Life Cycle Analysis results of fuel cell ships

Recommendations for improving cost effectiveness and reducing environmental impacts

Study carried out in the framework of the project
FCSHIP – Fuel Cell Technology in Ships

Final Report
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FCSHIP

Fuel Cell Technology in Ships

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Contents

ACRONYMS

CCR	Central Committee for Rhine Shipping
CGH_2	Compressed Gaseous Hydrogen
CH_4	Methane
CO_2	Carbon Dioxide
CO	Carbon Monoxide
EUR	Euro
FAME	Fatty Acid Methyl Esters
FC	Fuel Cell
FCSHIP	Fuel Cell Technology in Ships Project
GHG	Greenhouse Gases
GWP	Global Warming Potential
H_2	Hydrogen
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LCA	Life Cycle Analysis
LH_2	Liquid Hydrogen
LNG	Liquefied Natural Gas
MCFC	Molten Carbonate Fuel Cell
MGO	Marine Gas Oil
N_2O	Nitrous Oxide
NG	Natural Gas
NMVOC	Non-Methane Volatile Organic Compounds

NO_x	Nitrogen Oxide (calculated as NO_2)
PEMFC	Proton Exchange Membrane Fuel Cell
PO_4^{3-}	Phosphate
POX	Partial Oxidation
PM	Particulate Matter
SO_2	Sulfur Oxide
SOFC	Solid Oxide Fuel Cell

ABBREVIATIONS USED FOR FUEL PATHS

Case ship 1

HFO 3,5% S	Heavy Fuel Oil, 3.5% sulfur content
HFO 1,0% S	Heavy Fuel Oil, 1.0% sulfur content
Diesel 10 ppm	car diesel, 10 ppm sulfur content
LNG import	Liquefied natural gas imported by ship from remote locations (distance: 5000-6000 nautical miles)
LNG Norway	Liquefied natural gas from Norwegian natural gas fields
LNG onsite (Stirling)	Onsite liquefaction of natural gas (European mix from pipeline) at port using Stirling engines
LH2-NG (2,78 t/d)	Liquid hydrogen produced from natural gas; hydrogen generation and liquefaction plant capacity 2.78 tons per day
LH2-NG (216 t/d)	Liquid hydrogen produced from natural gas; hydrogen generation and liquefaction plant capacity 216 tons per day
LH2-HFO (216 t/d)	Liquid hydrogen produced from heavy fuel oil; hydrogen generation and liquefaction plant capacity 216 tons per day

LH2 wind (2,78 t/d)	liquid hydrogen from offshore wind power; hydrogen liquefaction plant capacity 2.78 tons per day
LH2 wind (216 t/d)	liquid hydrogen from offshore wind power; hydrogen liquefaction plant capacity 216 tons per day
LH2 hydro (2,78 t/d)	liquid hydrogen from hydro power; hydrogen liquefaction plant capacity 2.78 tons per day
LH2 hydro (216 t/d)	liquid hydrogen from hydro power; hydrogen liquefaction plant capacity 216 tons per day

Case ship 2

MGO < 0,2% S	Marine Gas Oil, 0.2% sulfur content
CGH2 wind offshore	compressed gaseous hydrogen produced onsite from offshore wind power
CGH2-NG-onsite (ATR)	compressed gaseous hydrogen produced onsite from natural gas using an autothermal reformer
CGH2-NG-onsite (SR)	compressed gaseous hydrogen produced onsite from natural gas using a steam reformer
CGH2-WW 2,5 MWth	compressed gaseous hydrogen produced onsite from waste wood in a gasification unit with a thermal capacity of 2.5 MW
CGH2-WF 2,5 MWth	compressed gaseous hydrogen produced onsite from wood farming in a gasification unit with a thermal capacity of 2.5 MW
CGH2-WW 10 MWth	compressed gaseous hydrogen produced onsite from waste wood in a gasification unit with a thermal capacity of 10 MW
CGH2-WF 10 MWth	compressed gaseous hydrogen produced onsite from wood farming in a gasification unit with a thermal capacity of 10 MW

OBJECTIVES

The objective of the present report is to integrate the results of several sub-studies into one comprehensive Life Cycle Analysis of the use of fuel cells in ships. Additionally, the report includes a fuel cost analysis.

