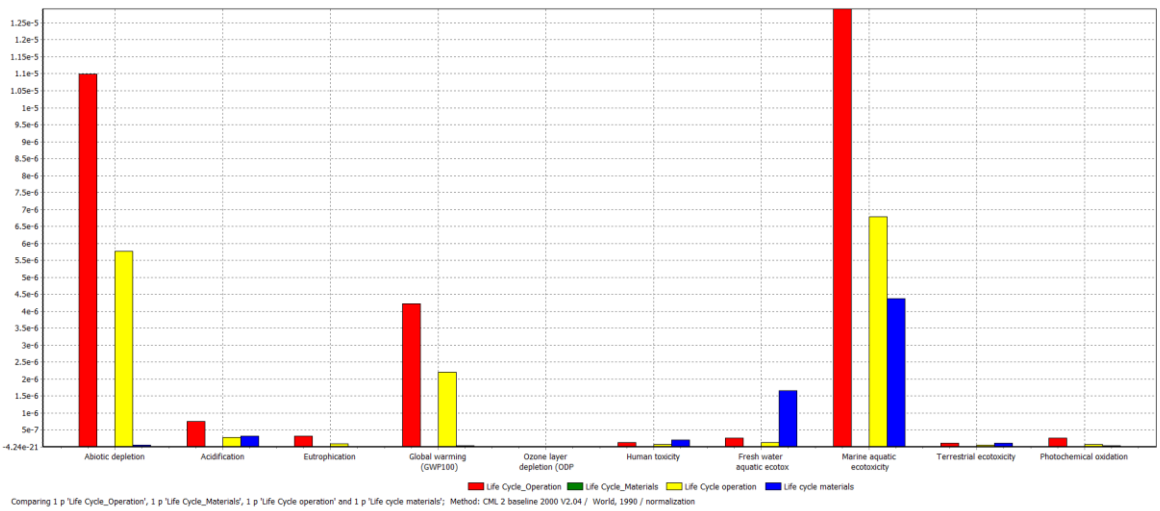


FIGURE 34: GAS ENGINE COMPARED TO FUEL CELL, MATERIAL AND OPERATION, CML NORMALIZED

## 7.4 Comparison between eco-indicator and CML categorization

Using eco-indicator as a characterization factor gives a different result. First the results divided in the sub-categories are shown, then in the three ending categories, Human health, Ecosystem quality and recourses. The structure is different from the CML categorization making the eco-indicator a damage approach. The first two figures (figure 35 and 36) display the damage assessment; this gives a percentage distribution of the environmental impact of the fuel cell in green and the gas engine in red. The gas engine has as similarity to the CML index, a larger impact in operation aspects while the fuel cell has larger impact on the materials and the use of resources. There are similarities with the CML 2001 approach, the difference between the fuel cell and the gas engine with respect on climate change is 48%. The same is for Ecotoxicity and minerals, with high impact from the fuel cell.

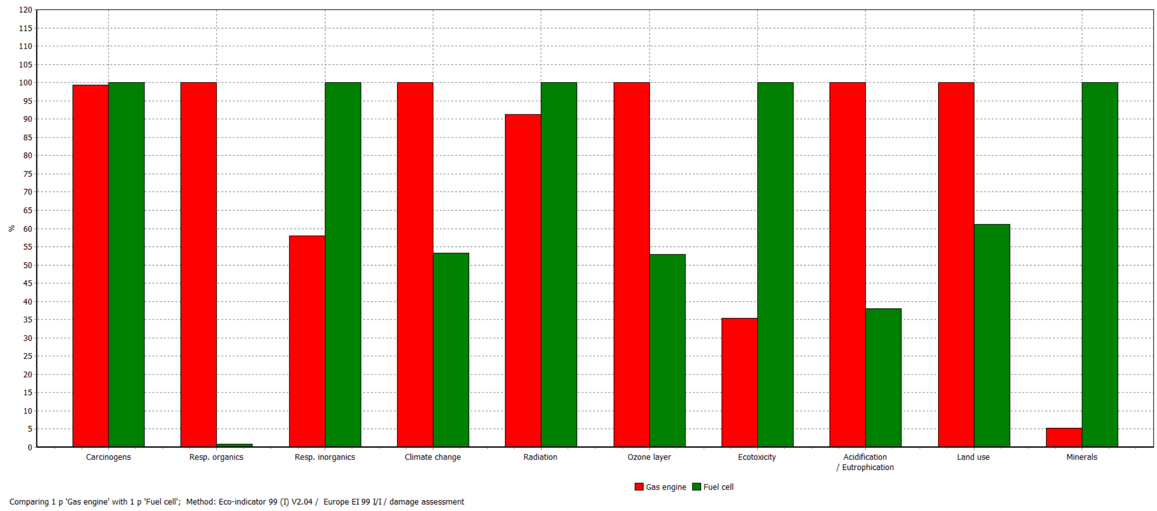


FIGURE 35: GAS ENGINE COMPARED TO FUEL CELL, ECO-INDICATOR DAMAGE ASSESSMENT

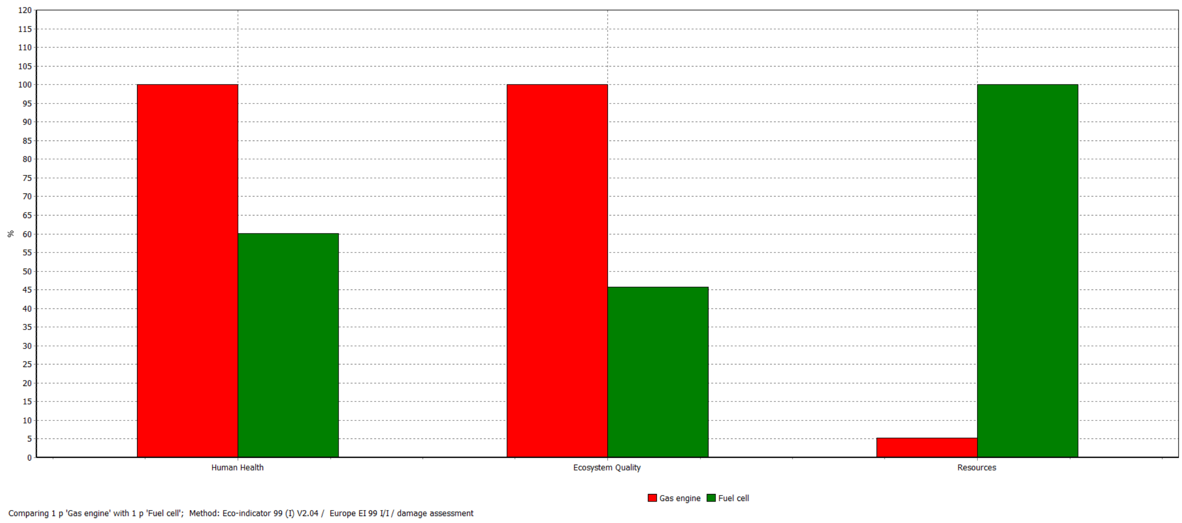


FIGURE 36: GAS ENGINE COMPARED TO FUEL CELL, ECO-INDICATOR DAMAGE ASSESSMENT

By normalizing the results the differences in a absolute value appear. Figure 37 and 38 display a large influence of the recourses.

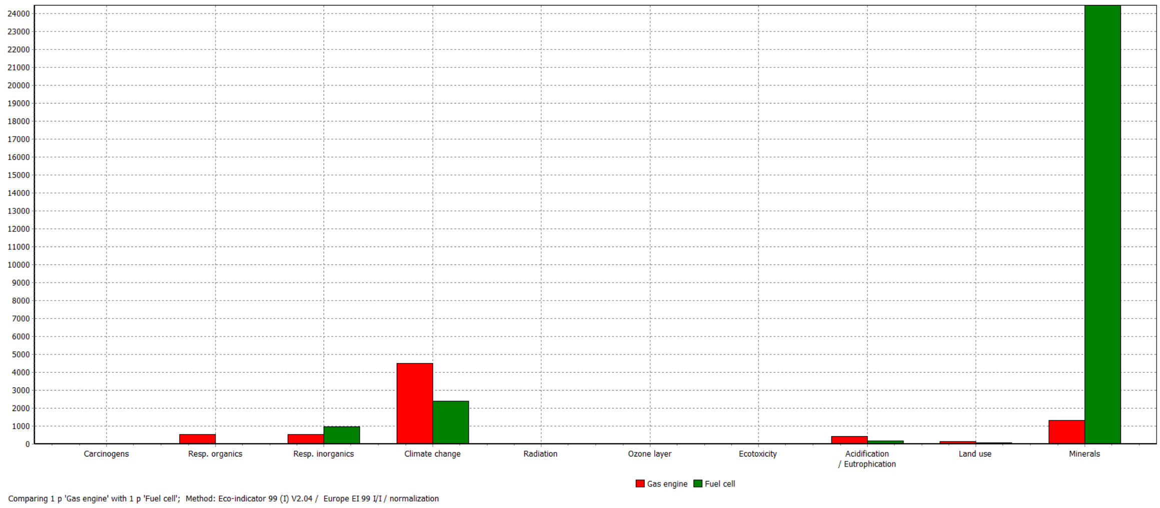


FIGURE 37: GAS ENGINE COMPARED TO FUEL CELL, ECO-INDICATOR NORMALIZED

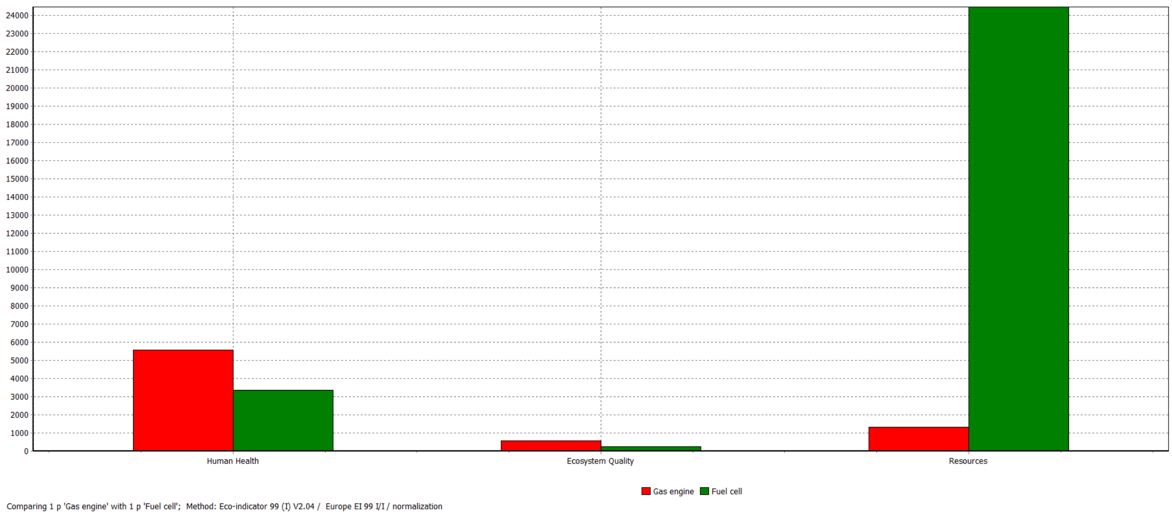


FIGURE 38: GAS ENGINE COMPARED TO FUEL CELL, ECO-INDICATOR NORMALIZED

After the normalization has been weighted the following results appear (figure 39 and 40). The difference from the normalization is that human health is weighted as a more important category making the final result more comparable.

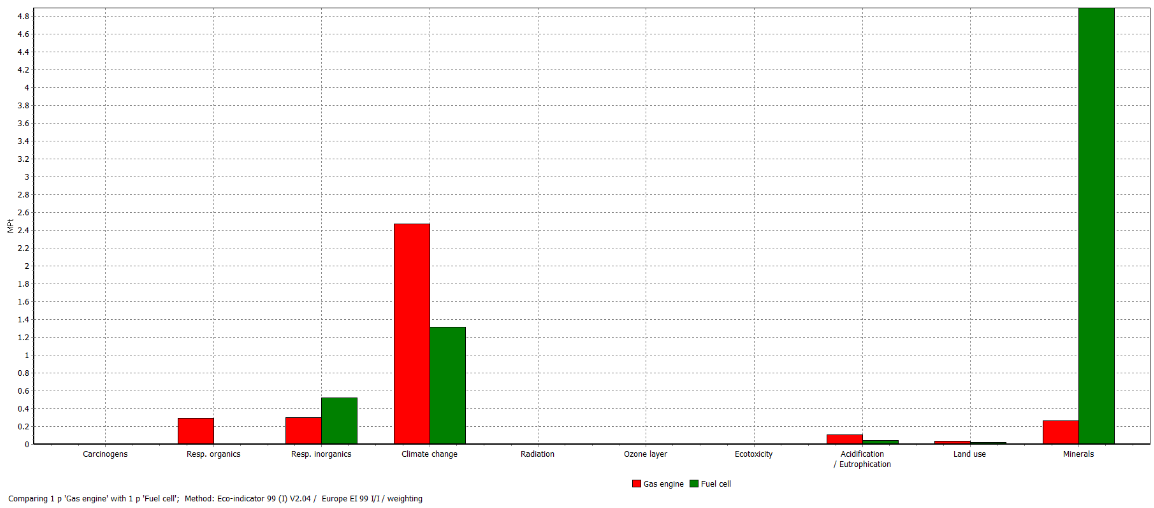


FIGURE 39: GAS ENGINE COMPARED TO FUEL CELL, ECO INDICATOR WEIGHTED

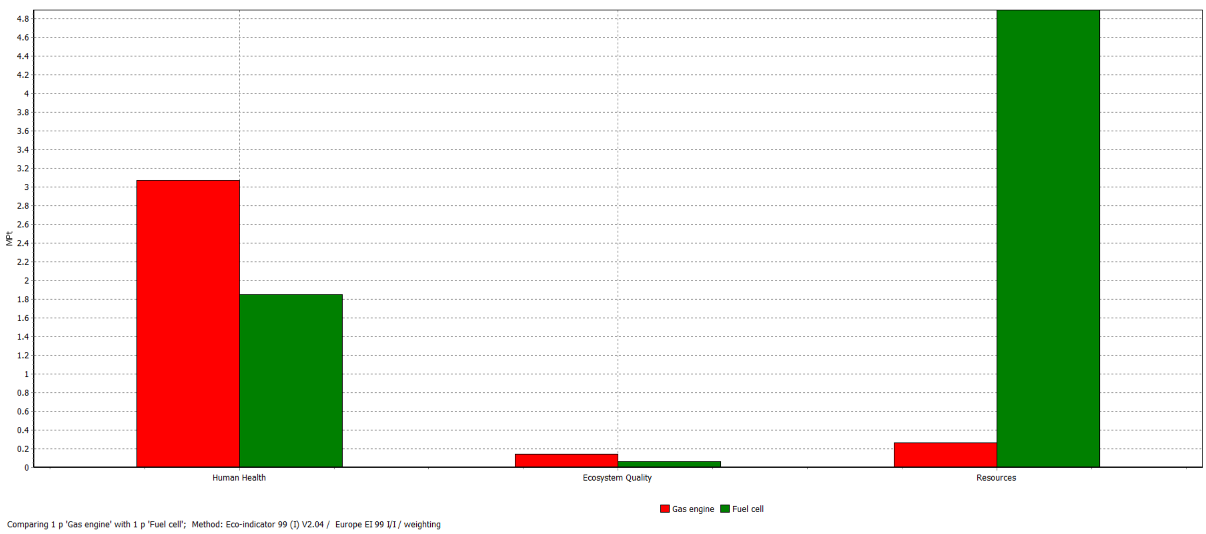


FIGURE 40: GAS ENGINE COMPARED TO FUEL CELL,ECO-INDICATOR WEIGHTED

Figure 41 and 42 displays the single score results. These figures give a total impact resulting in a larger impact from the fuel cell. The fuel cell has a total impact of 6,8 MPt which is an scale value, making it possible to merge the results into one denomination. The gas engine has a total impact of 3,5 MPt, making the gas engine 51% more environmentally friendly. Figure 42 reviles a large fuel cell impact of recourses, and a smaller impact of human health, this is comparable with the CML 2001 approach.

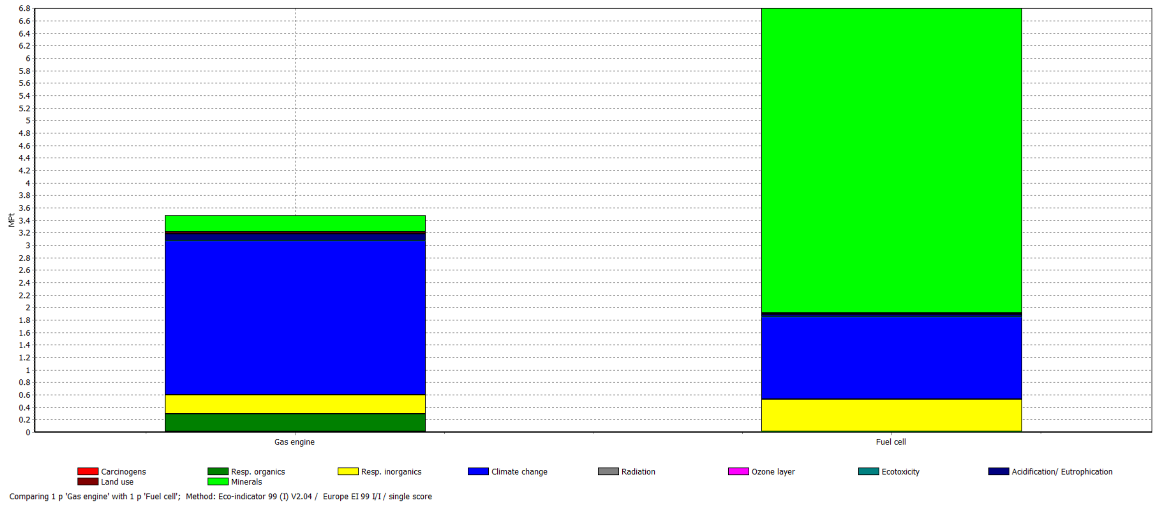


FIGURE 41: GAS ENGINE COMPARED TO FUEL CELL, ECO-INDICATOR SINGLE SCORE

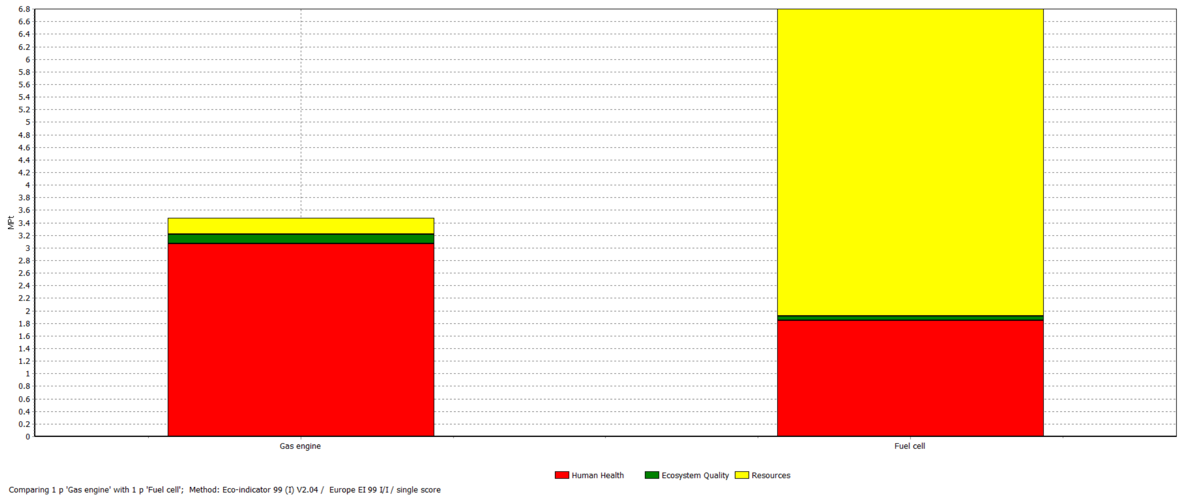


FIGURE 42: GAS ENGINE COMPARED TO FUEL CELL, ECO-INDICATOR SINGLE SCORE

## 7.5 Gas engine and fuel cell compared to diesel engine

By adding a third machinery solution, a diesel engine, it is possible to see the environmental gain by introducing natural gas as a fuel source. The diesel engine used in this comparison is a Rolls-Royce C-engine with clean design (DNV certification) using light fuel oil as fuel source. This means that the $NO_X$ emission is reduced to 20% below IMO's regulations. The engine is thereby a new and improved engine. The material components are the same as for the gas engine and new emission release for the diesel engine was collected from Rolls-Royce. (Valde 2010) Evaluating the three methods with respect to global warming potential (GWP), we can conclude with a 18% reduction switching from diesel engine to gas engine and a 55% reduction by implementing a fuel cell system. Locking at the other categories the diesel engine gives an overall more negative environmental output. The trend is an increased environmental impact from the lowest green fuel cell column to the highest yellow diesel engine column. The characterized values are displayed in figure 43, and the normalized values in figure 44.

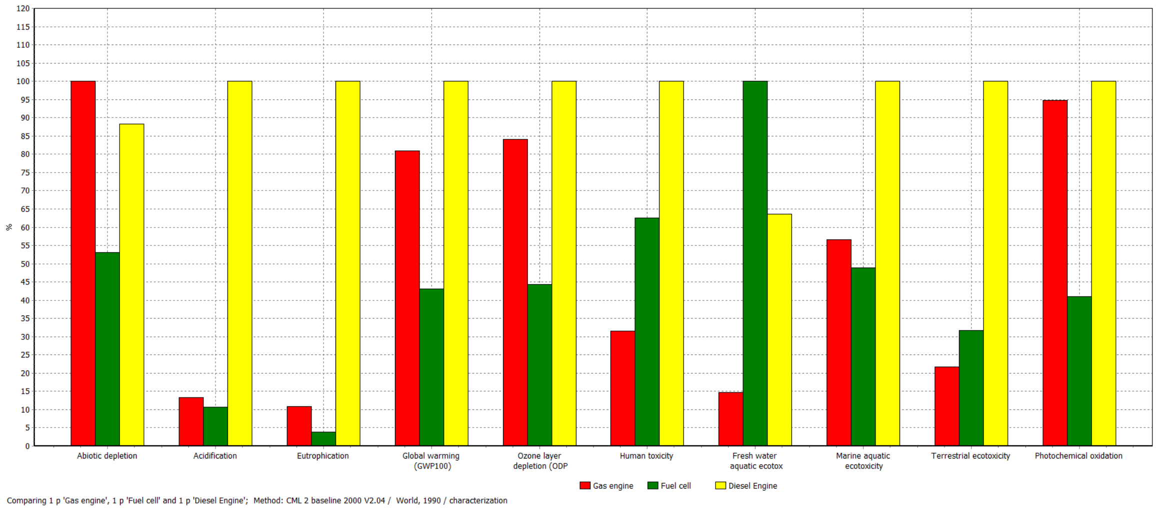


FIGURE 43: GAS ENGINE AND FUEL CELL COMPARED TO DIESEL ENGINE, CML CHARECTERIZED

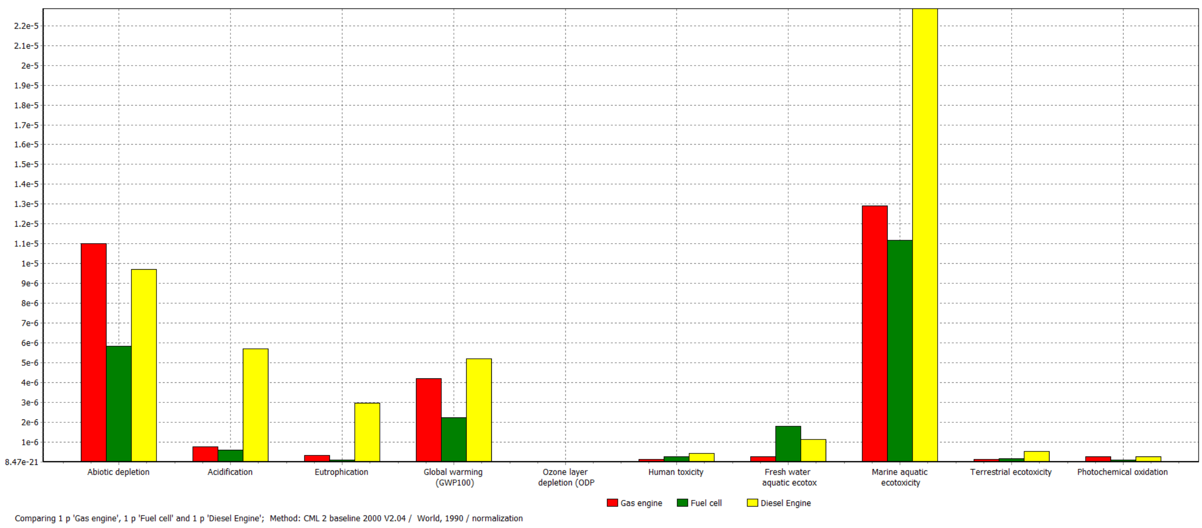


FIGURE 44: GAS ENGINE AND FUEL CELL COMPARED TO DIESEL ENGINE, CML NORMALIZED

Comparing the results with the eco-indicator approach the single score results are as displayed in figure 45 and 46 below. Because of the large impact from the resources the fuel cell has the highest total impact. Taking a closer look at the human health and ecosystems quality the fuel cell has the best score in these two categories. The gas engine and the diesel engine has the same material use, the biggest difference is the human health category where the gas engine reduce the impact by 35%. This is mainly due to lower direct emission to air. Figure 45 revile again the problem area, the fuel cell has to large environmental impact because of large material use.

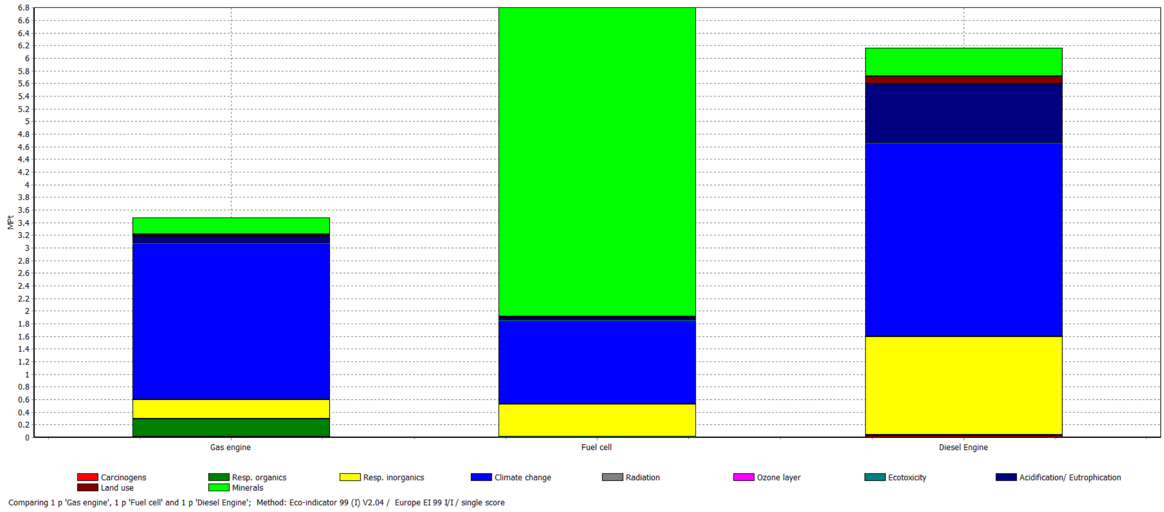


FIGURE 45: GAS ENGINE AND FUEL CELL COMPARED TO DIESEL ENGINE, ECO-INDICATOR SINGLE SCORE

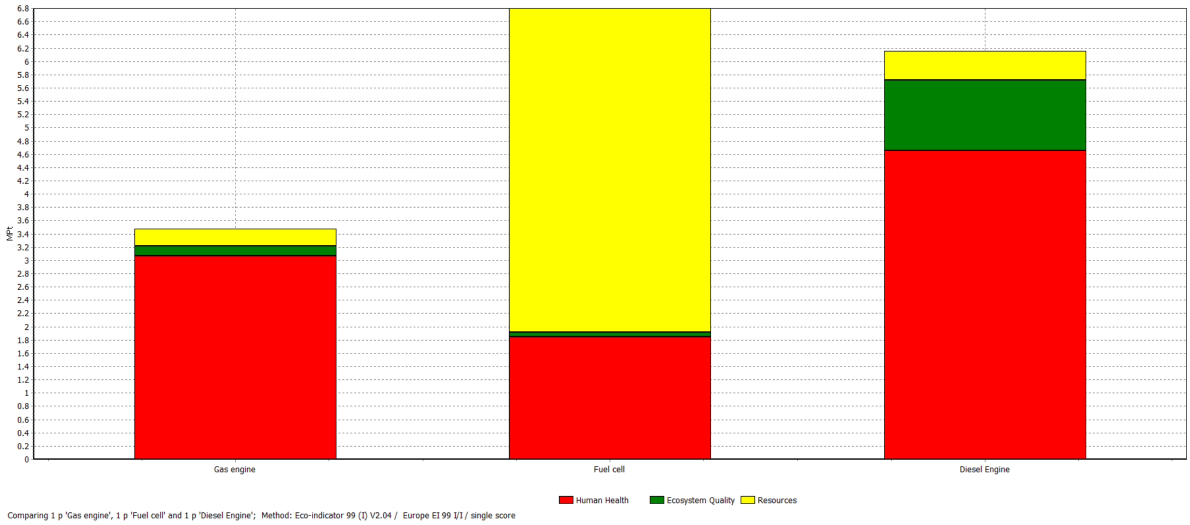


FIGURE 46: GAS ENGINE AND FUEL CELL COMPARED TO DIESEL ENGINE, ECO-INDICATOR SINGLE SCORE

# 8. EVALUATION OF THE STUDY

There are different ways to interpret the result of the study. It is important to look at different solutions from different points of view. To evaluate the final result it is important to do a completeness check, a sensitivity check and a consistency check. A completeness check is an evaluation of the processes included in the total product. The sensitivity check and consistency check evaluate how precise the results are. (ISO 2006) The results are divided into material and operation for both systems. Including the two categorization methods the displayed results give an overall picture of the environmental impact. The completeness of the result is considered to be sufficient in this case. Fuel cells and gas engines are not fully tested onboard ships, and the number of ships running entirely on LNG is relatively low. This makes it difficult to get sufficient data. In a further investigation, more material data can be applied. Information regarding where the material is produced and information regarding the assembly phase can also be added. This would include transportation data and energy consumption, which is not included in this study. Based on the consistency evaluation, the sensitivity is sufficient. Despite the missing information regarding energy consumption and transport, the information added in this study is reliable. The consistency of the study is evaluated as suitable. The interaction between the two compared systems is based on the same assumptions and the same choice of input values.

## 8.1 Evaluation of data

The quality of the data is vital, without the right data the analysis will fail. In this study almost all data are collected from suppliers directly connected to the product or process. By going directly to the suppliers the information gathered is based on first hand information. The quality of the material data can be discussed, the main material is established, but the energy used to produce the engine is not taken into account. This is because these numbers are very uncertain and difficult to obtain. The material selection in SimaPro is based on as similar products as possible. The production place is chosen to Europe to be able to neglect the transportation of materials and finished products. By producing the materials in Europe the fabrics are assumed more environmental friendly compared to materials produced in for instance china. The regulations for this are assumed stricter in Europe. The fuel cell material is classified; this is why this information is withdrawn from the report.

## 8.2 Evaluation of characterization models

There are differences between the impact categories in the CML 2001 approach. The unit is not similar, making the impacts difficult to compare. Based on MARPOL and other public and international governmental organizations the Global warming potential is an important category, this reflects on the media cover.

Large impact of eco-toxicity is a result of material use and fuel production. The problem with eco-toxicity is that there are few regulations that control the material use. The control area is located more locally at the fabric and production store, and is not attached to the shipping business. The focus to improve the ecosystems in shipping is based on factors connected with antifouling paint, sewage and garbage.

Evaluating the difference between the CML 2001 and the Eco-indicator 99 characterization models several differences appear. The CML 2001 method is a problem orientated approach, making the result based on the problem. It is not based on weighting; this means that the categories are not weighed between each other and thereby have different values and severity. This is a method that appeals to technical persons, the result has to be evaluated, but the result is concrete. The Eco-indicator 99 is based on a damage approach; this gives a more direct total damage. There are only three ending categories and these categories can be weighted, this means that the characterization model evaluate which categories makes the most damage to the environment. Based on this a single score can be established making a total evaluation possible. This method makes it easy to compare two products, and in a political and journalistic point of view it gives a clear and simple presentation. The problem with this method is the weighting; it is difficult to evaluate how the characterization model evaluate the results.

## 8.3 Evaluation of results

The result indicates that the fuel cell system is a better solution based on direct emission to air. A fuel cell has no combustion, giving fewer particles and other gasses to transform. In addition the fuel cell has lower fuel consumption than the gas engine. The marine aquatic eco-toxicity is mainly impacted from well exploration and drilling. This category is difficult to improve for the ship companies, the impact is locally connected to the on- and offshore gas production.

The gas engine has less impact on the marine ecosystems, both fresh water and oceans, as a consequence of the material use. Nickel is the material that contributes the most to damage the ecosystems, nickel contributes with about 40% of the marine ecosystem impact, and about 45% in the fresh water aquatic eco-toxicity category. To what extent the amount of nickel can be reduced is uncertain. Since nickel has a high economical value it is one of the most recycled metals in the world, and in Europe about 80% of nickel is reused. (Nickel-institute 2010)

In this study we have assumed that 75% of all materials are recycled, but it would be more realistic to send a larger share of the most impacting materials to reuse, and this would reduce the difference between the gas engine and the fuel cell materials.

In the comparison between the fuel cell and the gas engine including both construction and operation phase the fuel cell has the best result in all categories except the human toxicity, fresh water ecotoxicity and terrestrial ecotoxicity. As discussed above this is due to material use, and can be changed by sending more of the materials to reuse. Further development of the fuel cell can also contribute to reduction of the impact in these categories.

The change of fuel from MDO to LNG will reduce the emissions to air even if the efficiency is not changed, due to the properties of the fuels. Natural gas has lower carbon content per kilogram fuel than diesel, and at the same time the specific energy content is higher. This reduces the emission of $CO_2$. LNG is a more pure fuel than MDO, with low sulfur contain. This reduces the emissions of, $NO_X$, particles and $SO_X$. By switching to LNG emission taxes can be reduced and access to more ports and SECA is gained.

The result of the comparing the diesel engine, gas engine and fuel cell is taken into the study to show the effect of changing fuel type. It is important to know that we have not evaluated the problem with taken a third engine type into account. Allocations and other problems with the change of fuel are thereby not evaluated. The single score results gives an indication of the problem of the diesel engine; direct emissions to air is high. Because of the combustion process more particles, $NO_X$ and $SO_X$ is transformed. This can be more or less neglected in the fuel cell. Diesel engine is the most used engine type in shipping today, this is because of low cost and a developed system. To be able to compete with traditional engines the gas engine and the fuel cell has to be more environmental friendly and be able to compete in cost to be preferred. Taxes are one way to encourage more environmental friendly engine solutions.

# 9. ADVANTAGES AND DISADVANTAGES OF THE ENGINE SYSTEMS

In this chapter we want to consider the advantages and disadvantages of the engine systems. First a presentation of the technological status of the two engine systems will be given, followed by the collected information about the reliability. Then the lifecycle cost of the engine systems is calculated. The preferred choice of engine system is dependent of these factors, and in the end of the chapter we will look into what is required for future development to select one engine system above the other.

## 9.1 Fuel cell system

One of the main disadvantages of fuel cell systems is the large size and weight per power output. For land use this is usually not a problem, but onboard a ship the space available is limited. A MCFC has a weight power density in the range 18.1-27.2 kg/kW, and a volume power density in the range 0.028-0.060 $m^3$/kW. (Bolind 2000) For the 3550kW fuel cell we are considering, this gives a weight in the range 64-96 ton, and a volume in the range 99-213 $m^3$. These numbers do not include the surrounding heat capture and reuse system. We find it reasonable to consider a fuel cell of this size for our thesis even though it is not possible today, since we are only to evaluate the positive effects on the environment when this technology has been fully developed.

The limited lifetime of fuel cells is also a considerable disadvantage. They are in use for many applications onshore, but the experience with fuel cells of this type for marine applications is low. Due to this a fuel cell installation onboard a ship requires large amount of research and development, to a high cost. For this to be done it will require funding from institutions and governments, so that the ship owners do not have to carry out all of the costs.

The efficiency of the fuel cell does not vary with the size, meaning that the 3550kW fuel cell we are considering will have the same efficiency as the 320kW fuel cell onboard Viking Lady. (Fornybar.no 2010) This enables testing of small prototypes with reliable results before building a larger fuel cell. The fuel cell with the surrounding system can also be built as a module which easily can be lifted on and off the ship for testing.

There is another advantage of fuel cells regarding the efficiency: There is little variation in the efficiency on part load and full load. A traditional engine has the best efficiency at design load, with rapid decrease in efficiency on part load, giving higher fuel consumption per kWh output. For the fuel cell this will not be the case. Because of this the fuel cell is especially applicable in vessels operating with many different load conditions.

## 9.2 Gas engine

Compared to fuel cells gas engines have gained high lifetime, and are produced in a larger scale by different producers. This makes the gas engine a safer choice for machinery solution, since they have been thoroughly tested and developed. Testing reduces the risk of problems related to the operation of the system, and production in large scale gives a good access to spare parts when needed.

Another advantage of gas engines is that they have a low complexity when it comes to choice of materials and structure. This eliminates the weight and volume issues which are present in the fuel cell. The advantages mentioned above leads to another advantage of the gas engine: Low investment cost compared to the fuel cell. The competition between the different producers allows the investment cost of the gas engine to be lowered.

A disadvantage of the gas engine compared to the fuel cell is the efficiency. The lower efficiency gives higher fuel consumption, and thereby higher emission levels and fuel cost. The efficiency of the gas engine is limited by the Carnot limit, since thermal energy is converted into mechanical energy, and the efficiencies found in gas engines today cannot be improved to compete with the fuel cell efficiency. The fuel cell is not limited by the Carnot limit, since it is an electrochemical process, which does not involve conversion of thermal into mechanical energy. (Wright 2004)

## 9.3 Reliability

The MCFC operate at high temperatures and has a corrosive electrolyte, which both are factors contributing to material degradation. This is what limits the lifetime of the system. The metallic current collectors corrode and the electrolyte matrix is changing thickness and structure. When the electrolyte matrix change structure, the distribution of the electrolyte changes. This increases the conduction resistance within the cell. The realistic target for system lifetime is set to 40 000-58 000 hours of operation. (REF: Technical and research report R-55, SNAME) During this lifetime the open circuit voltage (OCV) drops at a linear rate the first third of the lifetime and with an accelerated rate thereafter.

During the lifetime the electrolyte is vaporizing and need to be supplied. In the first third of the lifetime, where we have a linear OCV drop, electrolyte loss is the main contributor for reduced performance. The maintenance expenses of the fuel cell will consist of electrolyte supply. The OCV drop is measurable, and the maintenance can be performed when needed.

In the last phase of the cells lifetime the material degradation is contributing to the OCV drop, and this cannot be reversed by maintaining the cell. When the fuel cell has operated for about 40 000 hours the performance has decreased to a level where the fuel cell is not performing adequately, and it needs to be replaced. (Vielstich, Gasteiger et al. 2003)

In a fuel cell we have no moving parts doing mechanical work, so the risk of total shutdown due to component failure is eliminated. The voltage drop due to material degradation and loss of electrolyte can be monitored and controlled at all times. This is not the case for the gas engine, which is performing mechanical work. If one of the components is defect this can lead to complete system shutdown. Because of this the maintenance surveillance of the gas engine has to be up to date.

A gas engine has a more complex fuel supply system than a diesel engine. Gaseous fuel does not contribute to lubrication of the engine components. In addition diesel engines use lubrication oil to grease the system. At the same time, LNG is a purer fuel than diesel and HFO, containing fewer particles. Particles damage the components in the engine. (Stenersen 2010) Testing of the Wärtsilä 34SG engine shows that the overhaul interval is as much as 24 000 hours of operation, and that the expected lifetime is up to 100 000 hours of operation. (Wärtsilä 2009) We expect the selected engine for this project to have the same overhaul interval and expected lifetime as this one.

## 9.4 Economical impact

The cost of the machinery systems, both capital costs and operational costs, will have an impact on how attractive they are to install in a vessel from the owners point of view. A system providing emission reduction beyond what is required from the rules will probably not be preferred if the cost is too high.

When collecting cost information we have found estimates in both Norwegian kroner (NOK) and Euro (EUR). For comparison Euro has been chosen as currency in the calculations, with the exchange rate 1EUR=8NOK. This was the exchange rate at the time of writing, April 2010. (DnBNOR 2010)

### 9.4.1 CAPITAL COST

The capital cost in this case is investment cost of the machinery systems. The capital cost of the gas engine is 10 million NOK. (Tepstad 2010) This investment will be done one time during the 20 years of operation.

The capital cost of the fuel cell system is a bit more uncertain, due to the fact that not many fuel cell systems for this use have been constructed. An estimate of 3000 EUR/kW has been given. (Sandaker 2010) For this fuel cell system the capital cost will then be about 10.65 million Euros. The realistic lifetime of the fuel cell is uncertain since they have not been thoroughly tested for longer periods of time. We have found information on 40000-58000 hours of operation being a realistic lifetime. For 20 years of operation, the fuel cell system will have to be replaced approximately every 6.5 years. (Bolind 2000)

| **Capital cost** | | | | |
|---|---|---|---|---|
| | Capital cost | Installed power | # of units 20 years operation | Total capital cost |
| | (EUR/kW) | (kW) | (-) | (EUR) |
| **Fuel cell system** | 3 000 | 3 550 | 3 | 31 950 000 |
| **Gas engine** | 352 | 3 550 | 1 | 1 250 000 |

TABLE 5: CAPITAL COST

From table 5 we see that the total capital cost of the fuel cell system is calculated to be about 25 times higher than the capital cost of the gas engine, given that fuel cell system has to be replaced two times during the 20 years of operation.

### 9.4.2 OPERATIONAL COST

The operational cost of the systems refers to the amount of LNG used and the maintenance cost of the systems. Good estimates on the maintenance cost of the two systems were not found, and only the operational cost of fuel consumption is included. The market price of LNG in Europe is at the time of writing 0,33NOK/kWh. (GASNOR 2010) This price is assumed constant over the 20 year period. The interest rate is set to be 2%. (DnBNOR 2010)

| **Operational cost** | | | | |
|---|---|---|---|---|
| | Fuel consumption | | Cost | Net present value |
| | (MJ/year) | (kWh/year) | (EUR/year) | (EUR/20 years) |
| **Fuel cell system** | 79 336 000 | 22 038 000 | 909 000 | 14 864 000 |
| **Gas engine** | 151 058 000 | 41 960 000 | 1 731 000 | 28 302 000 |

TABLE 6: OPERATIONAL COST

Because of the much higher fuel consumption of the gas engine, the annual operational cost of the gas engine has been calculated to be about 1.9 times as high as for the fuel cell system. The maintenance cost of the fuel cell system is expected to be much higher than for the gas engine, due to low lifetime. If this had been taken into account, the difference in operational cost of the two systems would have been reduced. The calculated operational net present values of the two options are shown in table 6.

### 9.4.3 LIFE CYCLE COST

The calculated life cycle cost of the two alternatives, including both capital- and operational costs, can be found in table 7.

| | Life cycle cost |
|---|---|
| | (EUR) |
| **Fuel cell system** | 46 814 000 |
| **Gas engine** | 29 552 000 |
| **Difference** | 17 262 000 |

TABLE 7: LIFE CYCLE COST

Even though the fuel consumption of the fuel cell system is very low compared to the gas engine, the high capital cost makes the fuel cell system a more expensive alternative. If the maintenance cost would be taken into account, we expect the difference to be even higher.

# 10. FUEL CELL DEVELOPMENT

To be able to compete with standard technology the fuel cell has to be improved. Based on the result of the environmental impact and economic aspect the fuel cell has to increase the lifetime.

## 10.1 Environmental impact of increased lifetime

Today the life time of the fuel cell is uncertain and not fully tested. In a 20 year perspective the fuel cell has to be replaced two times, making the environmental impact large with respect on recourses. The graph below displays the impact reduction by increasing the lifetime of the fuel cell. As viewed the total impact reduces from 6.8 E6 to 3.3 E6 Pt, where Pt is an indicator, by enlarging the lifetime from 7 to 20 years. This would give an impact reduction of 49%.

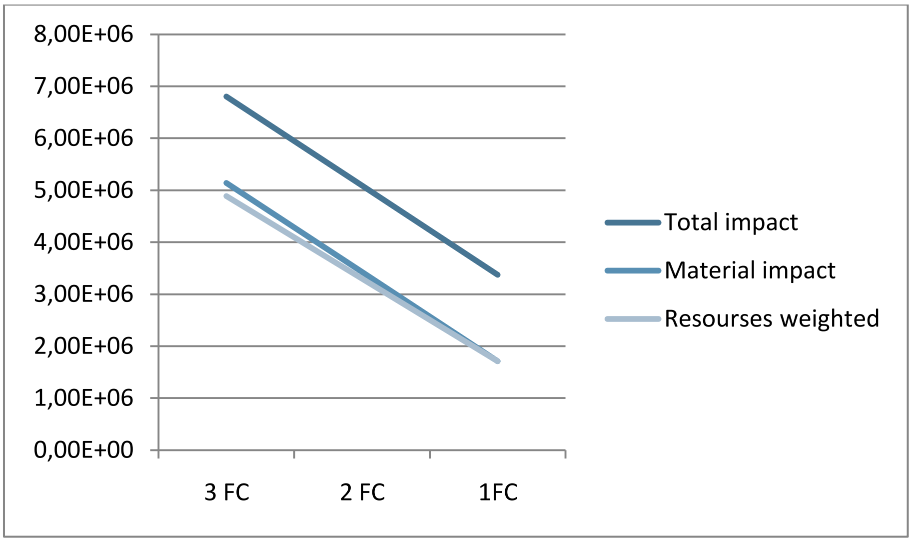


FIGURE 47: IMPACT REDUCTION BY INCREASING FUEL CELL LIFETIME

This gives a final single score graph which prefer the fuel cell compared to the gas engine. As we can see of the graph the fuel cell still has a high impact from recourses (yellow column). By improving the technology, the size of the fuel cell can be reduced making the fuel cell more favorable.


FIGURE 48: SINGLE SCORE COMPARISON, INCREASED LIFETIME FUEL CELL

## 10.2 Economical impact of increased lifetime

The life cycle cost of the gas engine is about 29.5 million Euros, where 96% of the cost is operational cost. (Tepstad 2010) The life cycle cost of the fuel cell is about 46.8 million Euros. (Sandaker 2010) For this solution the operational cost only contributes with 30%. In this part of the evaluation we want to consider how much the fuel cell will have to improve in the future to achieve equivalent life cycle cost with the gas engine. For this purpose we consider the operational cost (derived by the fuel consumption and fuel cost) fixed for both the fuel cell and the gas engine. Since the capital cost of the gas engine contribute with only 4% to the total life cycle cost, also considering this cost constant will not affect the result much.

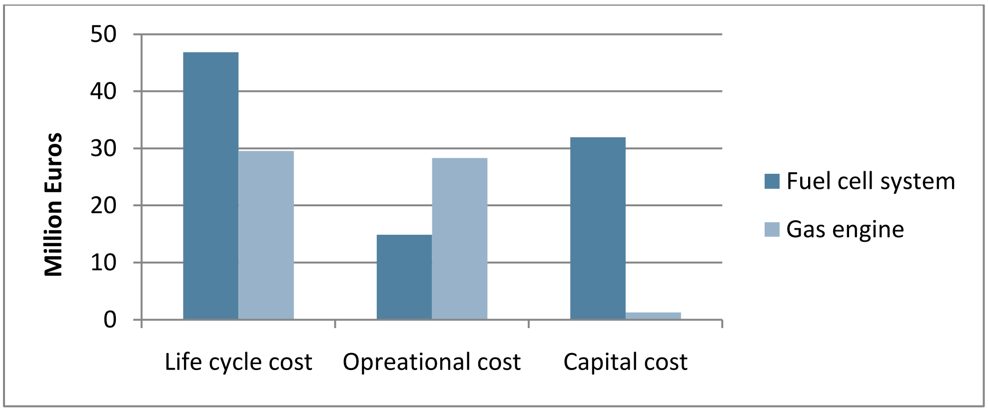


FIGURE 49: DISTRIBUTION LIFE CYCLE COST

With fixed operational cost there are two ways to decrease the life cycle cost of the fuel cell machinery solution: To increase the lifetime of the fuel cell and/or reduce the investment cost per kW installed power. As the lifetime of the fuel cell is today, the fuel cell onboard Viking Lady will have to be replaced two times during the period of 20 years of operation. If only one fuel cell was to be in use the entire lifetime of 20 years (162 590 hours of operation), the life cycle cost of the fuel cell would be 25.5 million Euros. This is 4 million Euros less than the life cycle cost of the gas engine. But a fuel cell lifetime of 20 years of operation seems unrealistic based on the status of the technology today.

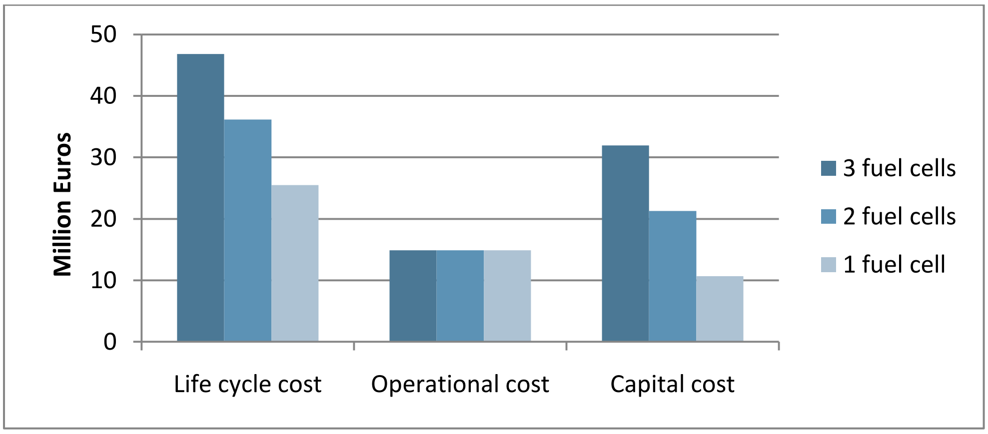


FIGURE 50: INCREASED LIFETIME, FUEL CELL

If two fuel cells are to cover the 20 years of operation, with 10 years of operation each, the life cycle cost would be 36.2 million Euros, only 7 million Euros more than the life cycle cost of the gas engine. This lifetime might be realistic in the future if time is put into further development of fuel cells. But increasing the lifetime of the fuel cell to 10 years of operation is not sufficient to achieve equivalent life cycle cost with the gas engine solution. A reduction in investment cost is also needed. In figure 51 the needed reduction in investment cost (EUR/kW) is illustrated, when the lifetime of the fuel cell is increased to 10 years of operation.