Based on the Life Cycle Analysis and cost analysis results several recommendations for improving cost effectiveness and further reduction of the environmental impacts of fuel cell ships are made.

EXECUTIVE SUMMARY

This Life Cycle Analysis of fuel cell ships includes fuel production, supply and use, fuel cell manufacturing and end-of-life as well as ship operation. Within FCSHIP, two case ship designs have been developed, a 140 m Ro-Ro Fast Ferry with a fuel cell for onboard power supply and a 30 m Ferry with fuel cell propulsion. Suitable fuels have been identified, and their possible production and supply options have been analyzed. Fuel cell types considered here include MCFC, SOFC and PEMFC.

Greenhouse gas and pollutant emissions related to various production, supply and use options of hydrogen, natural gas and conventional or advanced conventional ship fuels based on fossil (mineral oil, natural gas) and renewable sources of primary energy (wind power, hydro power, biomass) are assessed. A cost analysis for these fuel paths is conducted.

The analysis comes to the conclusion that fuel cells offer the potential for significant environmental improvements both in terms of air quality and climate protection. Local pollutant emissions and greenhouse gas emissions can be eliminated almost entirely over the full life cycle using renewable primary energies. The direct use of natural gas in high temperature fuel cells employed in large ships and the use of natural gas derived hydrogen in PEM fuel cells installed in small ships allows for a greenhouse gas emission reduction of 20%-40%. Fuel cells have the potential for further efficiency improvements over the values assumed here, which would translate into further reductions of greenhouse gas emissions for fossil based fuels.

Economically, natural gas fuel can compete with conventional fuels, which are untaxed, at oil prices above 25 US-$ per barrel. Fossil hydrogen is still

more expensive with future competitiveness depending on the development of the oil price. The cheapest renewable hydrogen option is comparable to hydrogen from natural gas.

From an environmental perspective, the development of fuel cell technology for marine applications is strongly recommendable. Dedicated developments of marine fuel cells will allow to exploit the full potential of the technology. Important synergies with stationary applications (large ships) and automotive applications (small ships and boats) should be used.

1 GOAL, SCOPE AND LIMITATIONS OF ANALYSIS

This Life Cycle Analysis evaluates the environmental impacts of the whole system of fuel cell applications on ships including fuel cell production, operation and end of life as well as fuel production and supply including the required infrastructure. The analysis does not include the construction and end of life of the ship itself. The same evaluation is carried out for conventional technologies in the same applications for comparison.

Additionally, a cost analysis has been carried out for fuel production and supply.

The evaluation relies on the technological status of today, but assumes technological advances until the time frame of 2010 to 2020.

Fuel cell technologies analyzed are Molten Carbonate Fuel Cells (MCFC), Solid Oxide Fuel Cells (SOFC) and Proton Exchange Membrane Fuel Cells (PEMFC). The conventional benchmark are diesel cycle internal combustion engines.

Fuels chosen include low sulfur car diesel (10 ppm sulfur content), liquefied natural gas, liquid and compressed gaseous hydrogen, respectively, as well as heavy fuel oil (3.5% and 1.0% sulfur content, respectively) and marine gas oil as conventional benchmarks. Primary energies used for fuel production are crude oil (heavy fuel oil, marine gas oil, car diesel, liquid hydrogen), natural gas (liquefied natural gas, liquid hydrogen, compressed gaseous hydrogen), renewable electricity (liquid and compressed gaseous hydrogen), biomass (compressed gaseous hydrogen).

For the analysis two case ships have been defined. Case ship 1 is a large passenger ferry operating between the Norwegian port of Oslo and the German port of Kiel. Based on this ship, a case ship analysis has been carried out using high or low temperature fuel cells for the supply of auxiliary power onboard the ship; the main propulsion is supplied by conventional ship engines. Three different fuels are considered for the fuel cells of case ship 1: low sulfur diesel (car diesel), liquefied natural gas (LNG) and liquid hydrogen (LH_2). Hydrogen will be used in a low-temperature PEM fuel cell, car diesel and LNG will be used in high-temperature fuel cells (MCFC – molten carbonate fuel cell or SOFC – solid oxide fuel cell). The electricity output for auxiliary power in case ship 1 is about 2 MW (2 generator sets with 1,080 kW each).

Figure 1. Case ship 1 (left) and case ship 2 (right)

Case ship 2 is a small commuter ferry operating in the Dutch city of Amsterdam. In the case ship 2 analysis PEM fuel cells supply the power for propulsion and for the auxiliary electricity consumption. Compressed gaseous hydrogen (CGH_2) is stored onboard the ship for the supply of the fuel cell. The total installed power of case ship 2 (two engines) which has to be replaced by the PEMFC power train is approximately 400 kW.

The Life Cycle Analysis is limited to gaseous emissions as here major advances by fuel cells and applicable fuels are to be expected and on the other hand major environmental problems related to conventional ship technology exist. Major impacts to be studied are emissions having a climate changing potential (mainly CO_2, CH_4 and N_2O), emissions contributing to acidification (SO_2, NO_x, NH_3) and emissions contributing to a eutrophication of waters (NO_x, NH_3).

The analysis of photochemical oxidation, an additional impact of major concern, requires information about the detailed composition of hydrocarbon emissions. As it was not possible in this project to go into such detail an analysis of photochemical oxidation improvements by fuel cells could not be performed.

Data for all stages of the Life Cycle Analysis have been compiled from a large variety of sources, including literature and direct contacts to manufacturers to name the most important.

Available data on fuel cell manufacturing are rather limited, restricting exactness and the reliability of this analysis of this stage. In addition, the assessment of future technology advances is difficult as fuel cells in general are not yet in a stage of commercial availability. Commercial MCFC prototypes for stationary applications are available, but not suitable for marine applications due to excessive weight and volume. SOFC technology is some years behind, being developed for stationary applications mainly. PEM fuel cells being developed mainly for automotive applications and small stationary applications. First fleets of demonstration fuel cell vehicles are emerging at present.

The reliability of fuel production and supply data and of ship operation data is very high.

2 BASICS

2.1 Efficiencies

2.1.1 Case ship 1

The efficiency of the natural gas fueled FC system (SOFC or MCFC) is assumed to be 47.8%. The efficiency of the diesel fueled FC system is assumed to be 41.8%.

Table 2-1: Efficiency of different electricity generation technologies

	Efficiency [%]	Reference
Diesel engine	43.3	[Bazari 2004]
Diesel MCFC	41.8	[Bazari 2004]
LNG MCFC or SOFC	47.8	[Bazari 2004]; [MT 2004], [WM 2003]; [DNV 2003]; [MTU 2003]
LH_2 PEMFC	50.0	[GM 2003]

2.1.2 Case ship 2

In contrast to case ship 1 the efficiencies of fuel cells in case ship 2 are significantly higher than those of conventional ship engines. This is due to the fact that case ship 2 largely operates in part load where internal combustion engines have lower efficiencies and fuel cells have higher efficiencies than at full load.

The efficiency of the diesel engine is indicated with about 26.8% whereas the overall efficiency of the fuel cell is approximately 50% [DUT 2003].

2.2 Emissions during ship operation

2.2.1 Case ship1

Table 2-2: Air pollutant emissions of a typical heavy fuel oil fueled diesel engine [Bazari 2004]

	g/kg_{HFO}	g/kWh_{HFO}	g/kWh_e
NO_x	57.0	5.11	11.80
PM (3.5% S) 1)	7.6	0.68	1.57
PM (1.0% S)	1.8	0.16	0.37
NMVOC	2.4	0.21	0.49
CO	7.4	0.66	1.53

1) in the Lloyd’s Register’s Marine Exhaust Emission Research Programme Report from where the data used in [Bazari 2004] are derived the 7.6 g per kg of heavy fuel oil have been measured at a sulfur content of 3% which is close to the 3.5% assumed here.