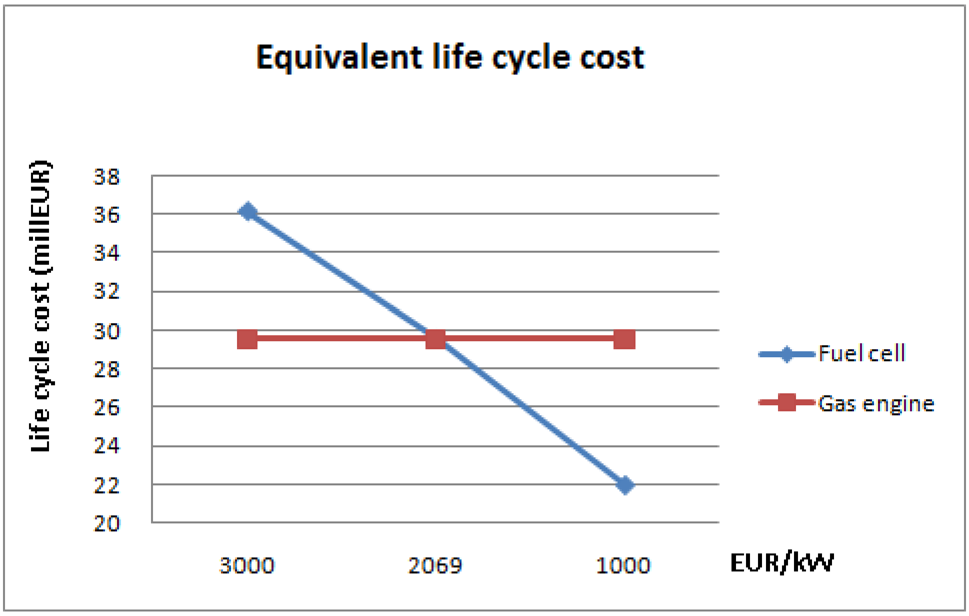


FIGURE 51: EQUIVALENT LIFE CYCLE COST

The investment cost of the fuel cell will have to be decreased by 31% to 2070 EUR/kW combined with a 50% increased lifetime to achieve equivalent life cycle cost with the gas engine. From the figure we can see that a further reduction in investment cost of the fuel cell will give savings in life cycle costs compared to the gas engine. A reduction in investment cost requires further development in choice of materials and production in a larger scale than today. An increased lifetime requires effort put into development and testing.

## 10.3 Future development and improvements

As the fuel cell technology status is today, it is not possible to install fuel cells with high power output for main propulsion onboard ships, because of the high volume and weight per power output, as discussed in chapter 11: Advantages and disadvantages. The choice of materials and design has not developed to any extent the last years, and it is uncertain what possibilities there are to solve the size and weight issues. Use of nanotechnology might be an option to solve this. The use of microcomposite structures might lead to a breakthrough in performance, which can allow smaller units with the same power output. (Selman 2006) Before these issues are solved, only smaller units for auxiliary power production are feasible onboard ships like the Viking Lady.

The building cost and the fuel consumption represent large contributors to the capital and operational costs of a vessel. For ship owners to consider the use of fuel cells or a gas engine, it has to be competitive to traditional machinery. The investment costs of fuel cell systems are high due the low maturity and lack of large scale production. The gas engine has a low investment cost, but a higher fuel consumption than the fuel cell. The fuel prices are getting higher if they follow the trend for the recent years (Shafiee and Topal 2010), and the importance of an efficient machinery solution will thereby increase. Fuel cells in combination with heat capture and reuse are shown to have a higher efficiency than conventional machinery and the savings in operational costs can be of considerable amounts.

The reduced emission levels from both the gas engine and the fuel cell compared to traditional engines can contribute to making these two solutions preferable. There are taxes given for emission from ships, and a reduction in emission will give savings in costs, and this contributes to increase the environmental awareness of the ship owners. The tax is calculated from the specific fuel consumption, specific $NO_X$ emission and fuel consumption. (Gude 2009) The image of the company is also an important driver for selecting a more efficient machinery system. People around the world are getting more concerned about the environment, and often prefer sustainable alternatives, even if it costs more. This trend is likely to continue.

One way to reduce emissions further in the future is to use pure hydrogen as fuel in gas engines and fuel cells. Hydrogen can be produced from fossil, nuclear and renewable energy sources, and the emission reduction will then depend on what energy source is used to extract the hydrogen. It costs energy to produce hydrogen, and this energy should be from renewable energy sources. To be able to make use of pure hydrogen for fuel cells and gas engines in the future, the production and storage technology will have to be improved. Today most of the hydrogen is extracted from natural gas, since the renewable technology is not efficient enough. The use of nanotechnology and nanoscale processes can increase the performance of solar hydrogen production, and make this a viable alternative to extraction from natural gas. Gaseous hydrogen has a very small specific volume, and storage in high-pressure tanks, liquefaction or solid state storage is necessary for use onboard ships. High-pressure hydrogen is highly flammable, presenting a potential hazard. Liquid hydrogen has about 30% energy loss due to refrigeration. The best alternative seems to be storage in solid state, but none of the existing technologies for this kind of storage are fulfilling all requirements when it comes to energy density, cost, flow rate, temperature, transient response, leakage and safety. These problems will have to be worked out before pure hydrogen can be used for power demands of these size onboard ships. (U.Sahaym 2008)

# 11. RECOMMENDATIONS AND CONCLUSION

Based on the result and the evaluations we feel that there are several issues to discuss. The results give a clear indication that the gas engine is the best option. The emission of global warming gases is low; the same is the impact of the materials. When it comes to expected lifetime and cost the gas engine is favorable. The maintenance cost of the machinery solutions has not been taken into account in the economical evaluation. We think that the gas engine would score better on this area, due to less complexity. Today the gas engine is the best solution.

What makes the fuel cell a less good solution is the environmental impact of the materials. If the material impact of the fuel cell is reduced by minimizing the size, improving the material composition and prolonging the lifetime, the fuel cell could be a better solution. The fuel cell has lower global warming impact than the gas engine. The high efficiency makes the fuel consumption low. This is an important factor for the future, when fossil fuels become more inaccessible. The fuel cell can also be run on hydrogen extracted from renewable energy, making the emission to air even smaller. Hydrogen is more difficult to store and produce than LNG and the accessibility in ports is low. By developing the marked, the demand will increase, making hydrogen more available in the marked. With these types of future development the fuel cell can be competitive with regular technologies.

The shipping marked is interested in implementing fuel cell technology. Eidesvik is testing their pilot project to establish more attention to the technology and gain experience on the use of high temperature fuel cells onboard ships. But this project would not have been performed without funding from the Norwegian Research Council, Innovation Norway and the German Federal Ministry of Economics and Technology. For ship owners to continue testing of fuel cells onboard their ships it is important that the governments contribute with funding.

Our conclusion is that gas engines should be the preferred machinery solution onboard ships today, due to low environmental impact. We will recommend continuing the development of fuel cells for marine applications with emphasis on choice of materials, size and enlarged lifetime. The goal should be to be able to implement fuel cells as main machinery onboard ships.

# 12. FURTHER WORK

To be able to give a more precise result, there are some issues that should be investigated further. The first is related to the materials. More precise input data can be collected, including the production stage. The production countries of the material of both the fuel cell and the gas engine were selected as close to assembly site as possible, without further investigation. We would recommend contacting the producers for more information on production countries.

In this assessment 75% of the materials were assumed recycled at end of life. We did not do an individual evaluation for each material. The actual distribution between recycling and waste for each material should be found through contacting the producers.

For the operational results to be accurate the efficiency of the fuel cell with the surrounding heat reuse system should be tested and implemented in the SimaPro analysis. This has not yet been performed in June 2010, and thereby the efficiency used in the assessment is only an estimate provided by Wärtsilä. The emission release should as well be measured and implemented with accurate values. Implementing maintenance data, will improve the study regarding material impact and cost.

The operation profile of Viking Lady was only given as an approximate sketch by Eidesvik, and had to be supplied with information from comparison ships. A more precise operation profile for Viking Lady should be obtained from Eidesvik. This would not affect the conclusion of the assessment, but the values in the results would be a little different.

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# 14. APPENDIX

## 14.1 Assignment text

# TMR 4905 – Master Thesis Marine Systems - spring 2010


**Kaja Jonsvik Aarskog**

**Kjersti Hestad Strand**


**Life cycle assessment of Fuel Cells onboard ships**

Livssyklusanalyse av bruk av brenselsceller om bord i skip

### Background

It is expected that the maritime community of the future will be challenged regarding the development and verification of environmental friendly concepts. Fuel cells are introduced as an alternative and more environmental friendly source for energy production on board ships. A relevant question is to ask whether fuel cells used on board ships are effective means of reducing the environmental impacts from sea transportation systems.

## Goal

The main intention of the thesis is to perform a comparative Life cycle Assessment (LCA) study comparing environmental consequences of switching from traditional engines to fuel cells.

Further, by implementing a cost and reliability discussion to the environment analysis, it is the intention to be able to recommend the implementing of fuel cells onboard a ship or not based on criteria defined by the students.

## Work description

In the first part of the thesis, the students will collect data from fuel cells onboard ships, define goal and scope for the environmental analysis including definition of system boundaries, functional unit and allocation procedure. A model for LCA in SimaPro shall be established. Basic criteria for evaluation of fuel cells versus conventional power systems shall further be defined.

In the second part the analysis will be run, and the information will be evaluated. The advantages and disadvantages regarding environmental issues, costs and reliability will be discussed and compared to an existing ship with traditional machinery.

A final evaluation shall be performed aiming at identifying whether use of fuel cells are recommendable as power supply sources onboard a ship or not.

## General

The work shall be carried out in accordance with guidelines, rules and regulations pertaining to the completion of a Master Thesis in engineering at NTNU.

The work shall be completed and delivered by: June 14th, 2010 in one electronic and 3 printed copies.

Trondheim, March 1, 2010

Harald Ellingsen

## 14.2 Material, fuel cell

## 14.3 Fuel consumption and operation information, fuel cell

| Fuel consumption, MJ/hour (70% system efficiency) | | | | |
|---|---|---|---|---|
| 100% MCR | 75% MCR | 50% MCR | 26% MCR | 13% MCR |
| 17214 | 12911 | 8607 | 4476 | 2238 |

| Emissions (gram/hour): | | | | | |
|---|---|---|---|---|---|
| | **100% MCR** | **75%MCR** | **50% MCR** | **26% MCR** | **13% MCR** |
| **$CO_2$** | 865,8804 | 649,4103 | 432,9402 | 225,1289 | 112,5644 |
| **CO** | 0,2960 | 0,2220 | 0,1480 | 0,0770 | 0,0385 |
| **$NO_X$** | 0,6809 | 0,5106 | 0,3404 | 0,1770 | 0,0885 |
| **PM** | 0,0518 | 0,0389 | 0,0259 | 0,0135 | 0,0067 |

## 14.4 Operational information, gas engine

Rolls-Royce Marine AS, Engines-Bergen

KV16 G4

Const. speed TA air. 1000rpm. 3550kW

| | | |
|---|---|---|
| Fuel gas: | 48,068 | [MJ/kg] |
| | 3550 | kW |

| **Mode** | | | | | | |
|---|---|---|---|---|---|---|
| Speed | [%] | 100 | 100 | 100 | 100 | 100 |
| Power | [%] | 99 | 75 | 50 | 26 | 13 |
| **Gasseous emission data :** | | | | | | |
| $NO_X$ specific | [g/kWh] | 1,34 | 0,69 | 0,67 | 0,31 | 0,23 |
| *spec. $CO_2$ emission* | [g/kWh] | 432,64 | 448,22 | 473,31 | 554,84 | 674,31 |
| *spec. CO emission* | [g/kWh] | 1,77 | 1,84 | 1,94 | 4,17 | 2,26 |
| *spec. HC emission* | [g/kWh] | 5,51 | 6,35 | 7,23 | 20,70 | 72,79 |
| **Engine data :** | | | | | | |
| Corrected spec. fuel consumption | [g/kWh] | 174,4 | 181,7 | 192,4 | 240,9 | 347,2 |
| *Virkningsgrad* | [%] | 42,9 | 41,2 | 38,9 | 31,1 | 21,6 |
| **Engine data :** | | | | | | |
| Corrected spec. fuel consumption | [MJ/h] | 29350,3 | 23139,0 | 16313,3 | 10528,6 | 7849,5 |
| *Virkningsgrad* | [%] | 42,9 | 41,2 | 38,9 | 31,1 | 21,6 |
| **Gasseous emission data :** | | | | | | |
| $NO_X$ specific | [kg/h] | 4,68 | 1,83 | 1,18 | 0,28 | 0,11 |
| *spec. $CO_2$ emission* | [kg/h] | 1535,87 | 1187,63 | 834,99 | 504,46 | 317,18 |
| *spec. CO emission* | [kg/h] | 6,20 | 4,87 | 3,42 | 3,79 | 1,06 |
| *spec. HC emission* | [kg/h] | 19,28 | 16,83 | 12,75 | 18,82 | 34,24 |

Rolls-Royce Marine AS, Engines-Bergen

Const speed TA air. 899rpm.

| | | | | | | |
|---|---|---|---|---|---|---|
| **Mode** | | | | | | |
| Speed | [%] | 100 | 100 | 100 | 100 | 100 |
| Power | [%] | 99 | 75 | 50 | 26 | 13 |
| EnginePwer | kWh | 1924,00 | 1433,00 | 957,00 | 473,00 | 189,00 |
| **Engine data :** | | | | | | |
| Corrected spec. fuel consumption | [g/kWh] | 193,7 | 193,8 | 202,3 | 229,9 | 329,3 |
| **Engine data :** | | | | | | |
| Corrected spec. fuel consumption | kg/h | 687,6 | 512,4 | 357,2 | 200,6 | 114,8 |
| **Gasseous emission data :** | | | | | | |
| $NO_X$ | [kg/h] | 28,60 | 21,98 | 15,30 | 10,19 | 4,67 |
| *$CO_2$ emission* | [kg/h] | 2096,05 | 1557,28 | 1088,62 | 608,89 | 335,81 |
| *CO emission* | [kg/h] | 0,63 | 0,59 | 0,63 | 0,68 | 0,74 |
| *HC emission* | [kg/h] | 0,68 | 0,65 | 0,63 | 0,41 | 0,37 |
| *$SO_2$ emission* | [kg/h] | 0,68 | 0,52 | 0,35 | 0,20 | 0,11 |

## 14.6 Operation profile

### 14.6.1 OPERATION PROFILE VIKING LADY

3 rountrips/ week

| | % time | Load condition | |
|---|---|---|---|
| In port | 28 % | 400-600 | kW |
| In transit | 28 % | 3500-4000 | kW |
| At field | 44 % | 800-1200 | kW |
| At field bad weather: | | 2000-3500 | kW |

## 14.6.2 OPERATION PROFILE, PETROATLANTIC

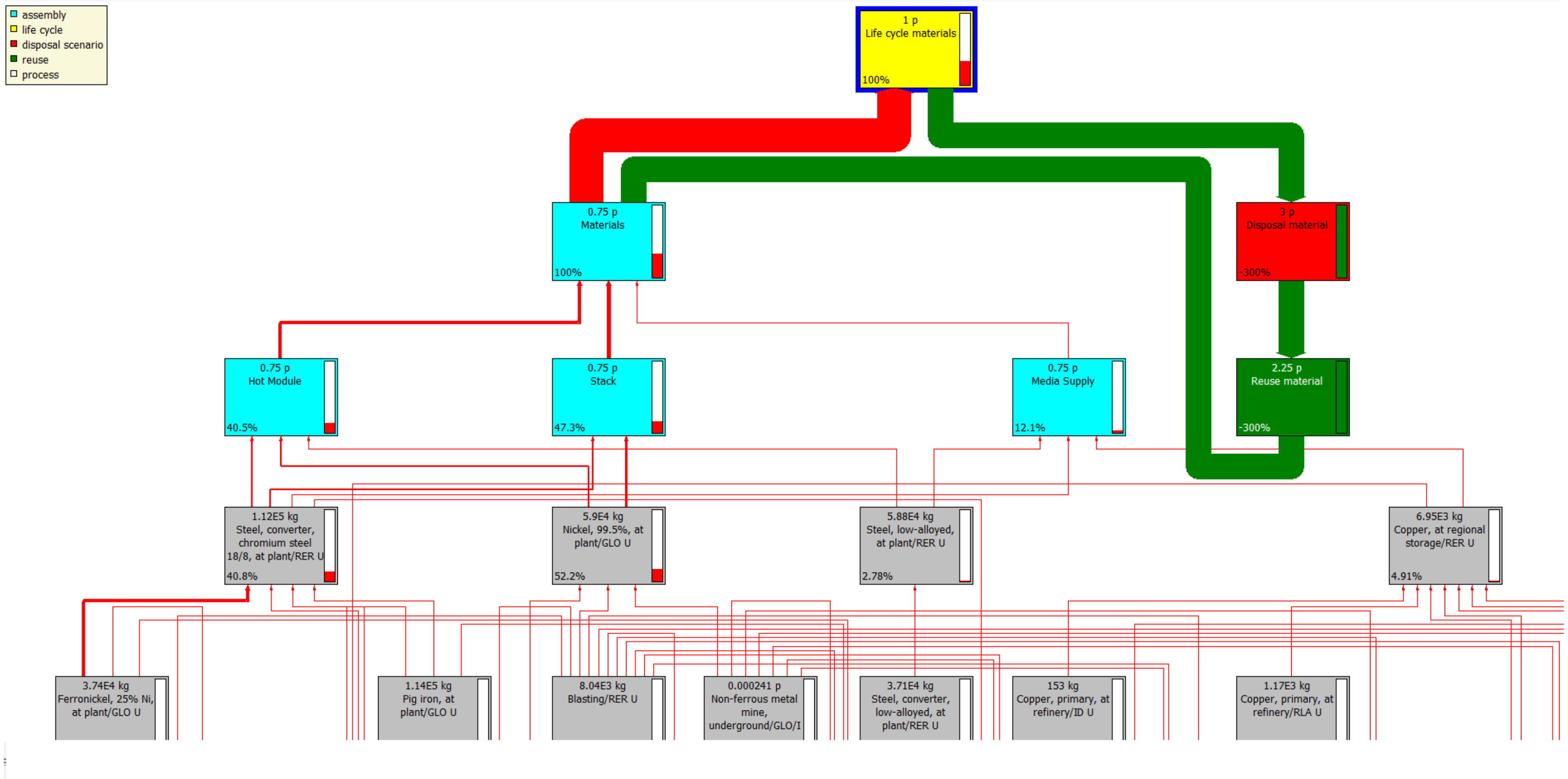
| Jan | ME | AVER. | Feb | ME | AVER. | march | ME | AVER. |
|---|---|---|---|---|---|---|---|---|
| DATE | HRS. | RPM | DATE | HRS. | RPM | DATE | HRS. | RPM |
| 1 | 24 | 66,2 | 1 | 23 | 72,0 | 1 | 24 | 74,5 |
| 2 | 24 | 67,3 | 2 | 24 | 76,9 | 2 | 24 | 91,2 |
| 3 | 24 | 76,5 | 3 | 2 | 68,3 | 3 | 6 | |
| 4 | 24 | 83,4 | 4 | 17 | 85,3 | 4 | 7 | 92,5 |
| 5 | | | 5 | 25 | 91,5 | 5 | 23 | 92,8 |
| 6 | | | 6 | | | 6 | 5 | |
| 7 | 22 | 99,6 | 7 | | | 7 | 0 | |
| 8 | 24 | 99,1 | 8 | | | 8 | 0 | |
| 9 | 3 | | 9 | | | 9 | 0 | |
| 10 | 0 | 0,0 | 10 | | | 10 | 17 | 92,8 |
| 11 | 5 | | 11 | | | 11 | 23 | 80,0 |
| 12 | 3 | 76,0 | 12 | | | 12 | 2 | |
| 13 | 23 | 72,8 | 13 | | | 13 | 2 | |
| 14 | 0 | 0,0 | 14 | | | 14 | 0 | |
| 15 | 6 | | 15 | | | 15 | 0 | |
| 16 | 18 | 92,4 | 16 | | | 16 | | |
| 17 | 25 | 64,2 | 17 | 1 | 101,3 | 17 | 3 | 102,6 |
| 18 | 24 | 64,9 | 18 | 24 | 87,2 | 18 | 24 | 79,6 |
| 19 | 24 | 70,2 | 19 | 24 | 70,4 | 19 | 24 | 72,5 |
| 20 | 24 | 70,8 | 20 | 24 | 67,3 | 20 | 24 | 65,6 |
| 21 | 24 | 63,3 | 21 | 24 | 63,9 | 21 | 24 | 64,7 |
| 22 | 24 | 70,5 | 22 | 24 | 69,7 | 22 | 24 | 69,3 |
| 23 | 24 | 69,2 | 23 | 24 | 70,7 | 23 | 24 | 84,1 |
| 24 | 24 | 72,9 | 24 | 24 | 63,3 | 24 | 3 | |
| 25 | 24 | 63,7 | 25 | 24 | 65,7 | 25 | | |
| 26 | 24 | 70,6 | 26 | 24 | 66,9 | 26 | 17 | 67,6 |
| 27 | 24 | 67,8 | 27 | 22 | 81,1 | 27 | 24 | 81,4 |
| 28 | 6 | 68,0 | 28 | 1 | 65,8 | 28 | 3 | |
| 29 | 23 | 69,7 | 29 | | | 29 | 20 | 73,2 |
| 30 | 24 | 64,0 | 30 | | | 30 | 24 | 69,3 |
| 31 | 24 | 90,0 | 31 | | | 31 | 24 | 86,7 |