The NOx, particulate matter (PM), non-methane volotile organic compounds (NMVOC) and CO emissions are derived from [Bazari 2004].

Table 2-3: Air pollutant emissions of a fuel cell with fuel processor [Bazari 2004]

	FC reformer g/kWh_{in}	Natural gas FC g/kWh_e	Diesel FC g/kWh_e
NO_x	0.0068	0.0141	0.0161
PM	0.0000	0.0000	0.0000
NMVOC	0.0033	0.0069	0.0079
CO	0.0135	0.0282	0.0323
CH_4	0.0304	0.0637	0.0728

The emissions are derived from [Barari 2004] using the efficiencies as discussed above.

2.2.2 Case ship 2

The emissions of the diesel engine of case ship 2 are derived from the emission limits issued by the Central Committee for Rhine Shipping (CCR) [CCR 2000]. The CCR has passed exhaust emissions requirements for new diesel engines above 37 kW. The emission limits have to be complied with in the Netherlands, Belgium, France, Germany and in Switzerland.

Table 2-4: Air pollutant emissions of new diesel engines for ship propulsion [CCR 2000]

	g/kWh_{mech}	g/kWh_{diesel}
NO_x	9.96	2.664
PM	0.54	0.144
NMVOC	1.30	0.348
CO	5.00	1.338

2.3 Fuel supply

The emissions of the various fuel supply chains are presented in detail in [LBST 2004].

Table 2-5 shows the emissions of air pollutants and GHGs for the supply of ship fuels for case ship 1. The reason for the negative emissions of N_2O and SO_2 in case of the supply of LH_2 from natural gas in a 2.78 t LH_2/d plant (LH_2 NG 2.78 t/d) is that the heat from the NG fueled co-generation plant substituting heat from a conventional heating plant which consumes small amounts of electricity for auxiliaries. The electricity for the auxiliaries is supplied by the EU electricity mix. As a result, this small amount of electricity from the EU electricity mix is saved giving an emission credit to the NG co-generation plant.

Table 2-6 shows the emissions of air pollutants and GHGs for the supply of ship fuels for case ship 2. The negative emissions of SO_2 in case of woody biomass derived CGH_2 in a 2.5 MW_{th} gasificaton plant (WW 2.5 MW_{th}, WF 2.5 MW_{th}) are from credits. It is assumed for the calculation that the excess heat from the gasification plant and from the gas engine substitutes heat from a biomass fueled heating plant. There is a large uncertainty concerning the emissions of SO_2 from the combustion of solid wood because a part of the sulfur is bound in the ash. The share of sulfur bound in the ash ranges from 40% to 90%. However, the emissions of SO_2 from the combustion of wood are low compared to the SO_2 emitted from the combustion of fossil fuels such as coal or high sulfur heavy fuel oil.

The negative NMVOC emissions in case of the woody biomass derived CGH_2 (WW 2.5 MW_{th}, WF 2.5 MW_{th}, WW 10 MW_{th}, WF 10 MW_{th}) are from credits. It is assumed for the calculation that the excess heat from the gasification plant and from the gas engine replaces heat from a biomass fueled heating plant. The emissions of NMVOC per kWh of heat from the wood fueled boiler are higher than those from the combustion of the formed wood coke in the gasification plant and the combustion of the tail gas of the PSA in the gas engine.

The relatively high SO_2 emissions of natural gas based hydrogen mainly stem from electricity consumption for natural gas reforming and hydrogen compression. The EU electricity mix is used here with SO_2 emissions more than a factor of two higher than those of the German electricity mix (even though the nuclear energy share is roughly the same).

Table 2-5: GHG and air pollutant emissions fuel supply or case ship 1 [g/kWh of ship fuel]

	HFO 3,5% S	**HFO 1,0% S**	**Diesel 10 ppm**	**LNG import**	**LNG Norway**	**LNG onsite**	**LH_2 NG (2,78 t/d)**	**LH_2 NG (216 t/d)**	**LH_2 HFO (216 t/d)**	**LH_2 wind (2,78 t/d)**	**LH_2 wind (216 t/d)**	**LH_2 hydro (2,78 t/d)**	**LH_2 hydro (216 t/d)**
GHGs													
CO_2	22.0	29.1	45.6	51.2	6.2	31.6	402.3	402.2	660.1	25.1	24.3	20.4	19.9
CH_4	0.199	0.207	0.209	1.207	0.847	0.827	0.912	0.879	0.485	0.063	0.060	0.031	0.030
N_2O	0.001	0.001	0.000	0.001	0.000	0.000	-0.001	0.005	0.000	0.001	0.000	0.000	0.000
CO_2 equiv.	26.9	34.2	50.5	79.3	25.7	50.6	423.0	423.8	671.4	26.7	25.8	21.2	20.7
Air pollutants													
SO_2	0.097	0.103	0.108	0.120	0.003	0.006	-0.001	0.011	0.163	0.023	0.022	0.009	0.008
NO_x	0.395	0.403	0.160	0.104	0.020	0.135	0.552	0.316	0.379	0.057	0.055	0.044	0.043
Dust/PM	0.029	0.030	0.008	0.011	0.002	0.002	0.002	0.004	0.016	0.016	0.015	0.009	0.009
NMVOC	0.083	0.085	0.130	0.006	0.002	0.043	0.143	0.010	0.180	0.004	0.004	0.001	0.001
CO	0.104	0.108	0.065	0.062	0.026	0.147	0.416	0.258	0.224	0.134	0.127	0.039	0.037
SO_2 equiv.	0.374	0.385	0.220	0.193	0.016	0.100	0.385	0.232	0.428	0.063	0.061	0.040	0.039
PO_4^{3-} equiv.	0.051	0.052	0.021	0.014	0.003	0.018	0.072	0.041	0.049	0.007	0.007	0.006	0.006

Table 2-6: GHG and air pollutant emissions fuel supply or case ship 2 [g/kWh of ship fuel]

	MGO < 0,2% S	**CGH_2 wind offshore**	**CGH_2 NG-onsite (ATR)**	**CGH_2 NG-onsite (SR)**	**CGH_2 WW 2,5 MW_{th}**	**CGH_2 WF 2,5 MW_{th}**	**CGH_2 WW 10 MW_{th}**	**CGH_2 WF 10 MW_{th}**
GHGs								
CO_2	29	25	424	419	7	16	7	18
CH_4	0.206	0.071	0.886	0.874	0.007	0.023	0.019	0.037
N_2O	0.001	0.000	0.003	0.003	0.021	0.126	0.014	0.136
CO_2 equiv.	34	27	445	440	14	54	12	59
Air pollutants								
SO_2	0.093	0.026	0.205	0.187	-0.017	-0.005	0.002	0.016
NO_x	0.394	0.057	0.262	0.341	0.412	0.467	0.444	0.508
Dust/PM	0.029	0.018	0.052	0.072	0.125	0.129	0.105	0.110
NMVOC	0.086	0.004	0.040	0.062	-0.092	-0.092	-0.039	-0.038
CO	0.109	0.165	0.129	0.151	0.270	0.282	0.298	0.312
SO_2 equiv.	0.369	0.066	0.388	0.426	0.271	0.321	0.313	0.371
PO_4^{3-} equiv.	0.051	0.007	0.034	0.044	0.054	0.061	0.058	0.066

2.4 Manufacturing of propulsion systems

2.4.1 Case ship 1

The energy requirement and emissions of greenhouse gases and air pollutants for the manufacture of the diesel fueled MCFC and the diesel engine are derived from [Alkaner 2004]. The lifetime of the MCFC stack is 40,000 full load hours and the lifetime of the balance of plant is 160,000 full load hours. Four MCFC stacks are used over the lifetime of 160,000 full load hours which are reached after 20 years. The emissions and energy requirements for the manufacture of the diesel engine is based on a life cycle of 20 years and 160,000 hours of full load operation.