## 14.6.3 OPERATION PROFILE PETRONORDIC

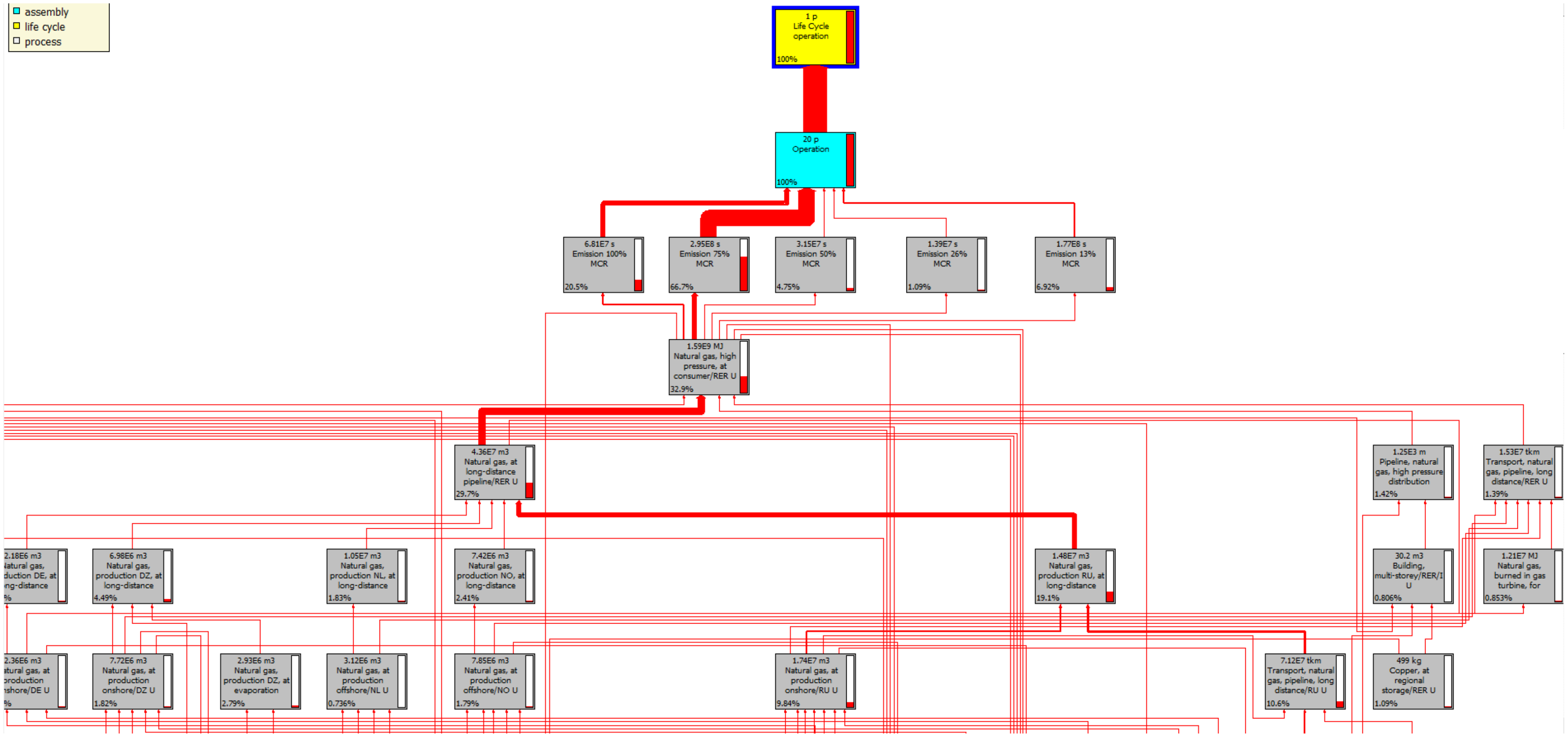
| Jan | MAIN ENG. | | Feb | MAIN ENG. | | March | MAIN ENG. | |
|---|---|---|---|---|---|---|---|---|
| | | AVER. | | | AVER. | | | AVER. |
| DATE | HRS. | RPM | DATE | HRS. | RPM | DATE | HRS. | RPM |
| 1 | 23 | 81,9 | 1 | 5 | 79,6 | 1 | 0 | 0 |
| 2 | 19 | 73,1 | 2 | 21 | 70,8 | 2 | 0 | 0 |
| 3 | 25 | 63,0 | 3 | 24 | 74,1 | 3 | 2 | 0,0 |
| 4 | 22 | 69,9 | 4 | 3 | 61,0 | 4 | 19 | 69,5 |
| 5 | 0 | 0,0 | 5 | | | 5 | 24 | 70,5 |
| 6 | 16 | 87,5 | 6 | 19 | 87,3 | 6 | 0 | 0,0 |
| 7 | 23 | 91,5 | 7 | 22 | 89,4 | 7 | 0 | 0,0 |
| 8 | 0 | 0,0 | 8 | | | 8 | 19 | 72,7 |
| 9 | 21 | 64,1 | 9 | | | 9 | 24 | 75,4 |
| 10 | 24 | 67,7 | 10 | 16 | 88,4 | 10 | 4 | |
| 11 | 24 | 73,3 | 11 | 24 | 72,9 | 11 | 0 | |
| 12 | 23 | 63,7 | 12 | 24 | 62,8 | 12 | 20 | 76,3 |
| 13 | 20 | 71 | 13 | 24 | 64,3 | 13 | 24 | 70,5 |
| 14 | 24 | 68,2 | 14 | 24 | 69,9 | 14 | 24 | 63,1 |
| 15 | 24 | 75,1 | 15 | 21 | 100,3 | 15 | 24 | 73,4 |
| 16 | 24 | 63,6 | 16 | 17 | 97,1 | 16 | 24 | 67,1 |
| 17 | 24 | 64,1 | 17 | 23 | 98,3 | 17 | 23 | 64,5 |
| 18 | 24 | 67,8 | 18 | 5 | | 18 | 24 | 67,2 |
| 19 | 24 | 80,3 | 19 | 16 | 68,1 | 19 | 1 | 72 |
| 20 | 24 | 72,1 | 20 | 22 | 68,1 | 20 | 24 | 67,8 |
| 21 | 23 | 101,2 | 21 | 13 | 80,7 | 21 | 25 | 64 |
| 22 | 24 | 97 | 22 | 25 | 63,5 | 22 | 8 | 92,6 |
| 23 | 0 | 0 | 23 | 20 | 67,1 | 23 | 0 | 0 |
| 24 | 0 | 0 | 24 | 0 | 0 | 24 | 0 | 0 |
| 25 | 0 | 0 | 25 | 0 | 0 | 25 | | |
| 26 | 0 | 0 | 26 | 0 | 0 | 26 | | |
| 27 | 4 | 60,5 | 27 | 0 | 0 | 27 | | |
| 28 | 24 | 80,4 | 28 | 0 | 0 | 28 | | |
| 29 | 25 | 81,6 | 29 | | | 29 | | |
| 30 | 24 | 79,1 | 30 | | | 30 | 19 | 67,9 |
| 31 | 24 | 73,5 | 31 | | | 31 | 5 | 71,2 |