The energy requirement and emissions of greenhouse gases and air pollutants for the manufacture of the LNG fueled SOFC are derived from [DNV 2004]. The lifetime of the LNG fueled SOFC unit is assumed to be 40,000 full load hours.

The energy requirement and emissions of greenhouse gases and air pollutants for the manufacture of the hydrogen fueled PEMFC system are derived from a stationary natural gas fueled PEMFC co-generation power plant with an electricity output of 250 kW as described in [Pehnt 2002]. The lifetime of the PEMFC plant is indicated with 40,000 full load hours. The platinum loading is 1 mg/cm^2. The bipolar plates are made from graphite composite material. After 40,000 full load hours the graphite containing bipolar plates (graphite composite) are re-used during recycling. The manufacture of graphite is rather energy intensive. In [Pehnt 2002] it has been assumed that the bipolar plants can be re-used 4 times leading to a total lifetime of 160,000 full load hours.

The energy requirement and emission data for the PEMFC co-generation plant indicated in [Pehnt 2002] include the balance of plant. Since the PEMFC co-generation plant in [Pehnt 2002] is fueled with natural gas the balance of plant includes the natural gas reformer system including two-stage CO shift and selective CO oxidation for final clean up. For the LH_2 fueled PEMFC in case ship 1 no reformer system is required. The reformer system consisting of four reactors and several heat exchangers mainly consist of steel. As a result there is an overestimate of the energy demand for the manufacture of the LH_2 fueled PEMFC system and the associated emissions. On the other hand the energy requirement for the manufacture of the LH_2

storage is not taken into account. However the data derived from [Pehnt 2002] can be considered as a conservative estimate.

Table 2-7: Energy requirements for the manufacture of different electricity generation technologies [Alkaner 2004], [DNV 2004], calculations based on [Pehnt 2002]

	Unit	**Diesel engine**	**Diesel MCFC**	**NG SOFC**	**H_2 PEMFC**
Energy	MJ/kW_e	579	6,993	6,361	6,170
Equivalent full load period	h/yr	8,000	8,000	8,000	8,000
Time	yr	20	20	5	5
Specific energy	kWh/kWh_e	0.001	0.012	0.044	0.043

Table 2-8 shows the emissions of air pollutants from the manufacture of the different onboard electricity generation technologies per kW of installed capacity.

Table 2-8: GHG emissions from the manufacture of different electricity generation technologies [Alkaner 2004], [DNV 2004], calculations based on [Pehnt 2002]

	Unit	**Diesel engine**	**Diesel MCFC**	**NG SOFC**	**H_2 PEMFC**
CO_2	kg/kW_e	53.44	460.56		356.86
CH_4	kg/kW_e	0.17	0.83		0.72
N_2O	kg/kW_e	0	0.02		0.03
CO_2 equivalent	kg/kW_e	57.35	485.57	382.00	382.05

The combination of the lifetime indicated in Table 2-7 with the GHG emissions per kW of installed capacity in Table 2-8 leads to the specific GHG emissions shown in Table 2-9. The GHG emissions in Table 2-8 are related to an equivalent full load period of 160,000 hours in case of the Diesel engine and in case of the diesel fueled MCFC system. The MCFC stacks have a lifetime of 40,000 full load hours and are replaced four times, while the balance of plant has a lifetime of 160,000 full load hours. The lifetime of the LNG fueled SOFC and the LH_2 fueled PEMFC is assumed to be 40,000 full load hours each.

Table 2-9: Specific GHG emissions from the manufacture of different electricity generation technologies [Alkaner 2004], [DNV 2004], calculations based on [Pehnt 2002]

	Unit	Diesel engine	Diesel MCFC	NG SOFC	H_2 PEMFC
CO_2	g/kWh_e	0.334	2.879		8.922
CH_4	g/kWh_e	0.001	0.005		0.018
N_2O	g/kWh_e	0.000	0.000		0.001
CO_2 equivalent	g/kWh_e	0.36	3.03	9.55	9.55

Table 2-10 shows the emissions of air pollutants from the manufacture of the different onboard electricity generation technologies per kW of installed capacity.