## 14.7 Flow chart, implementing in SimaPro

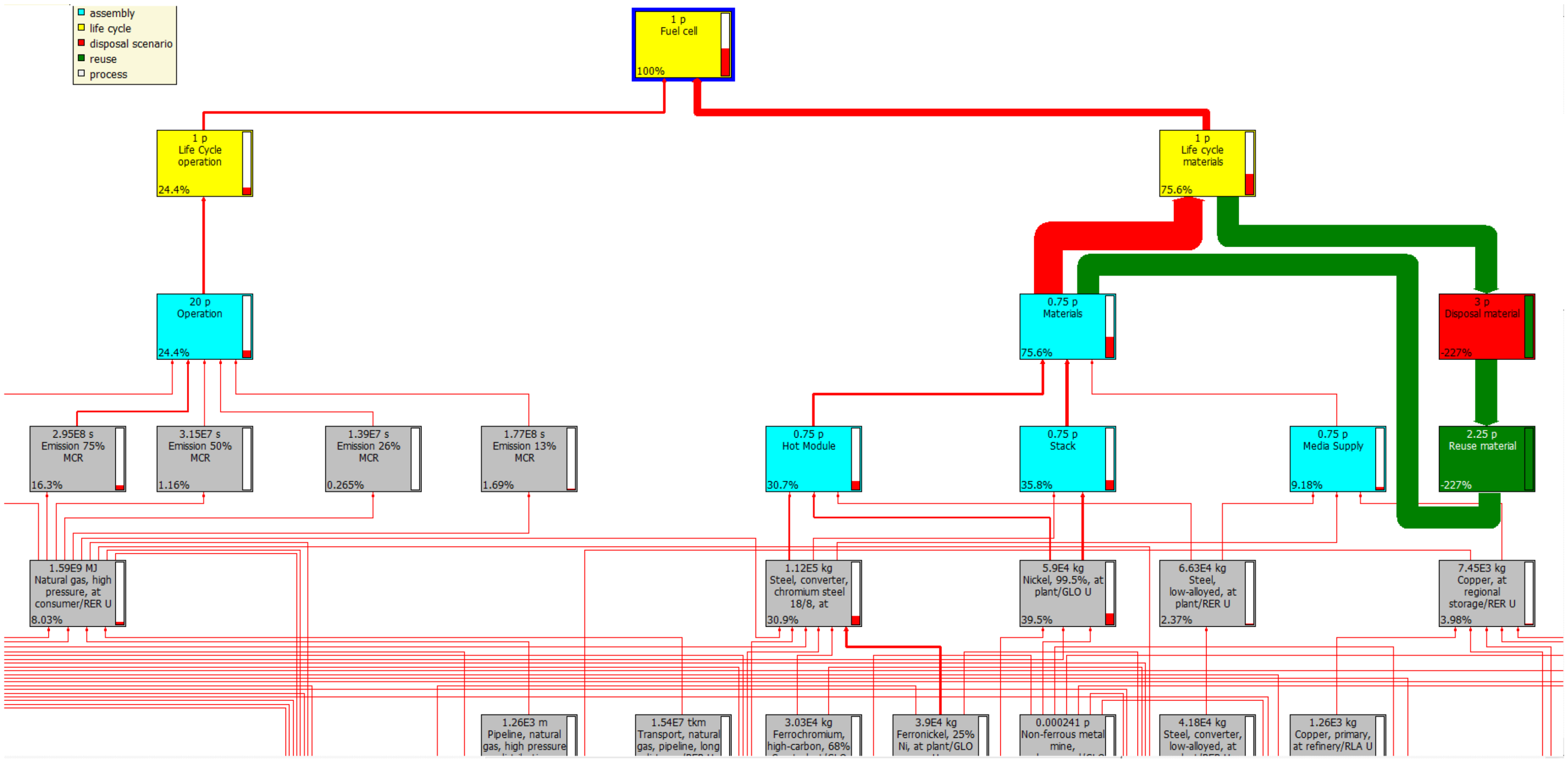
## 14.7.1 FUEL CELL MATERIALS



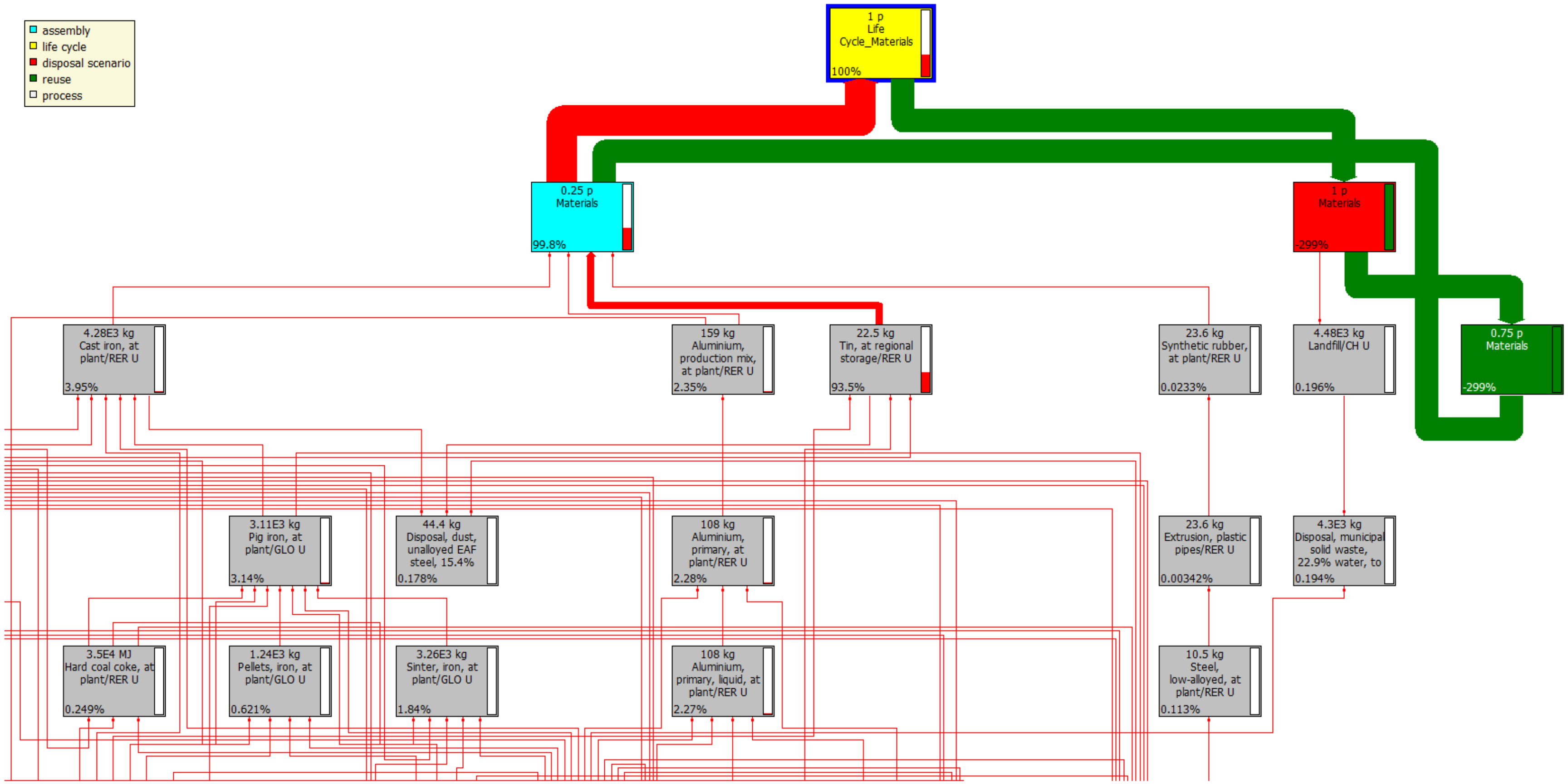
## 14.7.2 FUEL CELL OPERATION



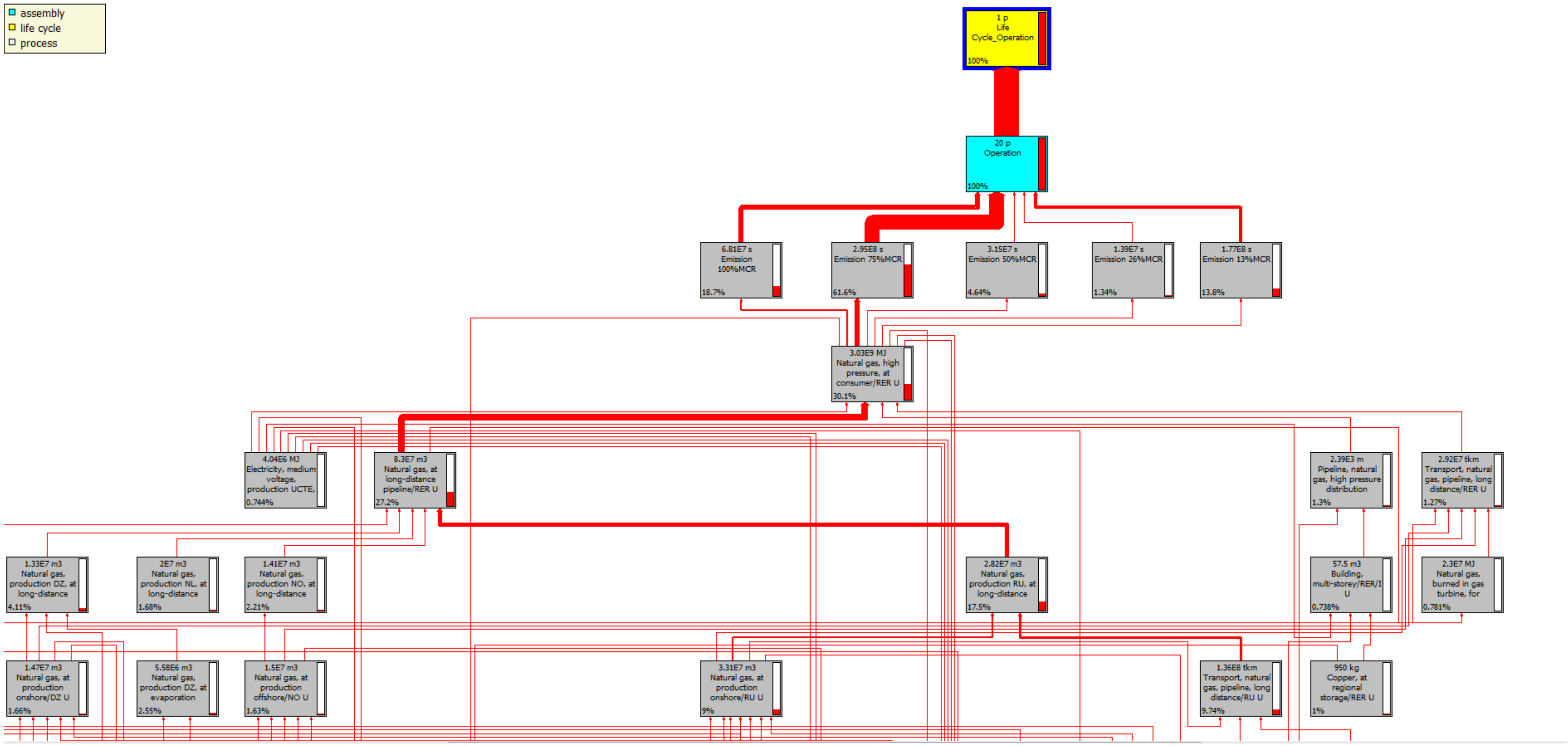
## 14.7.3 FUEL CELL



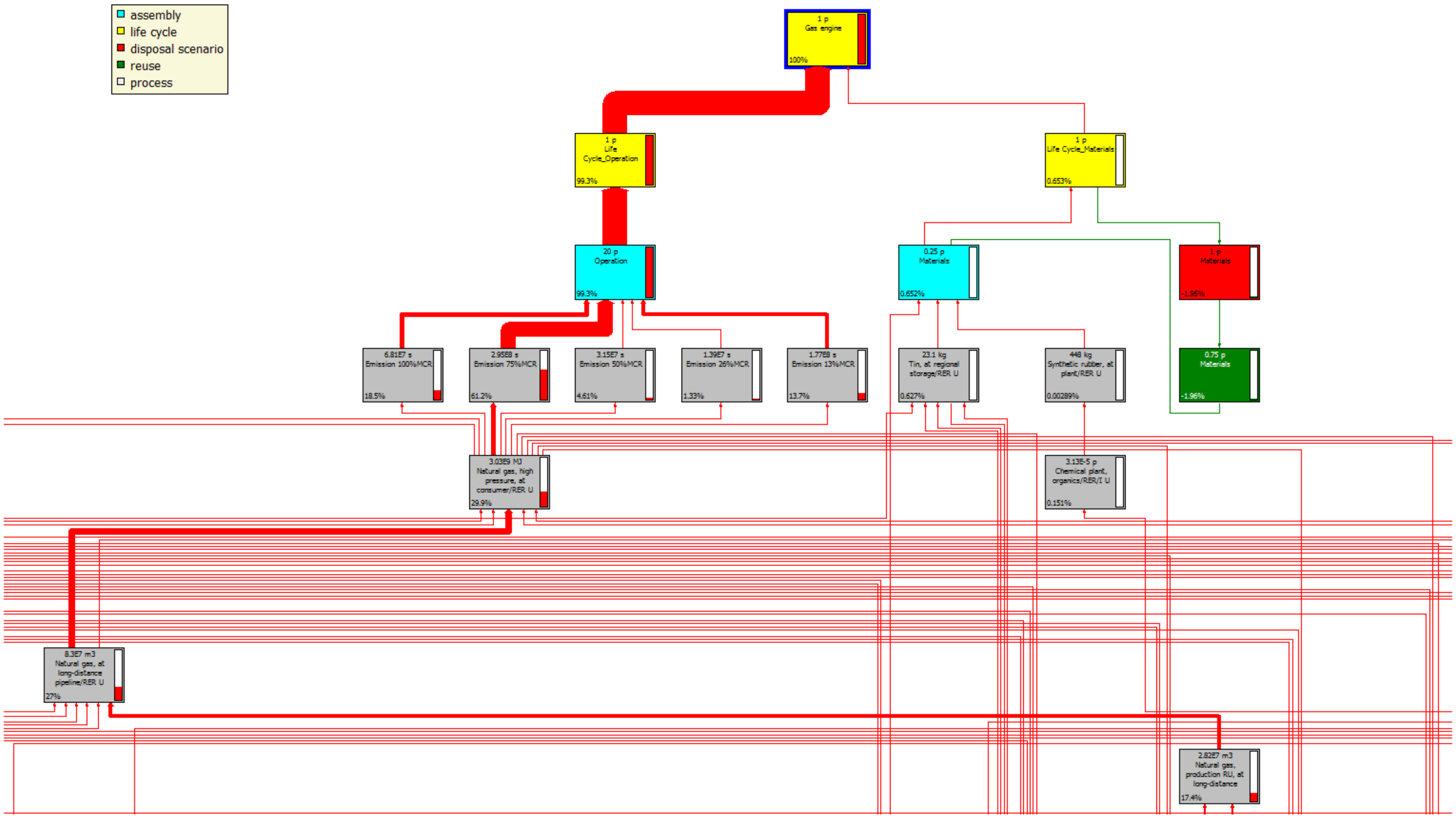
## 14.7.4 GAS ENGINE MATERIALS



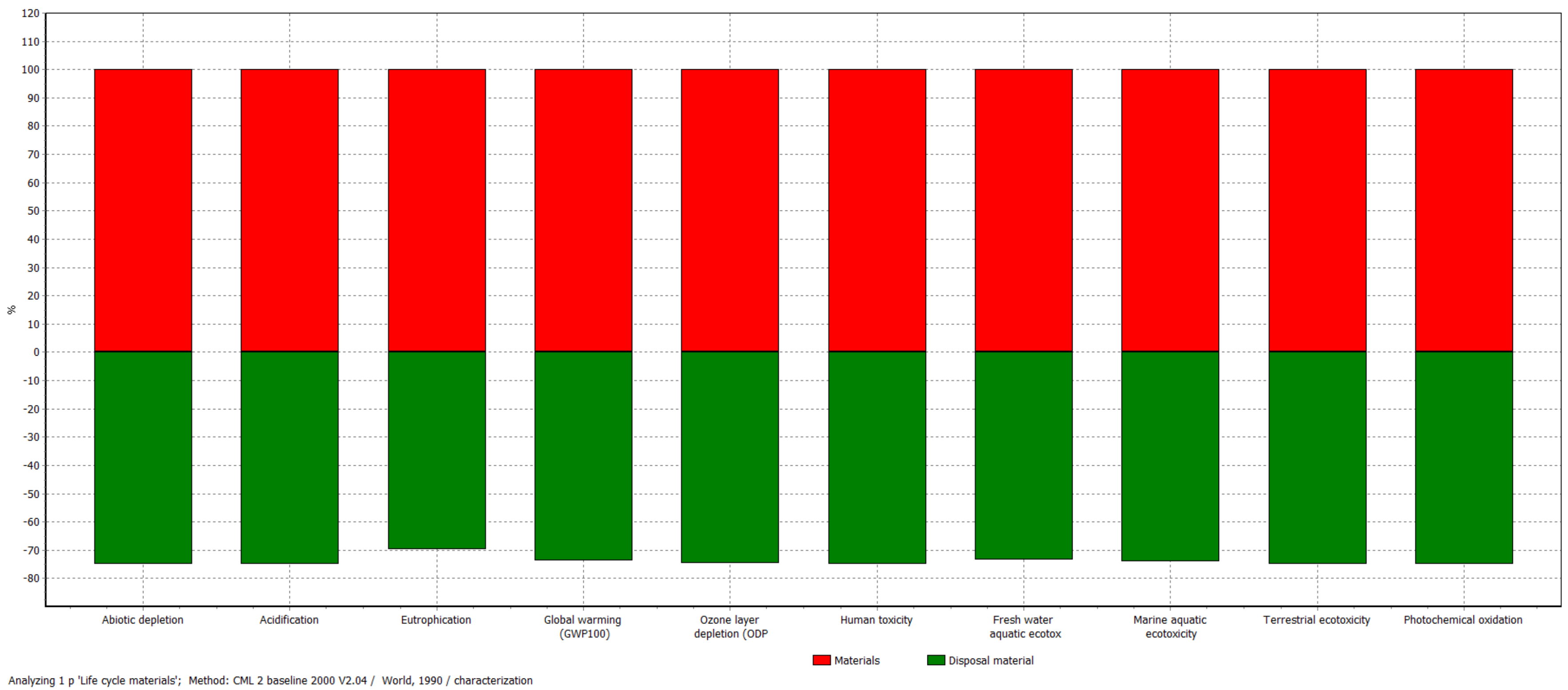
## 14.7.5 GAS ENGINE OPERATION



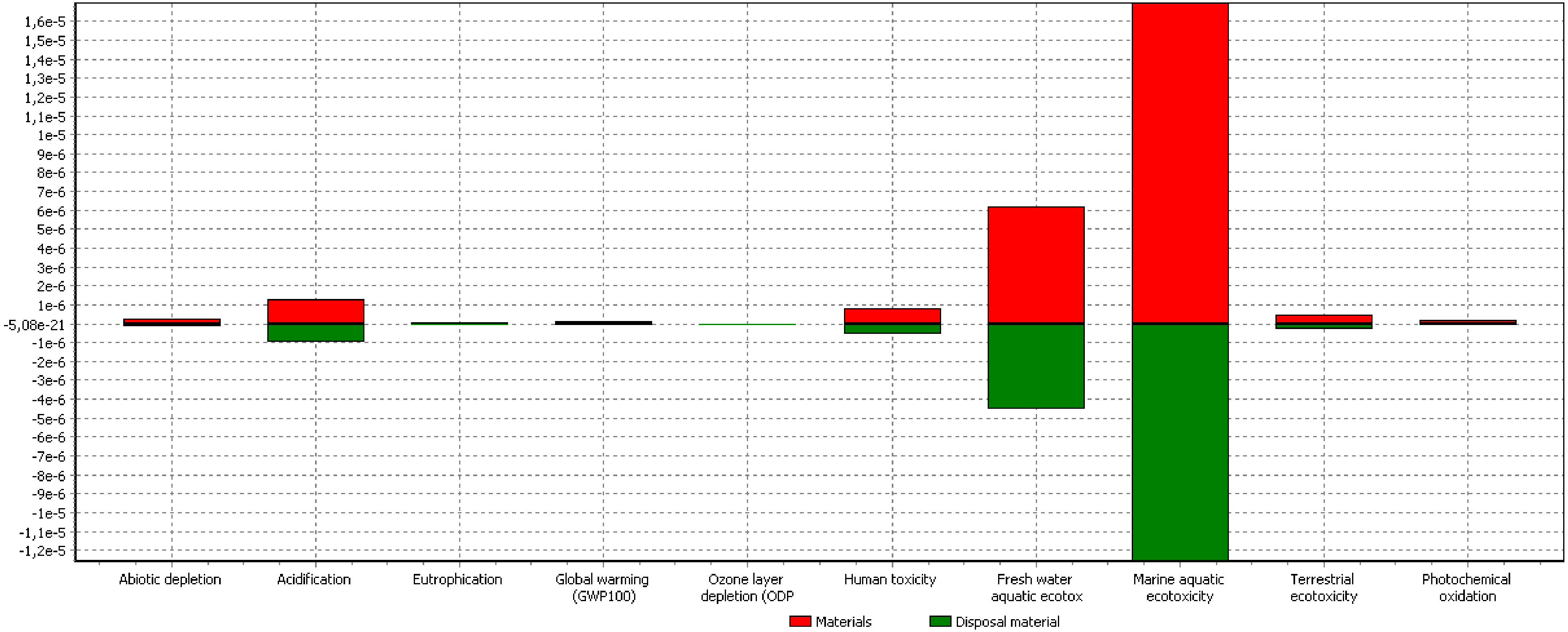
## 14.7.6 GAS ENGINE



## 14.8.1 FUEL CELL MATERIALS, CML CHARACTERIZED

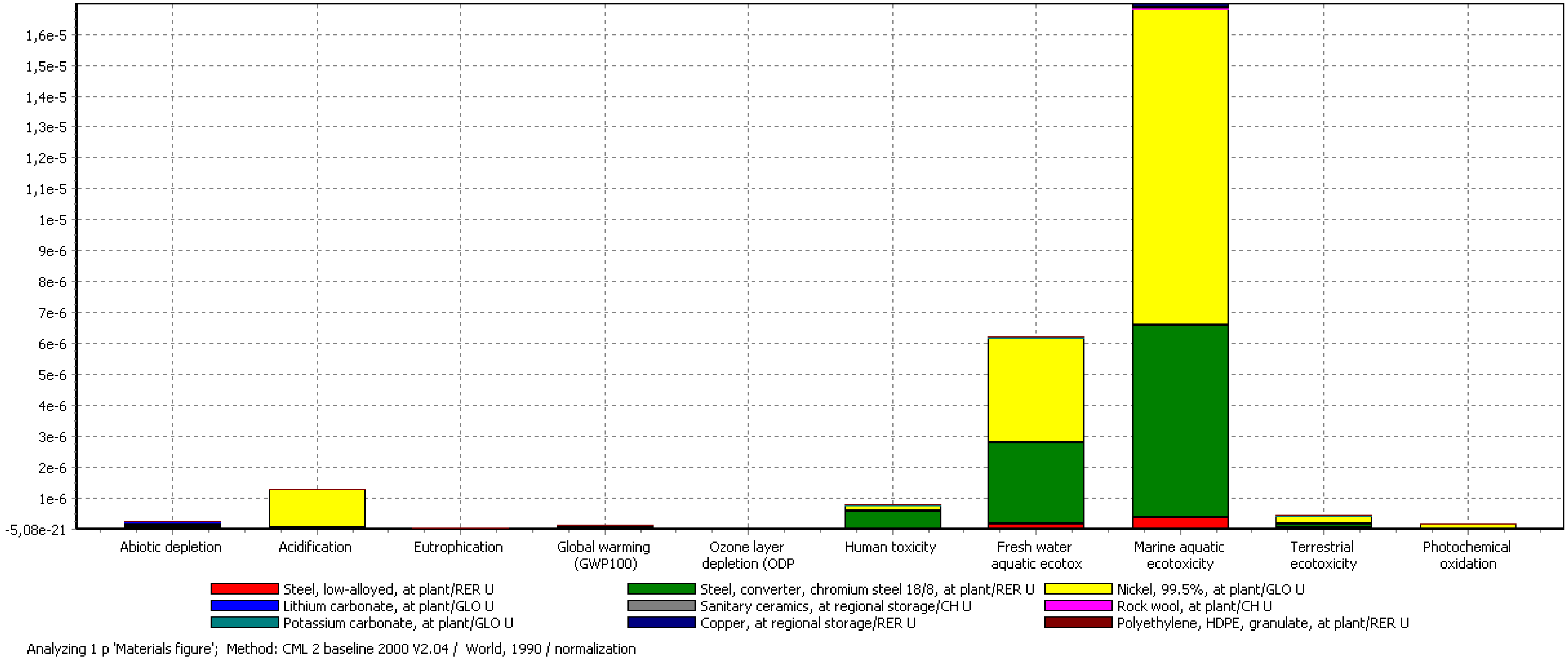


## 14.8.2 FUEL CELL MATERIALS, CML NORMALIZED

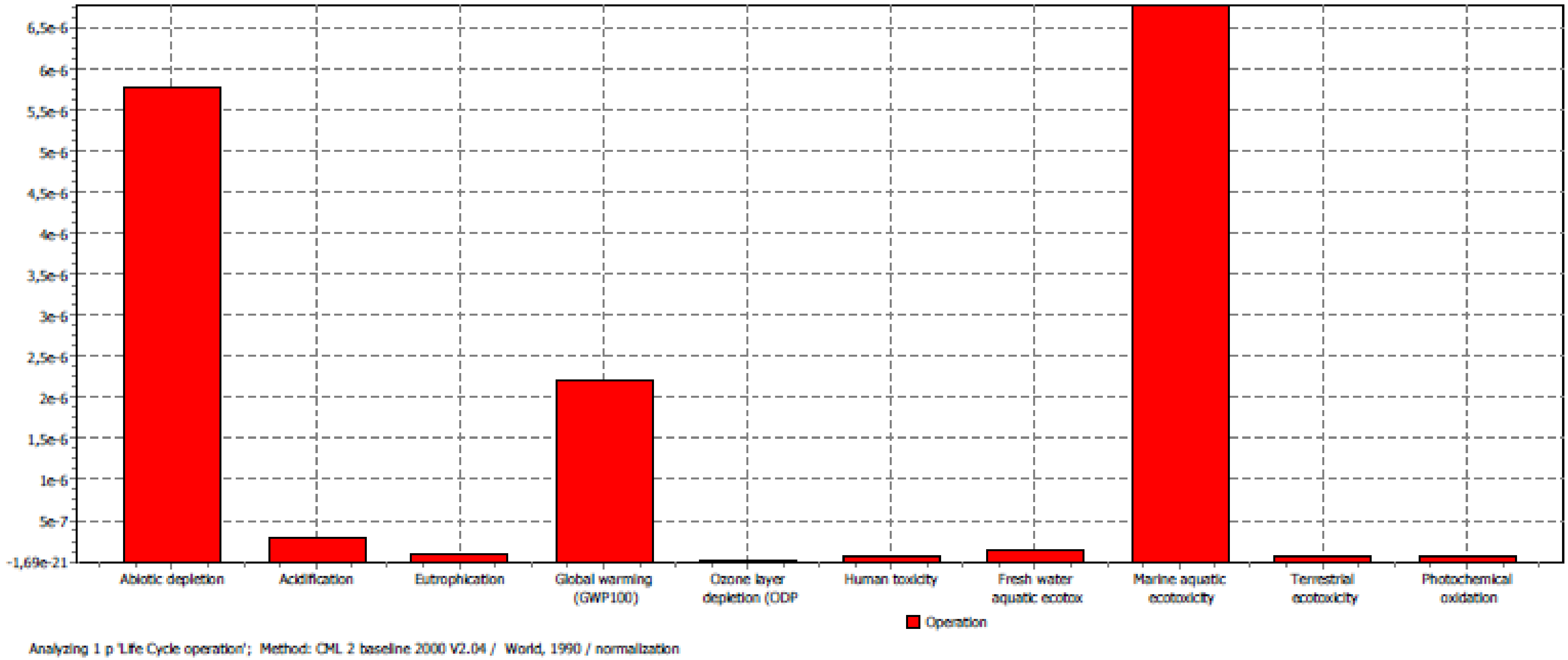



Analyzing 1 p 'Life cycle materials'; Method: CML 2 baseline 2000 V2.04 / World, 1990 / normalization

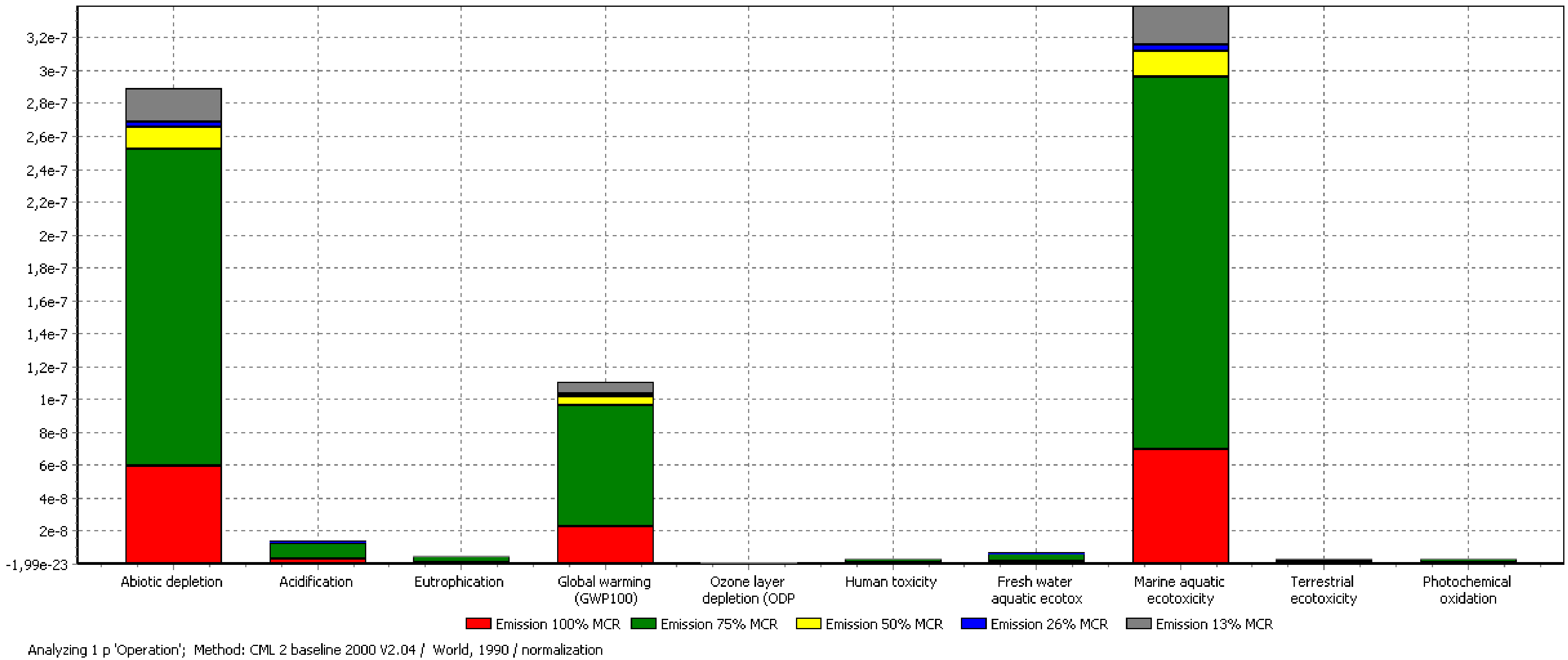
## 14.8.3 FUEL CELL MATERIALS, CML NORMALIZED



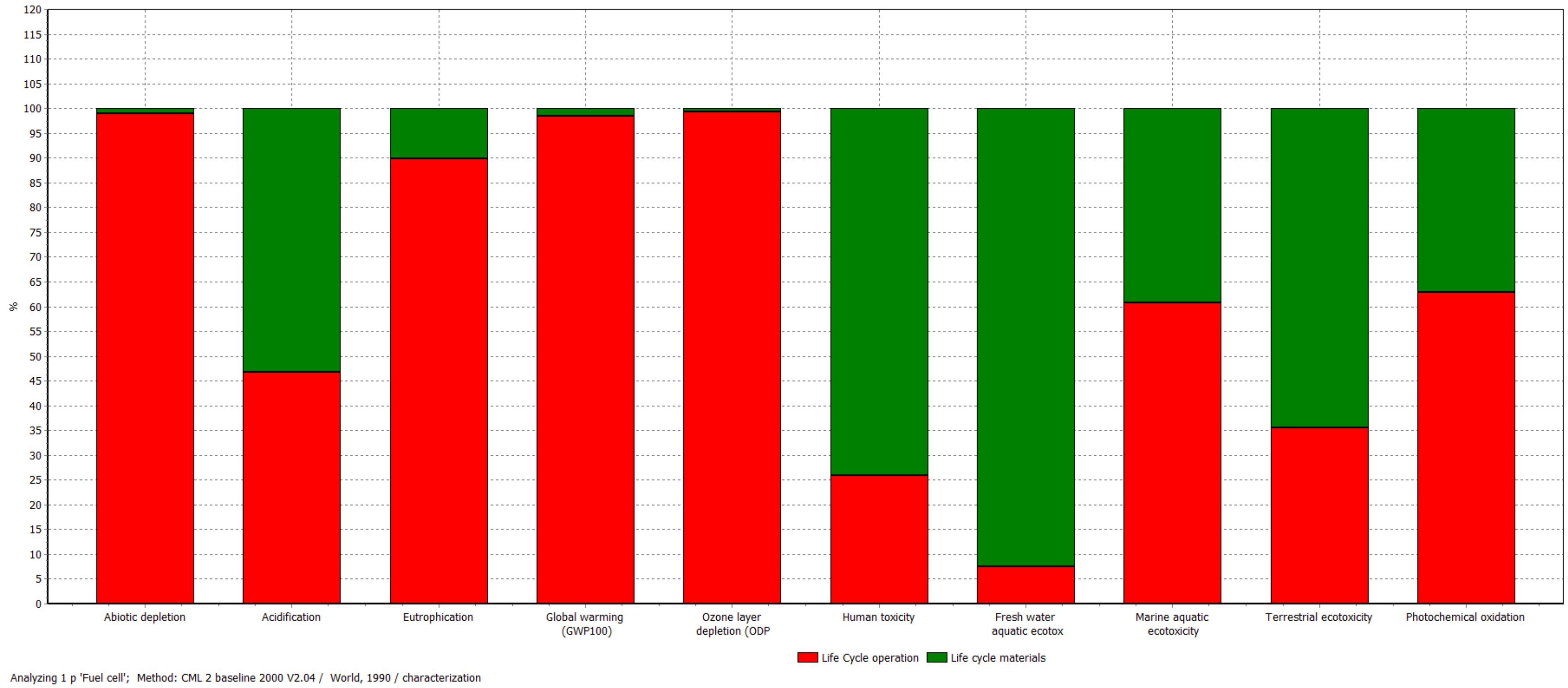
## 14.8.4 FUEL CELL OPERATION, CML NORMALIZED



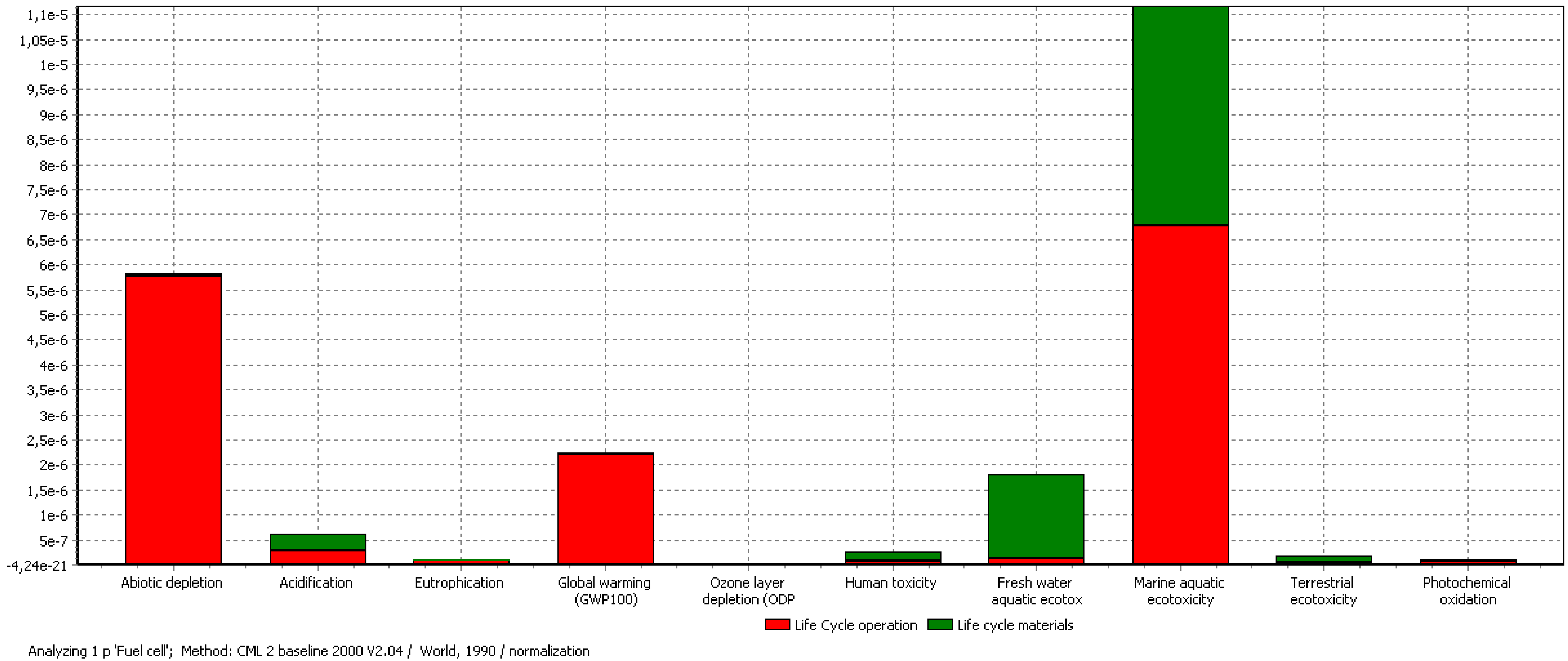
### 14.8.5 FUEL CELL OPERATION, CML DISTRIBUTED



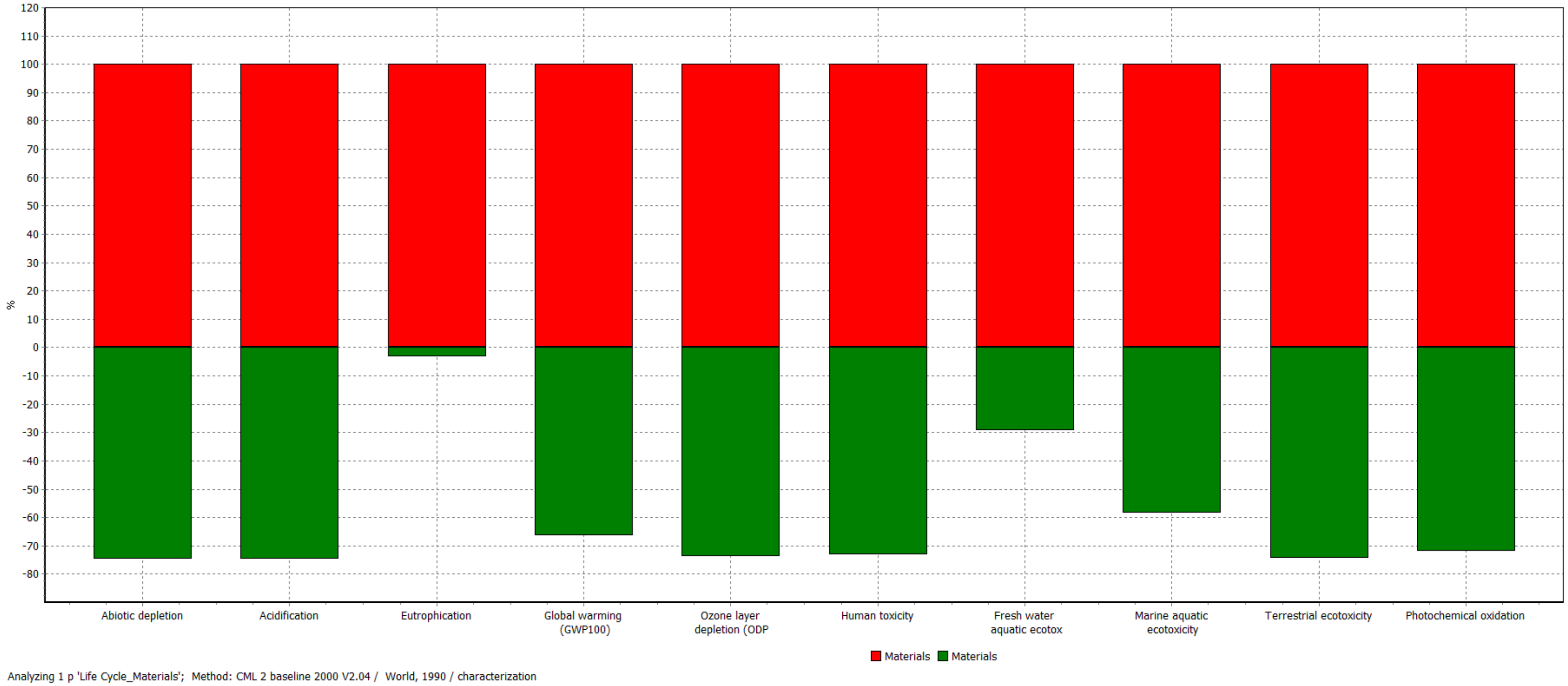
## 14.8.6 TOTAL RESULT FUEL CELL, CML CHARACTERIZED



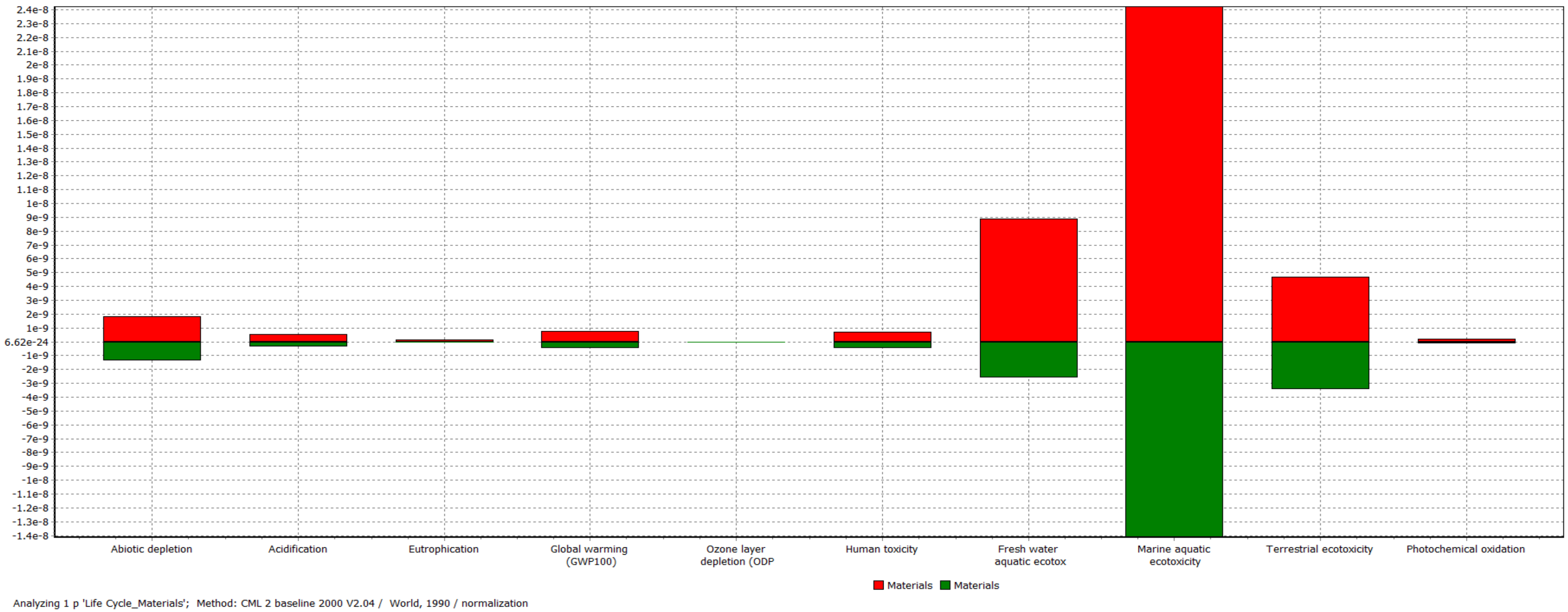
### 14.8.7 TOTAL RESULT FUEL CELL, CML NORMALIZED



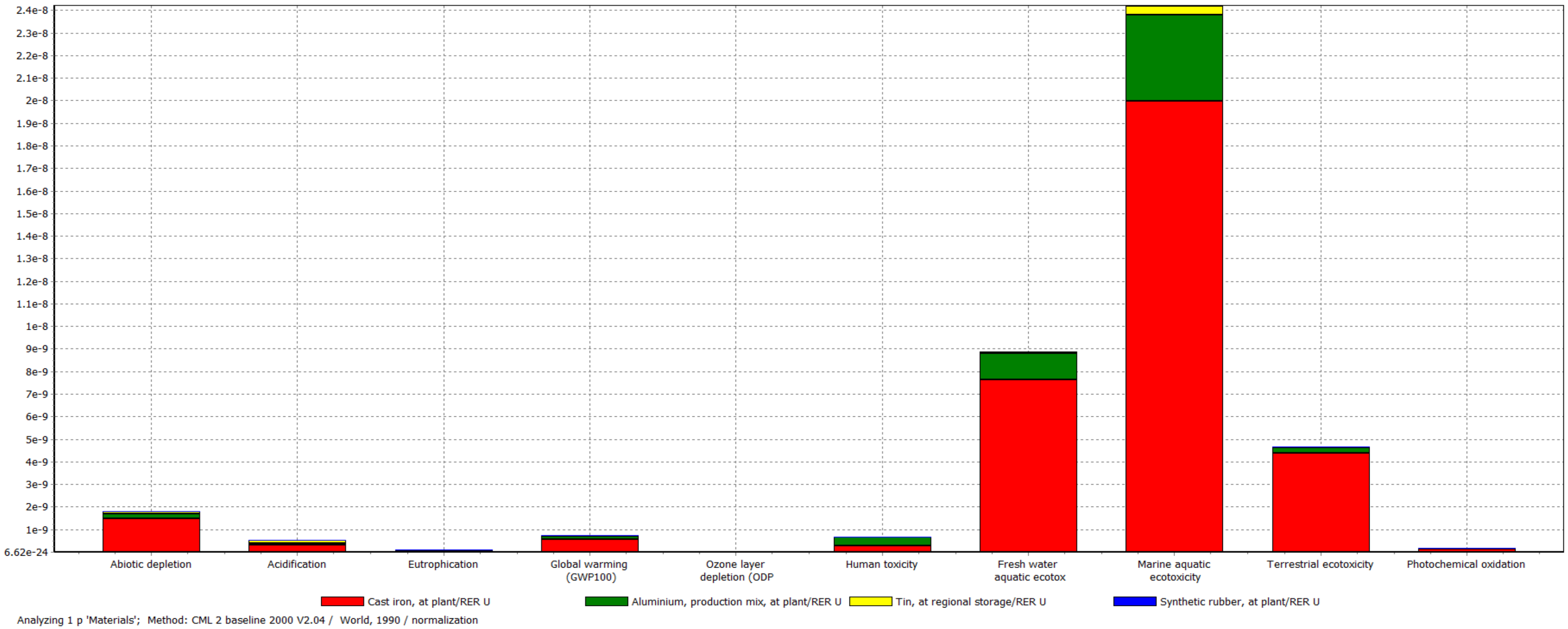
## 14.8.8 GAS ENGINE MATERIAL, CML CHARACTERIZED