Table 2-10: Air pollutant emissions from the manufacture of different electricity generation technologies [Alkaner 2004], [DNV 2004], calculations based on [Pehnt 2002]

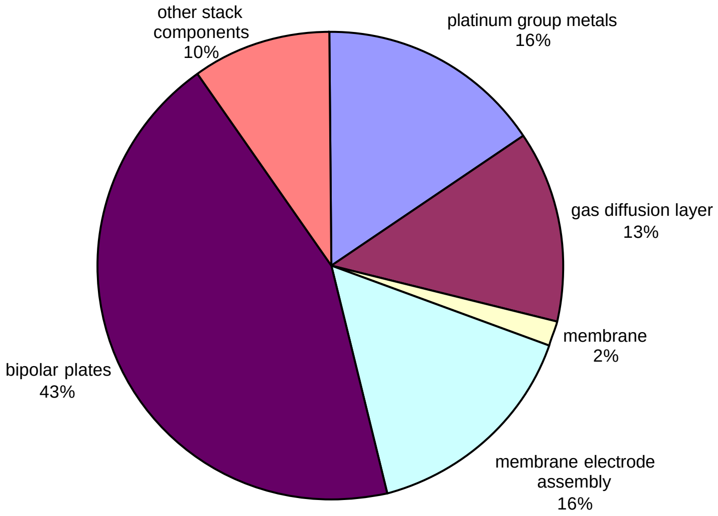
	Unit	Diesel engine	Diesel MCFC	NG SOFC	H_2 PEMFC
CO	kg/kW_e	0.280	1.590	0.374	1.197
NO_x	kg/kW_e	0.260	1.500	0.742	0.679
SO_2	kg/kW_e	0.130	9.200	2.970	1.319
NMVOC	kg/kW_e	0.030	5.570	0.002	0.236
Dust/PM	kg/kW_e	0.030	1.930	0.647	0.216

The combination of the lifetime indicated in Table 2-7 with Table 2-10 leads to the specific GHG emissions shown in Table 2-11. The lifetime of the Diesel engine and the diesel fueled MCFC is 160,000 full load hours (stack replaced four times). The lifetime of the LNG fueled SOFC and the LH_2 fueled PEMFC is assumed to be 40,000 full load hours each.

Table 2-11: Specific air pollutant emissions from the manufacture of different electricity generation technologies [Alkaner 2004], [DNV 2004], calculations based on [Pehnt 2002]

	Unit	Diesel engine	Diesel MCFC	NG SOFC	H_2 PEMFC
CO	g/kWh_e	0.002	0.010	0.009	0.030
NO_x	g/kWh_e	0.002	0.009	0.019	0.017
SO_2	g/kWh_e	0.001	0.058	0.074	0.033
NMVOC	g/kWh_e	0.000	0.035	0.000	0.006
Dust/PM	g/kWh_e	0.000	0.012	0.016	0.005

Figure 2-1: Share of different PEMFC stack components on GHG emissions from the manufacture of a PEMFC stack for vehicles (platinum recycling considered); calculations based on [Pehnt 2002]



A major contribution to the GHG emissions and to the energy requirement for the manufacture of the PEMFC stack stems from the supply of graphite for the bipolar plates.

Figure 2-1 presents the breakdown of GHG gas emissions by PEMFC stack components.

The choice of material for bipolar plates is crucial to the performance and lifetime of a PEMFC stack. Graphite has a good electronic conductivity and an excellent corrosion resistance. But pure graphite bipolar plates which were used in early PEMFC stacks are bulky, heavy and sensitive to concussion and the manufacturing process is expensive. Meanwhile PEMFC bipolar plates are made from composites which are fabricated from a combination of graphite or carbon powder and a polymer resin. Composites generally have lower electrical properties than metallic bipolar plates but they offer low-cost material and manufacturing costs together with good corrosion stability [Mepsted 2003]. For the 250 kW_e PEMFC plant used as basis for this study bipolar plates are made from graphite containing composite.