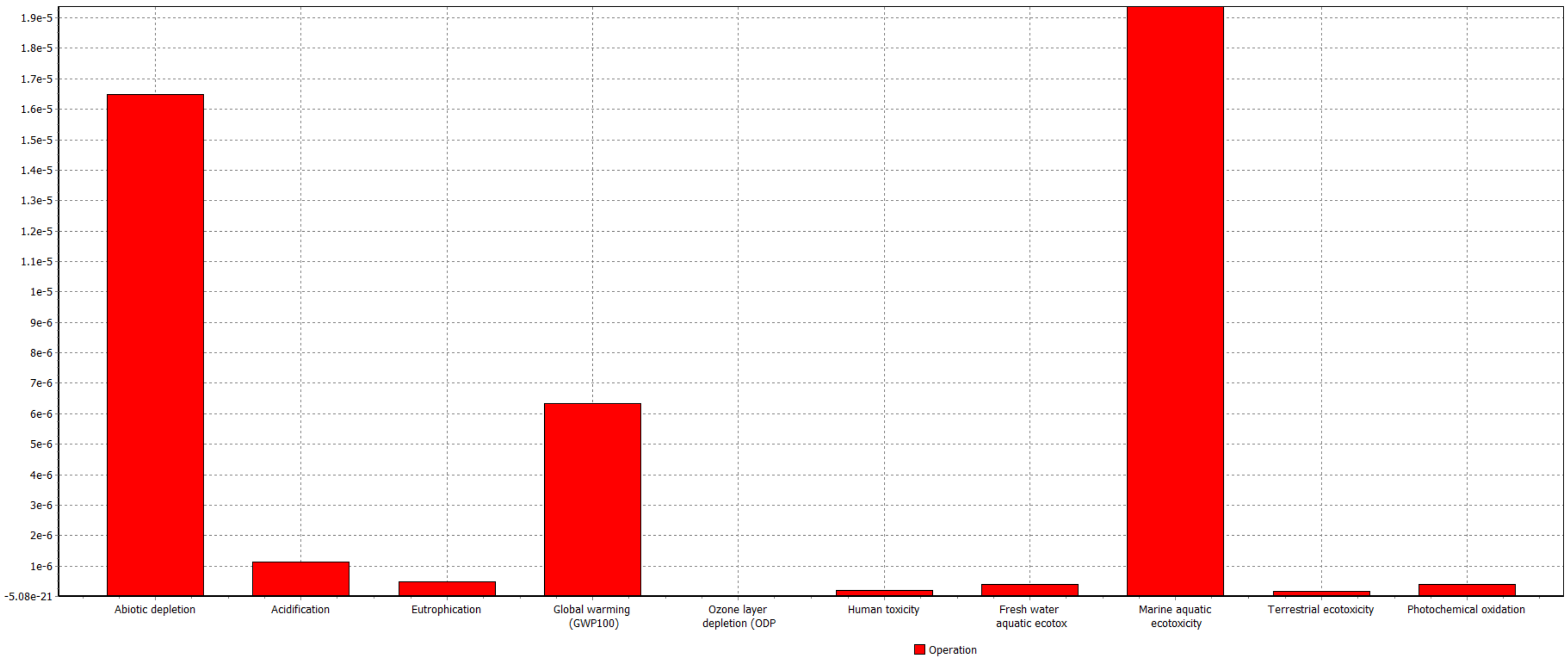
## 14.8.9 GAS ENGINE MATERIAL, CML NORMALIZED



## 14.8.10 GAS ENGINE MATERIAL, CML DISTRIBUTED

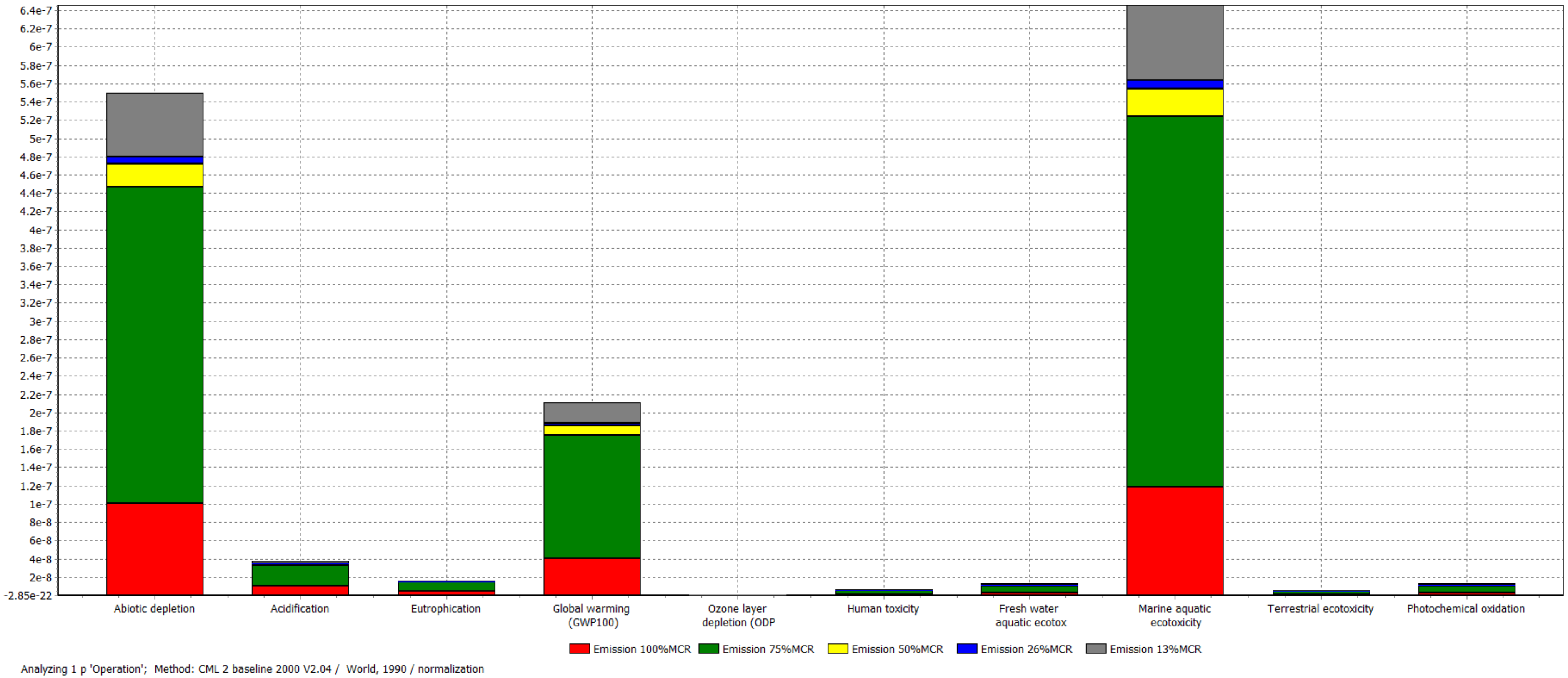


## 14.8.11 GAS ENGINE OPERATION, CML NORMALIZED

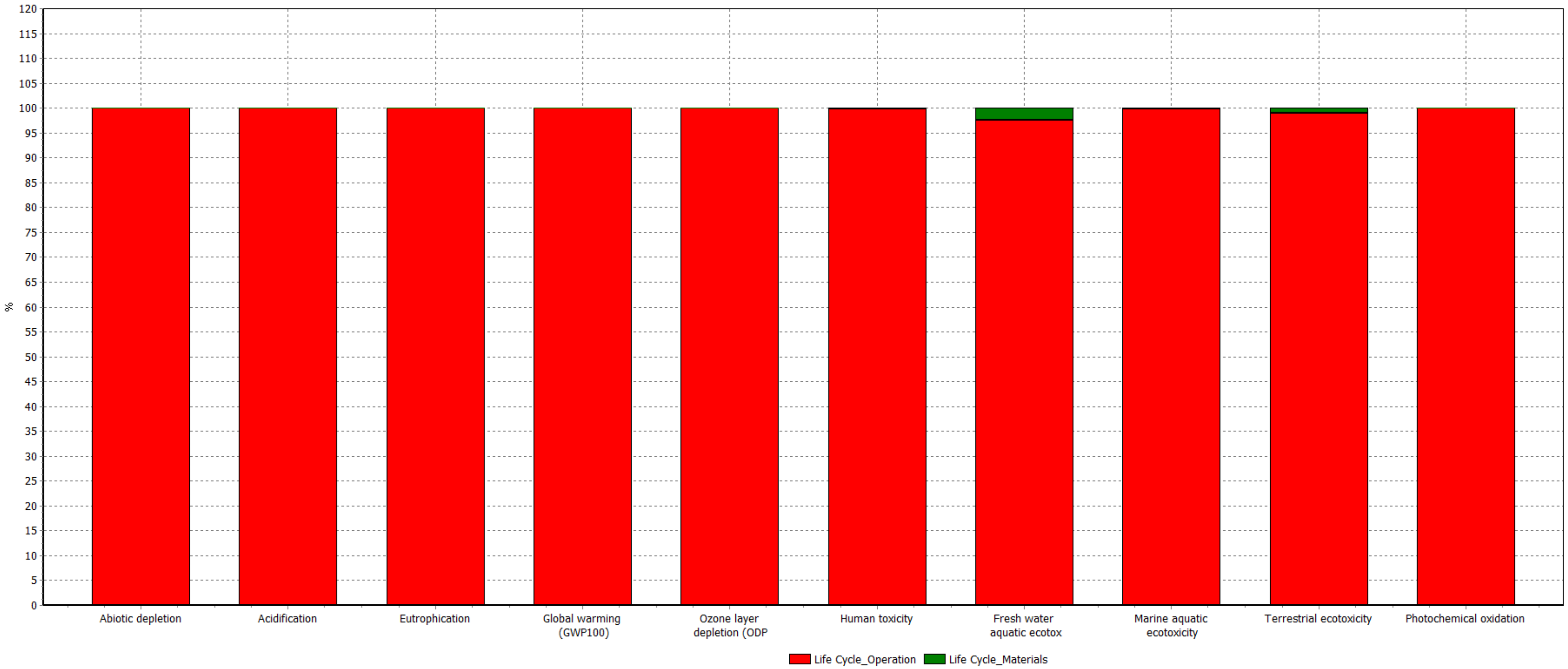



Analyzing 1 p 'Life Cycle_Operation'; Method: CML 2 baseline 2000 V2.04 / World, 1990 / normalization

## 14.8.12 GAS ENGINE OPERATION, CML DISTRIBUTED

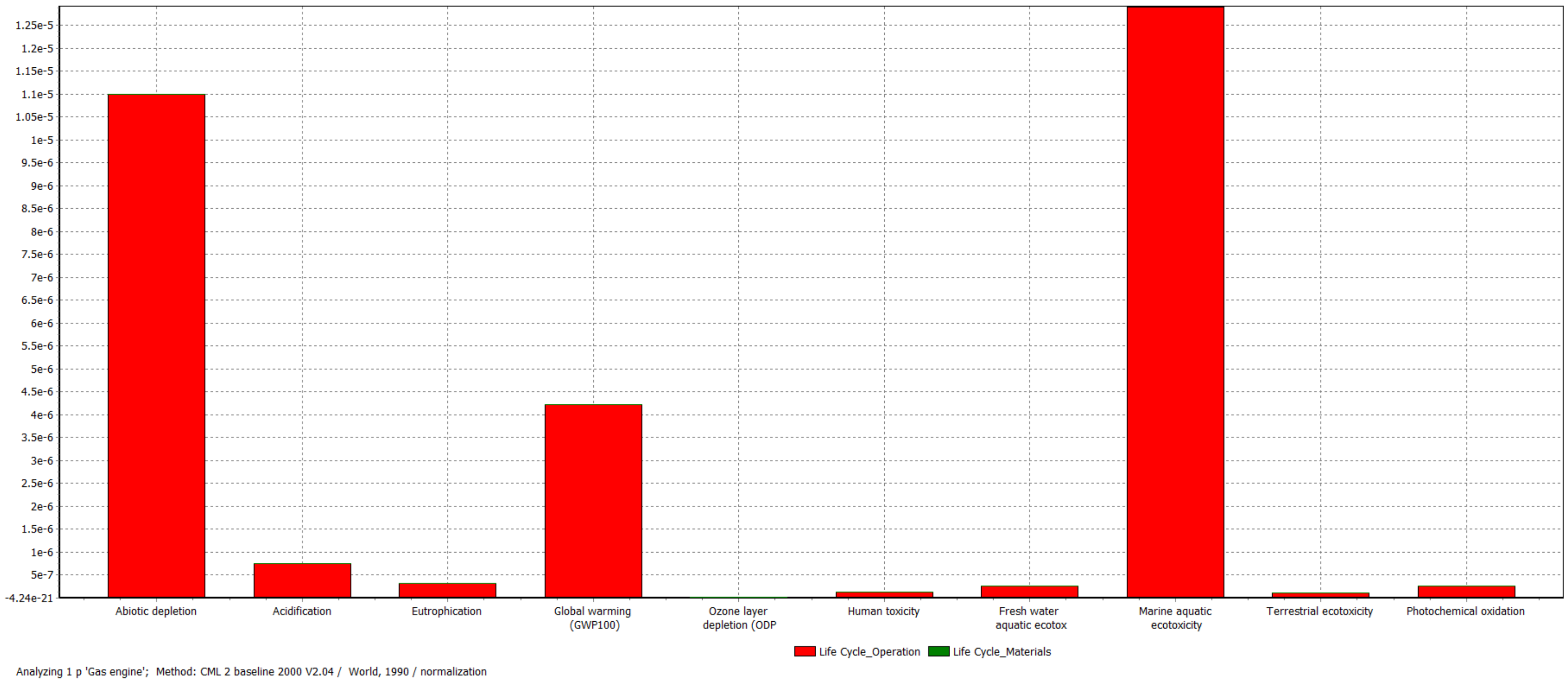


## 14.8.13 TOTAL RESULT GAS ENGINE, CML CHARACTERIZED

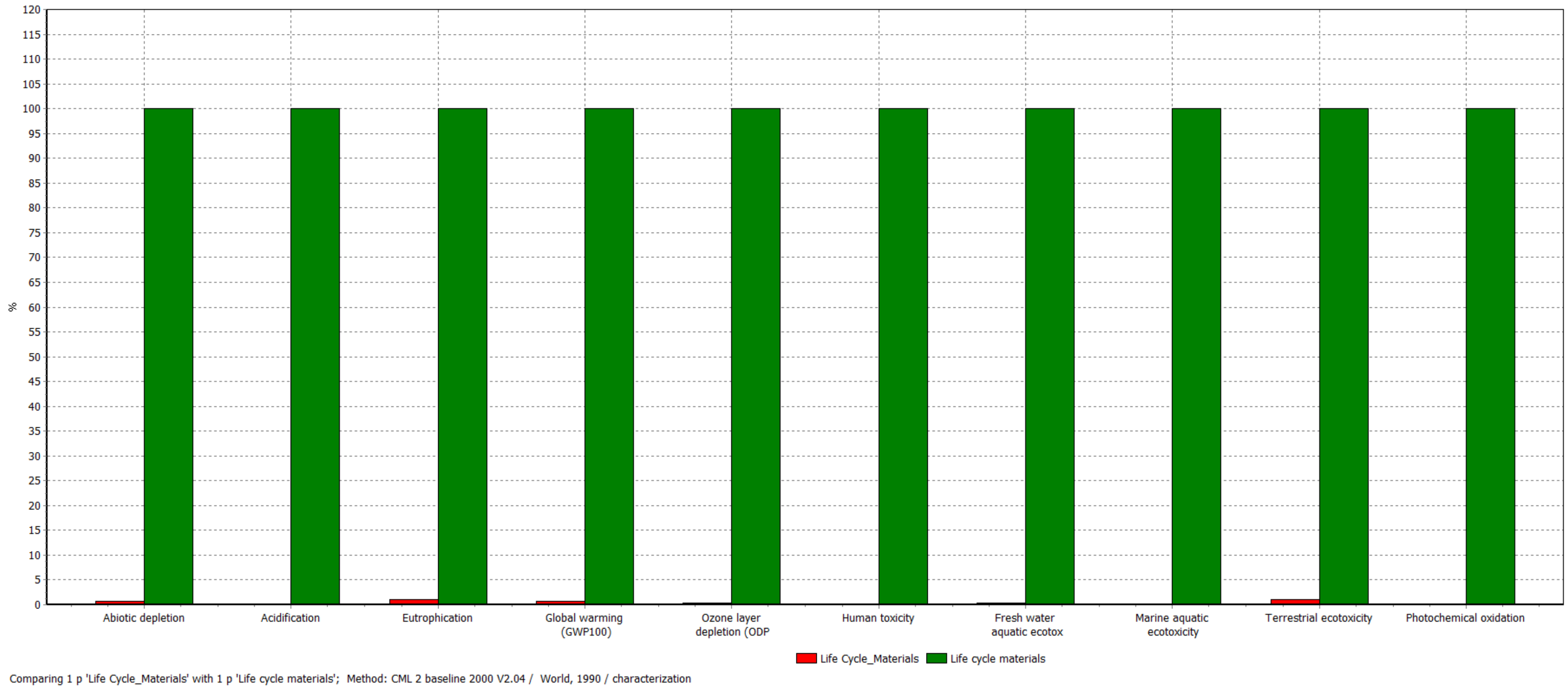


Analyzing 1 p 'Gas engine'; Method: CML 2 baseline 2000 V2.04 / World, 1990 / characterization

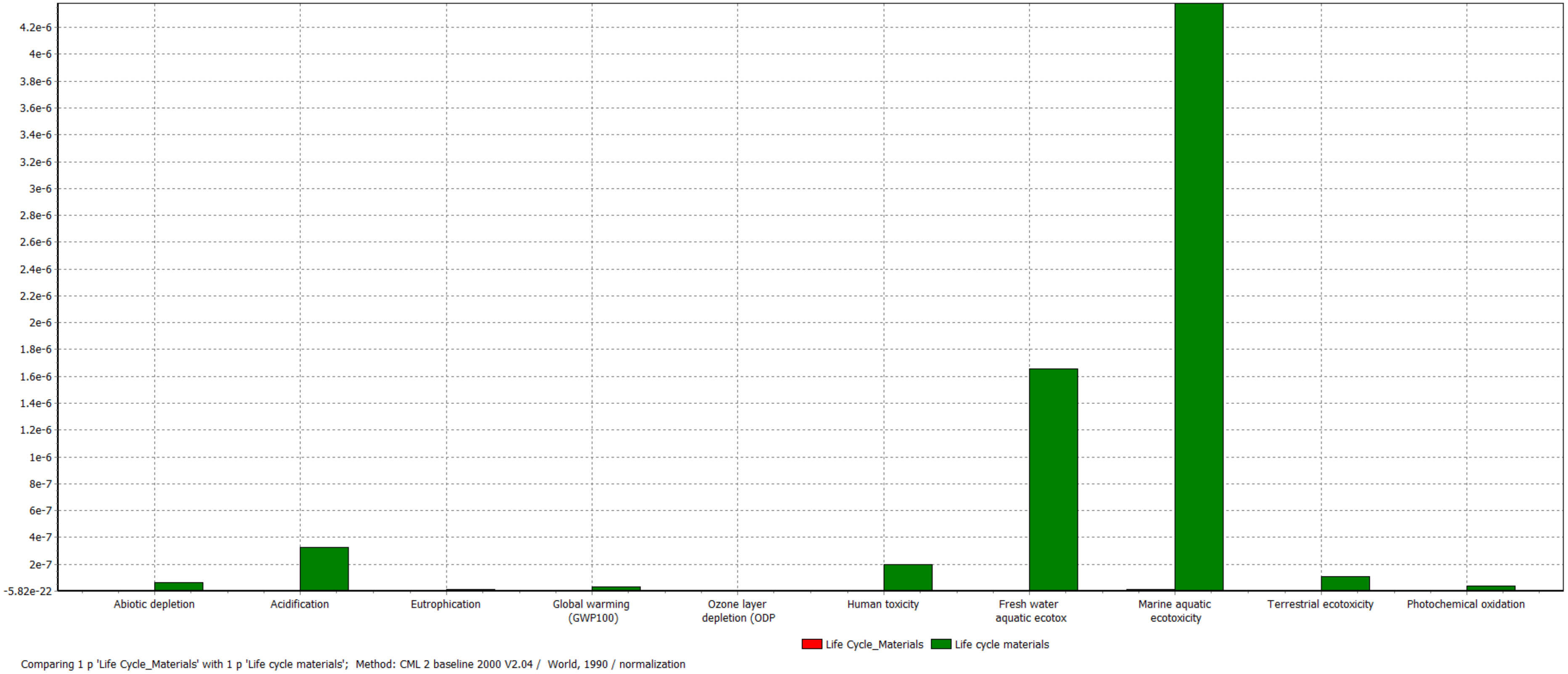
## 14.8.14 TOTAL RESULT GAS ENGINE, CML NORMALIZED



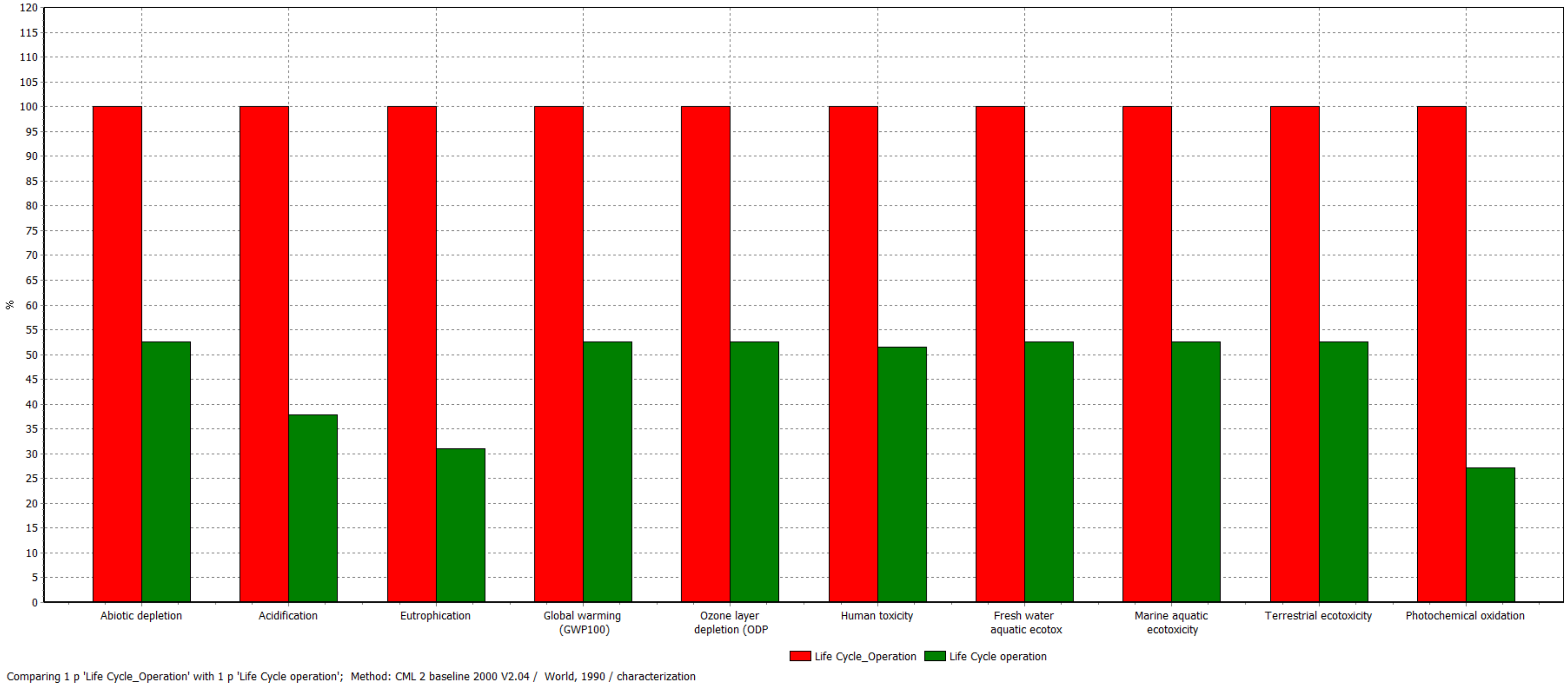
## 14.8.15 GAS ENGINE COMPARED TO FUEL CELL, MATERIALS, CML CHARACTERIZED



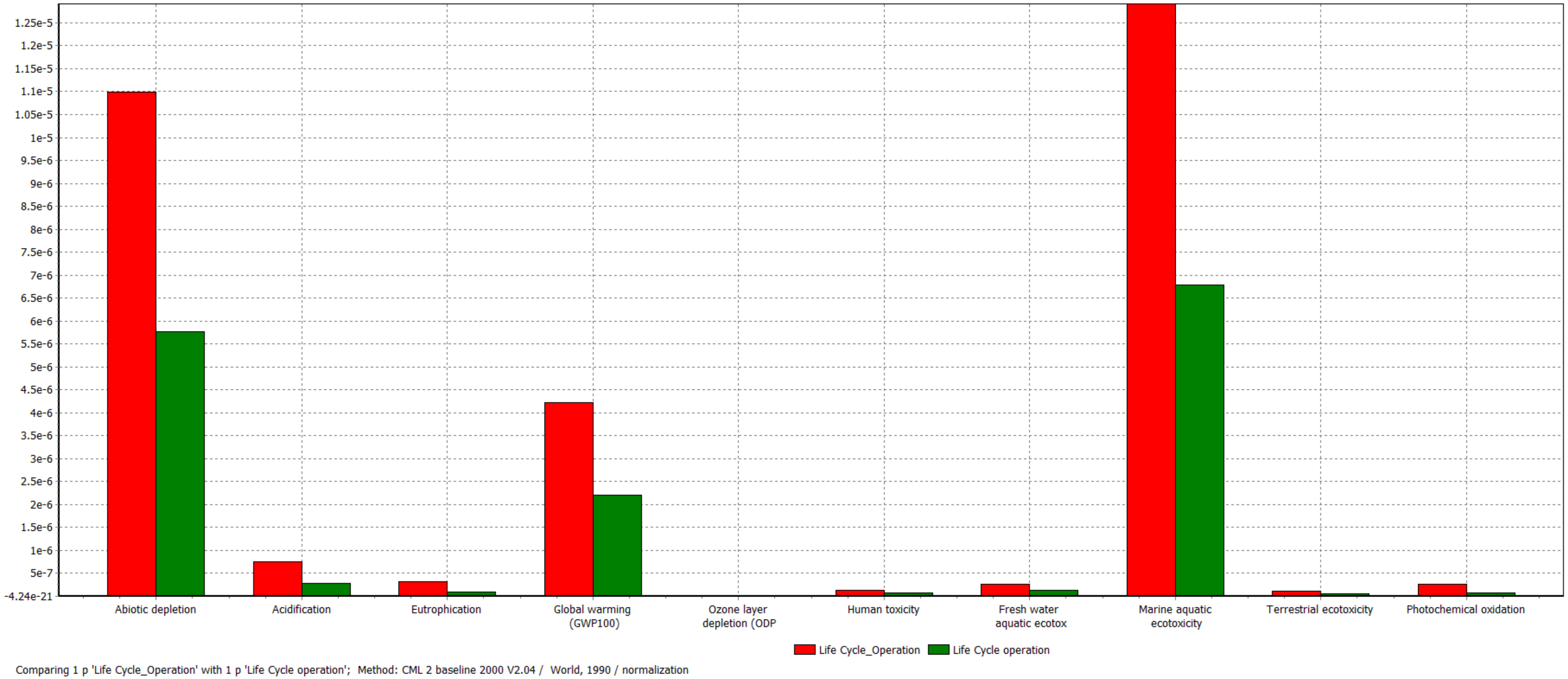
## 14.8.16 GAS ENGINE COMPARED TO FUEL CELL, MATERIALS, CML NORMALIZED



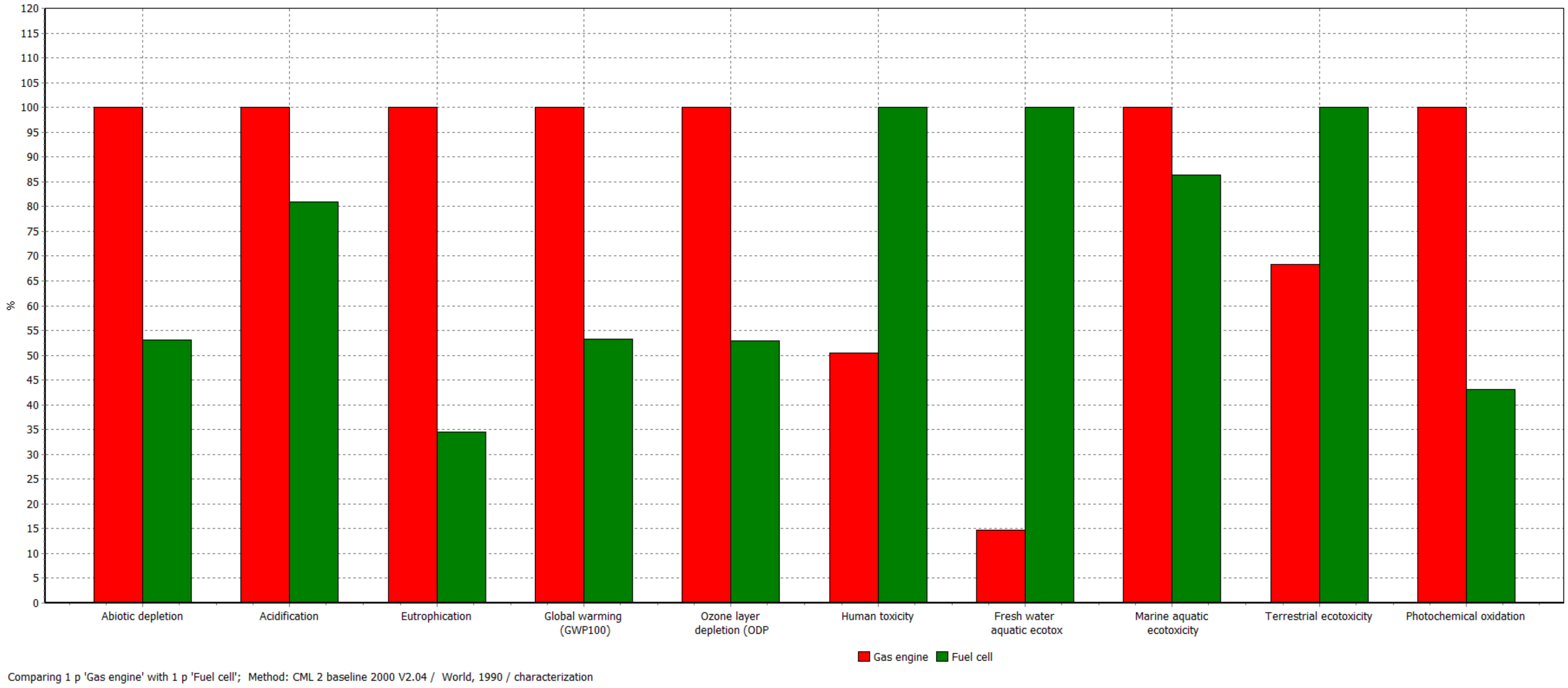
## 14.8.17 GAS ENGINE COMPARED TO FUEL CELL, OPERATION, CML CHARACTERIZED



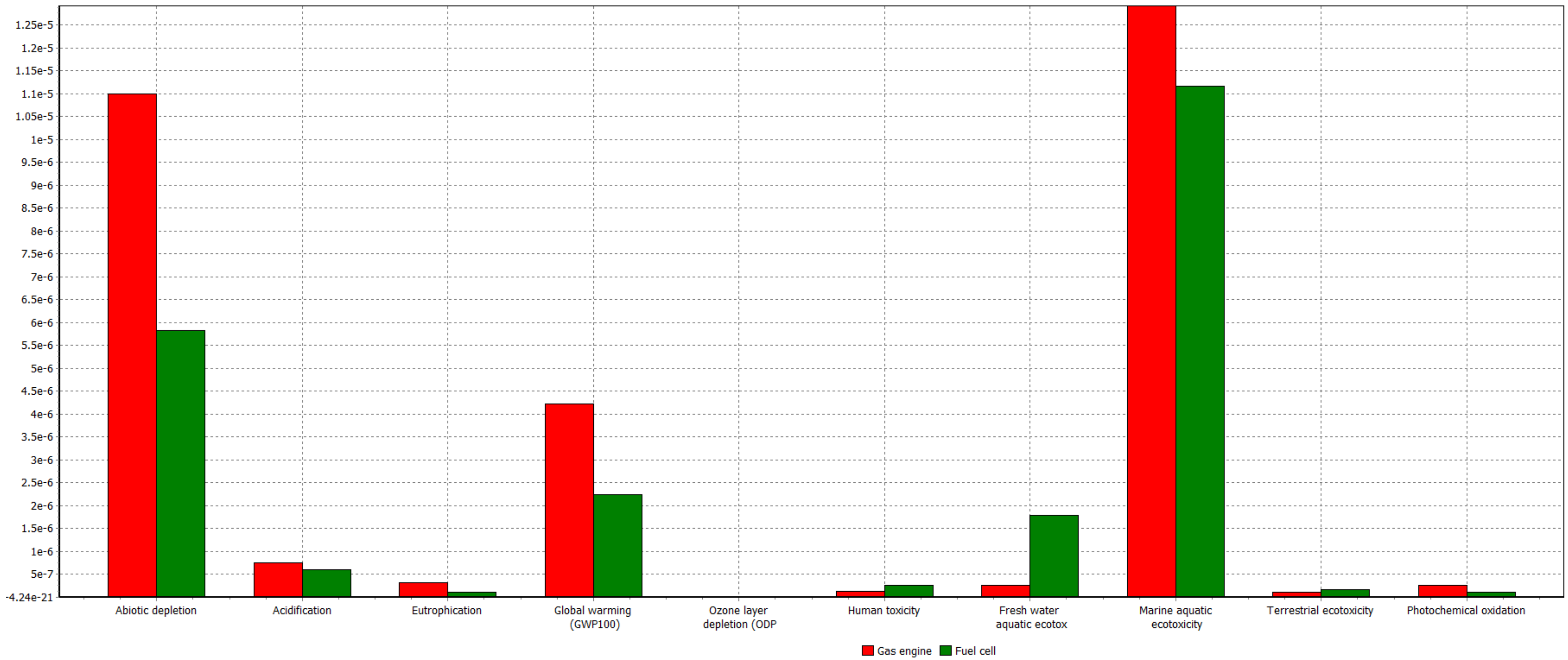
## 14.8.18 GAS ENGINE COMPARED TO FUEL CELL, OPERATION, CML NORMALIZED



## 14.8.19 GAS ENGINE COMPARED TO FUEL CELL, TOTAL, CML CHARACTERIZED

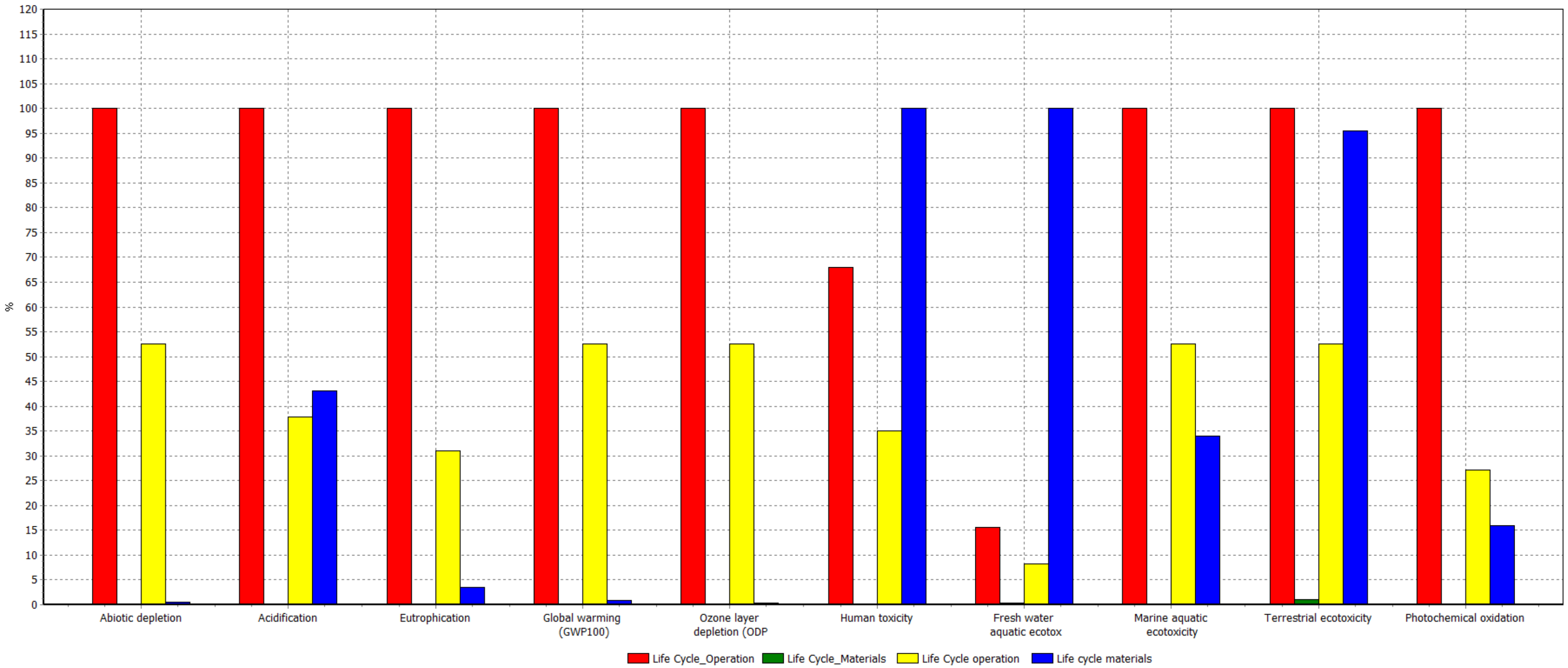


## 14.8.20 GAS ENGINE COMPARED TO FUEL CELL, TOTAL, CML NORMALIZED



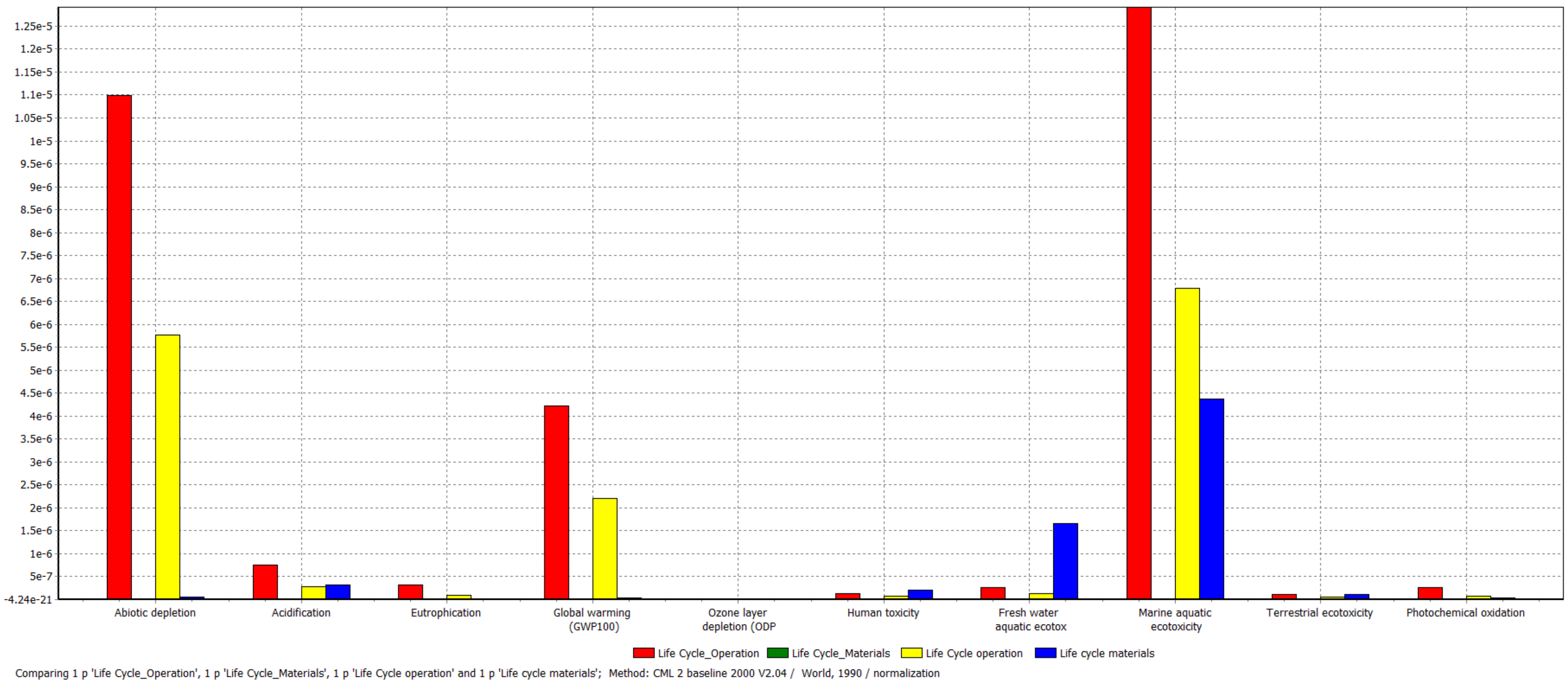

Comparing 1 p 'Gas engine' with 1 p 'Fuel cell'; Method: CML 2 baseline 2000 V2.04 / World, 1990 / normalization

## 14.8.21 GAS ENGINE COMPARED TO FUEL CELL, MATERIALS AND OPERATION, CML CHARACTERIZED

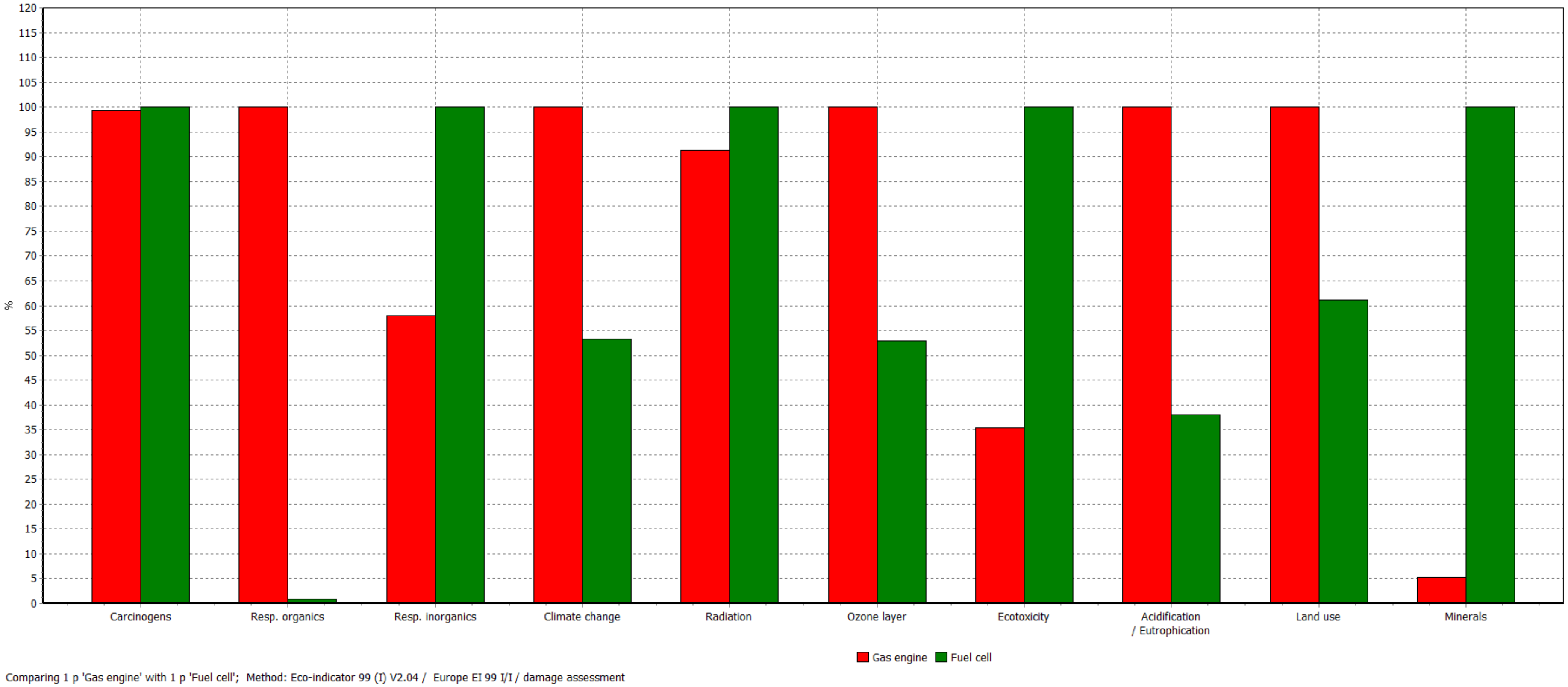



Comparing 1 p 'Life Cycle_Operation', 1 p 'Life Cycle_Materials', 1 p 'Life Cycle operation' and 1 p 'Life cycle materials'; Method: CML 2 baseline 2000 V2.04 / World, 1990 / characterization

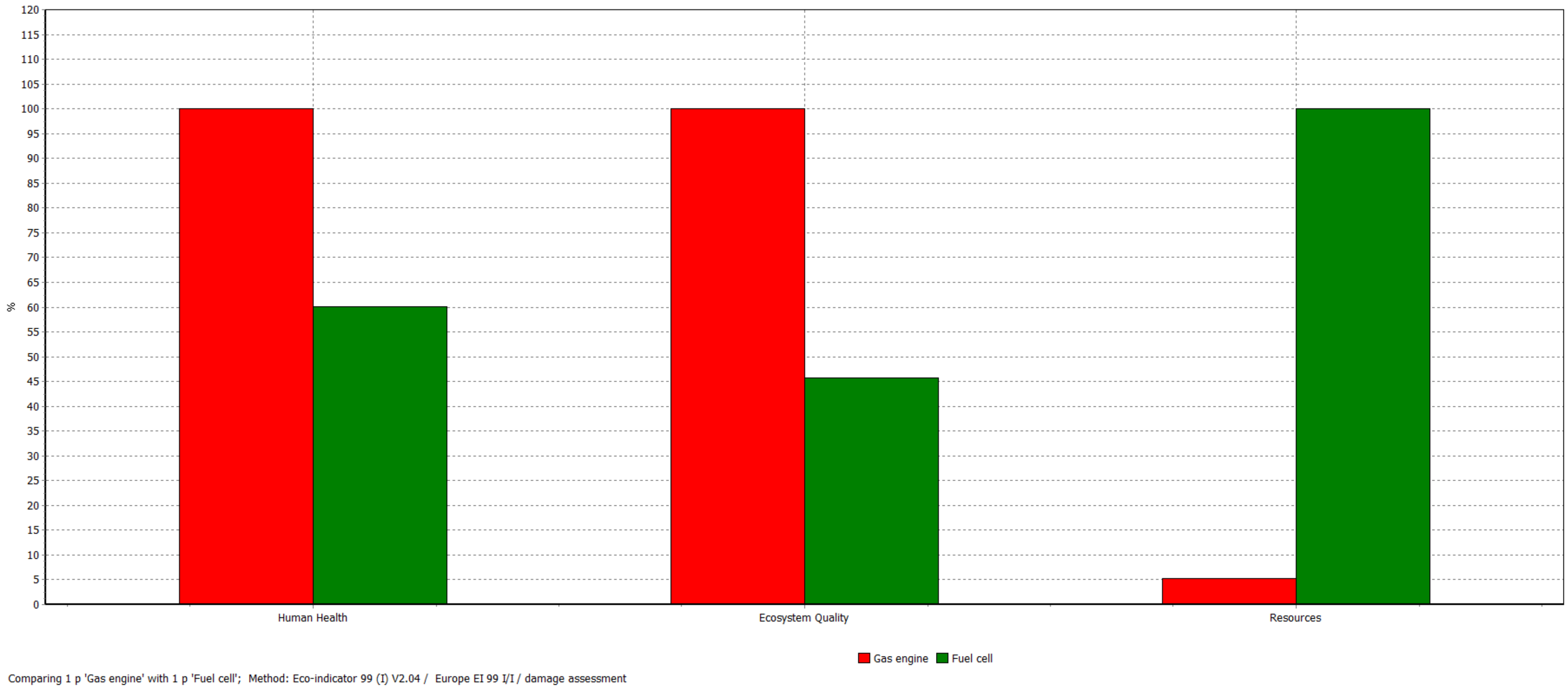
## 14.8.22 GAS ENGINE COMPARED TO FUEL CELL, MATERIALS AND OPERATION, CML NORMALIZED



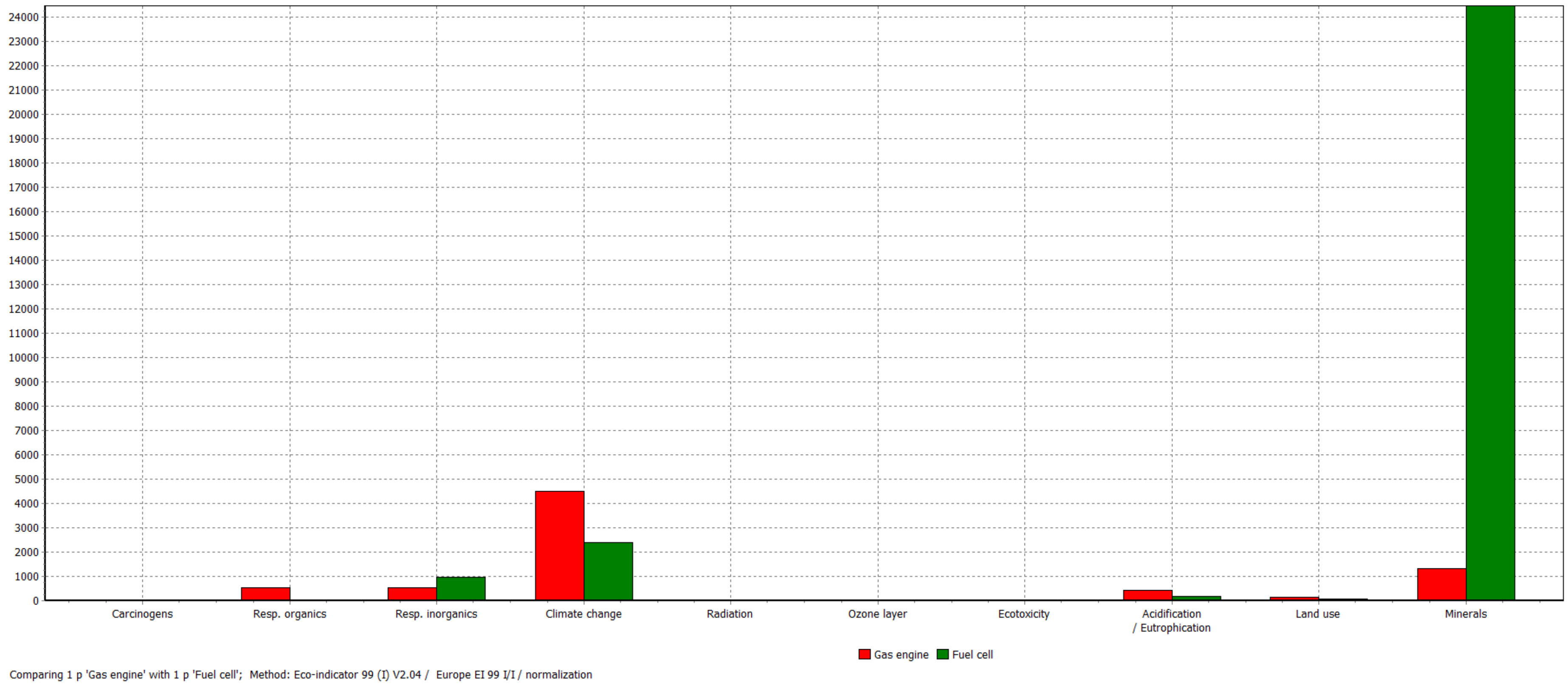
## 14.8.23 GAS ENGINE COMPARED TO FUEL CELL, ECO-INDICATOR DAMAGE ASSESSMENT



## 14.8.24 GAS ENGINE COMPARED TO FUEL CELL, ECO-INDICATOR DAMAGE ASSESSMENT



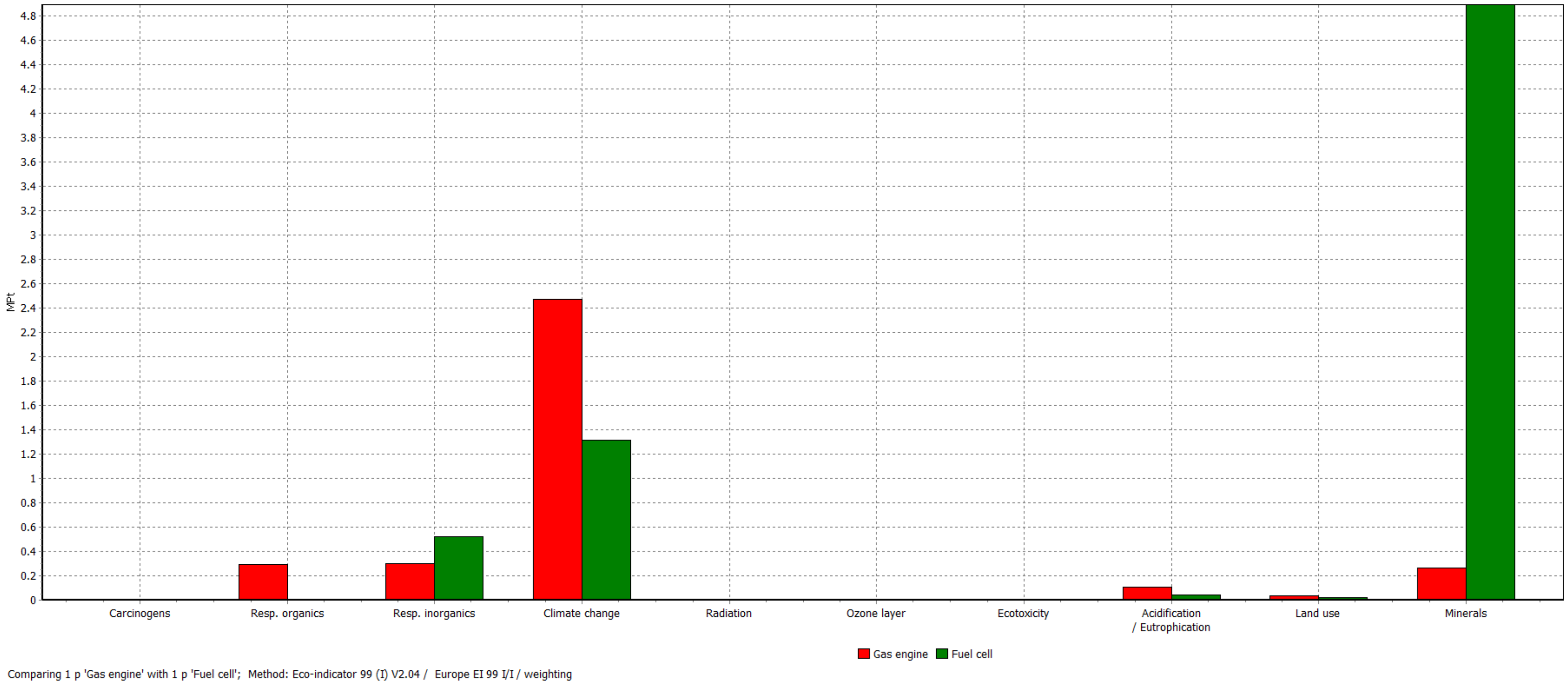
## 14.8.25 GAS ENGINE COMPARED TO FUEL CELL, ECO-INDICATOR NORMALIZED



## 14.8.26 GAS ENGINE COMPARED TO FUEL CELL, ECO-INDICATOR NORMALIZED


Comparing 1 p 'Gas engine' with 1 p 'Fuel cell'; Method: Eco-indicator 99 (I) V2.04 / Europe EI 99 I/I / normalization

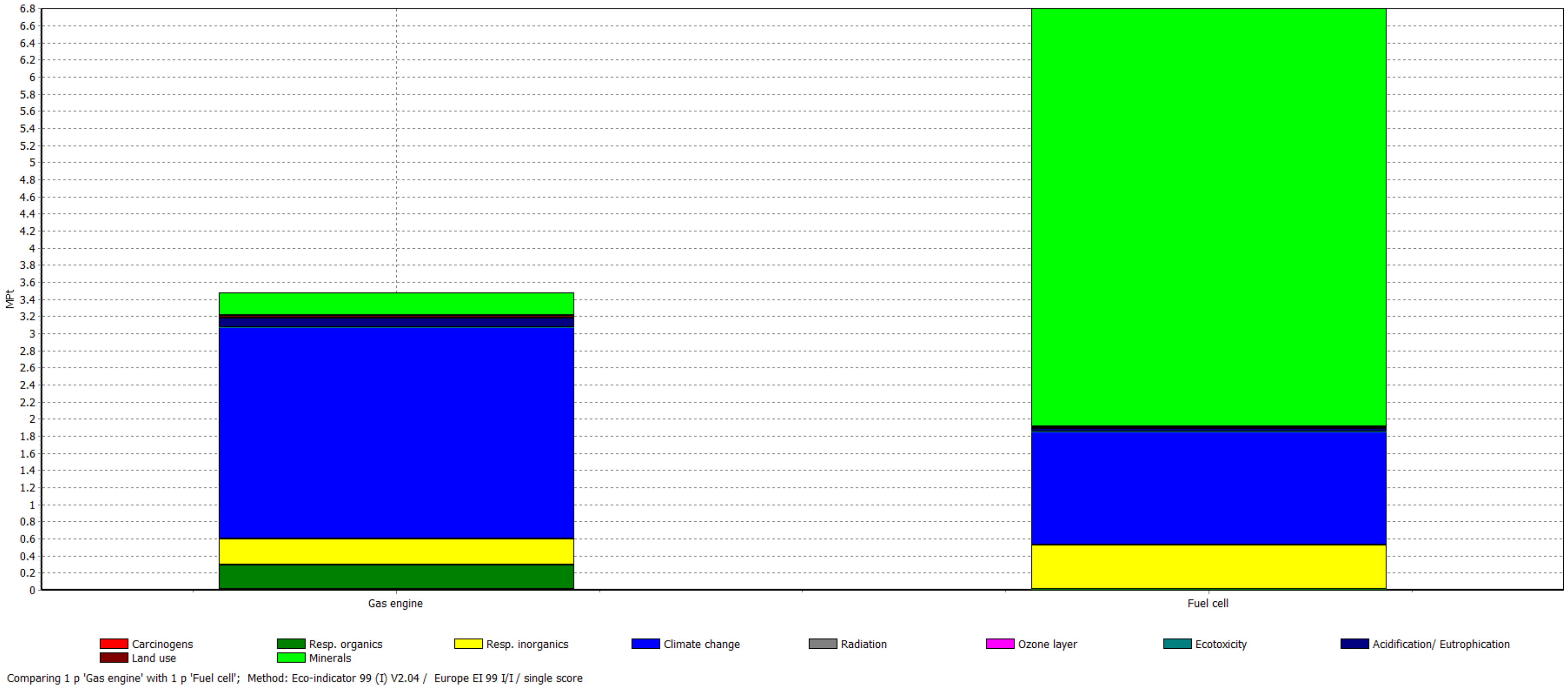
## 14.8.27 GAS ENGINE COMPARED TO FUEL CELL, ECO-INDICATOR WEIGHTED



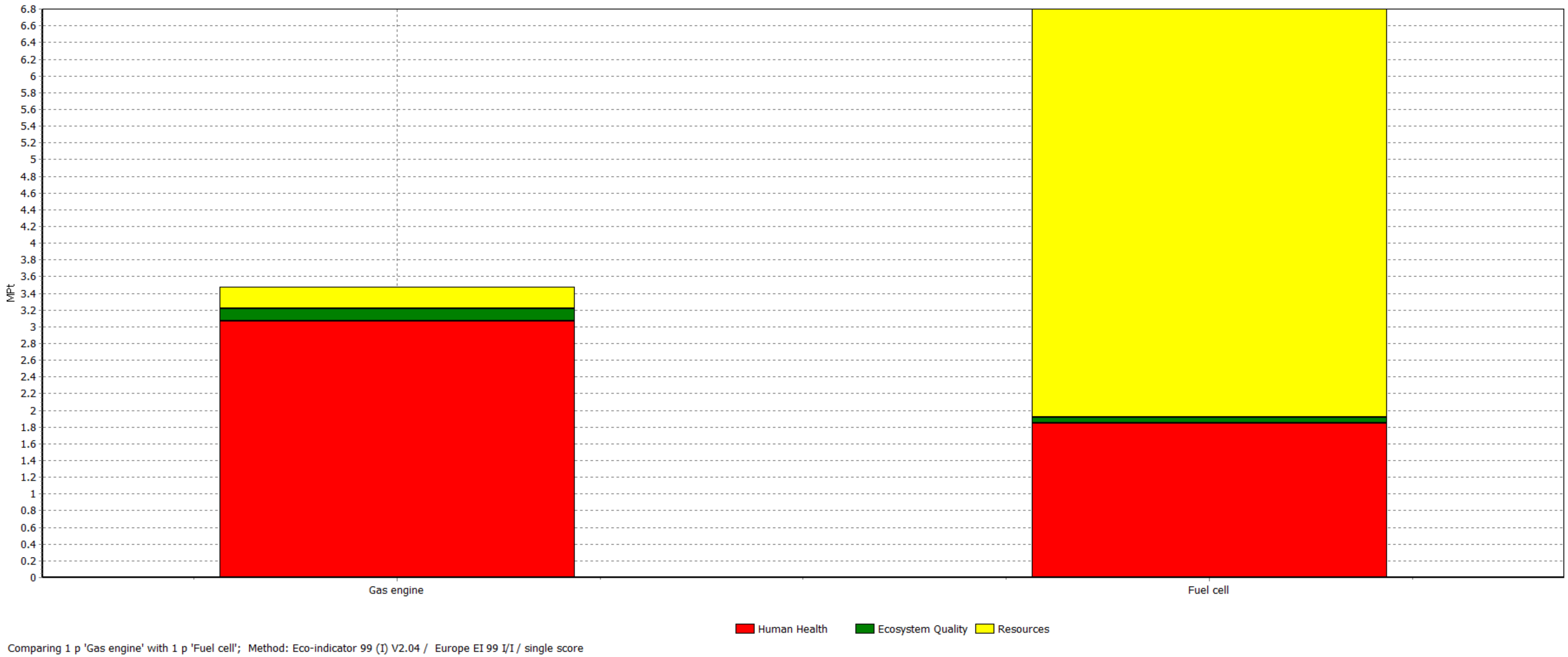
## 14.8.28 GAS ENGINE COMPARED TO FUEL CELL, ECO-INDICATOR WEIGHTED


Comparing 1 p 'Gas engine' with 1 p 'Fuel cell'; Method: Eco-indicator 99 (I) V2.04 / Europe EI 99 I/I / weighting

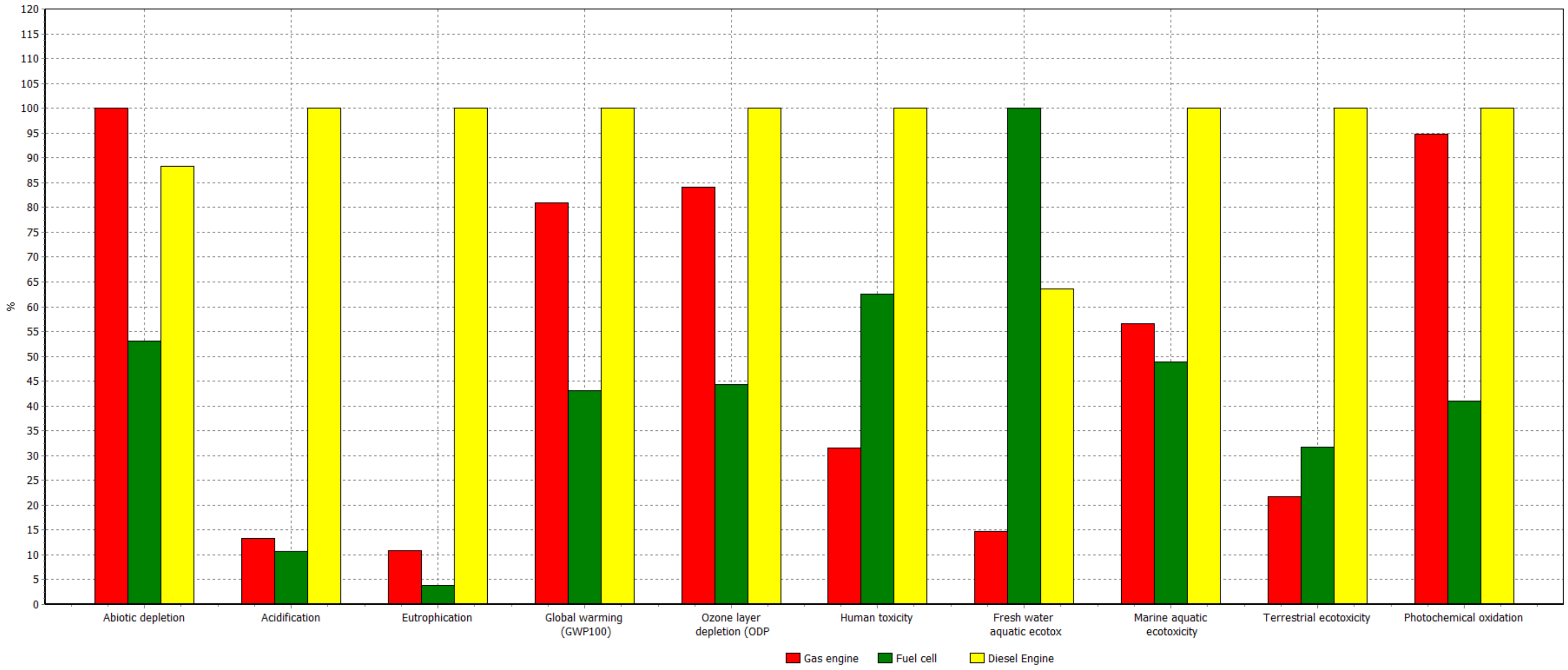
## 14.8.29 GAS ENGINE COMPARED TO FUEL CELL, ECO-INDICATOR SINGLE SCORE



## 14.8.30 GAS ENGINE COMPARED TO FUEL CELL, ECO-INDICATOR SINGLE SCORE

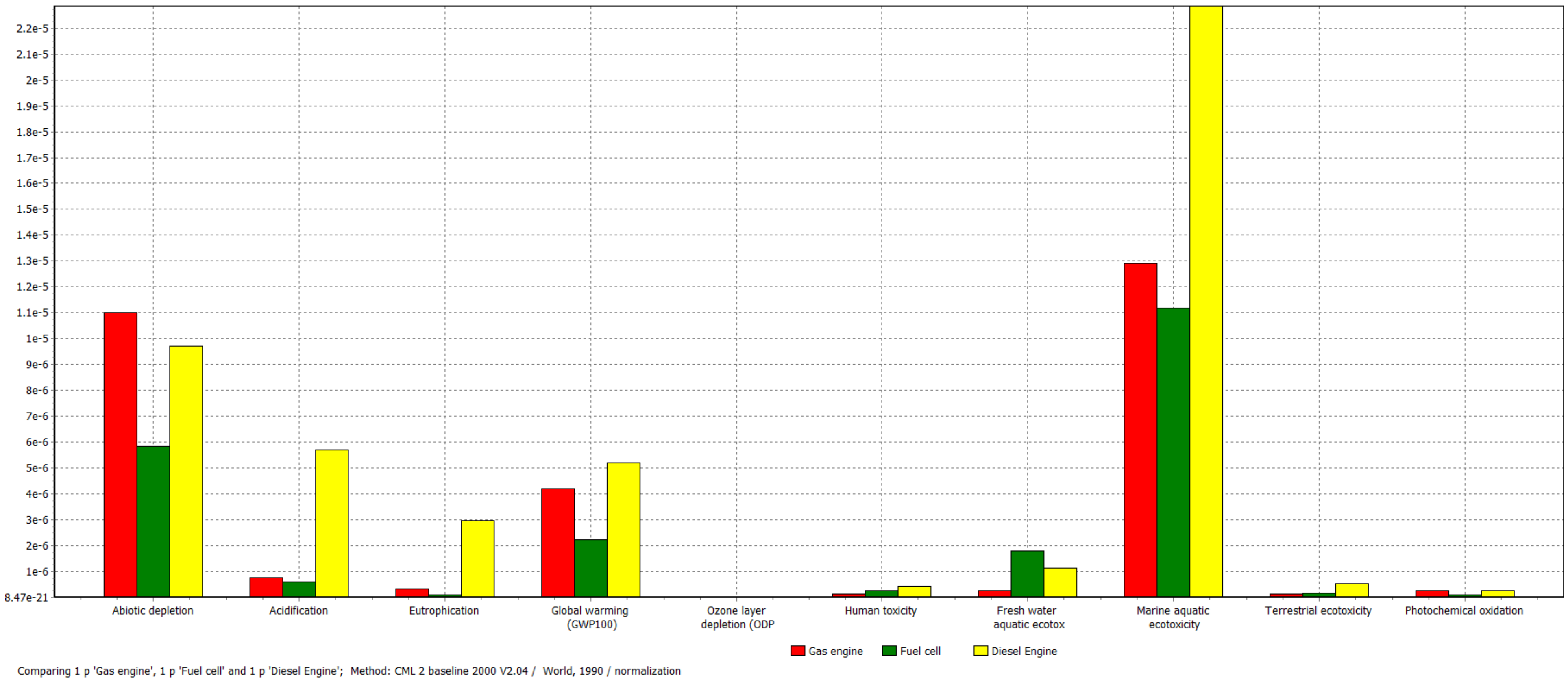


## 14.8.31 GAS ENGINE AND FUEL CELL COMPARED TO DIESEL ENGINE, CML CHARACTERIZED

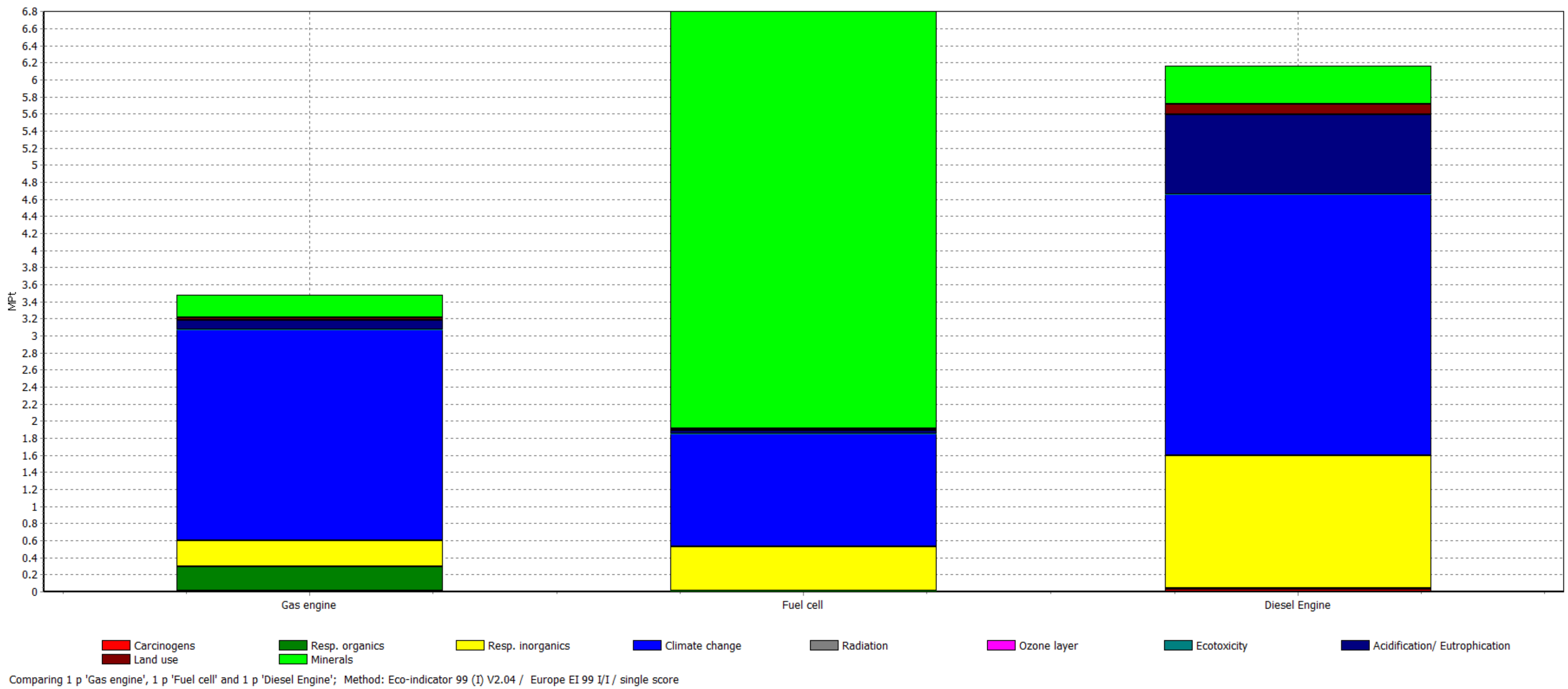


Comparing 1 p 'Gas engine', 1 p 'Fuel cell' and 1 p 'Diesel Engine'; Method: CML 2 baseline 2000 V2.04 / World, 1990 / characterization

## 14.8.32 GAS ENGINE AND FUEL CELL COMPARED TO DIESEL ENGINE, CML NORMALIZED



## 14.8.33 GAS ENGINE AND FUEL CELL COMPARED TO DIESEL ENGINE, ECO-INDICATOR SINGLE SCORE



## 14.8.34 GAS ENGINE AND FUEL CELL COMPARED TO DIESEL ENGINE , ECO-INDICATOR SINGLE SCORE