For the use in passenger vehicles alternative materials bipolar plates made from metals such as titanium, aluminum and stainless steel are under development. Metal made bipolar plates are lightweight and have a good electronic and a good heat conductivity which is important for the application in passenger vehicles. Titanium offers excellent electrical performance and power density (volumetric and gravimetric) but is expensive and requires precious metal coatings to avoid corrosion. Stainless steel offers reasonable electrical performance, low material and production cost but may require application of coating [Mepsted 2003]. The corrosion stability of metals can be improved by using alloys, e.g the corrosion stability of titanium can be enhanced by alloying with vanadium and zirconium. The non-renewable energy requirement for the supply of graphite ranges between 160 and 180 MJ per kg which is slightly below of the non-renewable energy required for the production of primary aluminum [Pehnt 2002]. The energy demand for the supply of stainless steel amounts to some 60 MJ per kg.

2.4.2 Case ship 2

The energy requirement and emissions of greenhouse gases and air pollutants for the manufacture of the diesel engine are derived from the diesel engine of a passenger vehicle as described in [Pehnt 2002]. The efficiency of the diesel engine over the driving cycle is indicated with 26% which is approximately equivalent to the efficiency of the diesel engine used in case ship 2 (≈ 27%).

The energy requirement and emissions of greenhouse gases and air pollutants for the manufacture of the hydrogen fueled PEMFC system are derived from a PEMFC system designed for passenger vehicles as described in [Pehnt 2002]. The platinum loading is 0.3 mg/cm^2. The bipolar plates are made from graphite.

The lifetime of the passenger vehicle is indicated with 150,000 km, the hydrogen fuel consumption is 1.03 MJ/km. Propulsion systems for city buses have to achieve a lifetime of 1,000,000 km. The propulsive power of buses ranges between 150 and 300 kW, similar to that of case ship 2. Therefore, a lifetime related to a driving distance of 1,000,000 km has been assumed for the propulsion system in case ship 2. The 150,000 km for the passenger car are equivalent to an operating time of approximately 3,000 hours. The 1,000,000 km for the bus are equivalent to an operating time of 20,000 hours, which is still below the 40,000 full load hours used for the onboard electricity generation unit in case ship 1.

Table 2-12 shows the energy requirements for the manufacture of propulsion systems for case ship 2 related to the fuel input (diesel and hydrogen, respectively). The energy requirements for the PEMFC system includes the hydrogen storage and the electric motor.

Table 2-12: Energy requirements for the manufacture of different ship propulsion technologies; calculations for PEMFC based on [Pehnt 2002]

	Unit	Diesel engine	H_2 PEMFC
Specific energy	kWh/kWh_{in}	0.022	0.073

Table 2-13: Specific GHG emissions from the manufacture of different ship propulsion technologies; calculations for PEMFC based on [Pehnt 2002]

	Unit	Diesel engine	H_2 PEMFC
CO_2	g/kWh_{in}	3.207	13.184
CH_4	g/kWh_{in}	0.009	0.027
N_2O	g/kWh_{in}	0.000	0.001
CO_2 equivalent	g/kWh_{in}	3.44	14.16

Table 2-14: Air pollutant emissions from the manufacture of different ship propulsion technologies; calculations for PEMFC based on [Pehnt 2002]

	Unit	Diesel engine	H_2 PEMFC
CO	g/kWh$_{in}$	0.013	0.017
NO_x	g/kWh$_{in}$	0.006	0.023
SO_2	g/kWh$_{in}$	0.013	0.037
NMVOC	g/kWh$_{in}$	0.001	0.006
PM	g/kWh$_{in}$	0.005	0.004

3 LIFE CYCLE INVENTORY ANALYSIS

This chapter presents the combined inventory analyses carried out in the different reports of the FCSHIP project.

3.1 Case ship 1

Figure 3-1 shows the total primary energy input for the different fuel/ propulsion system combinations split into fuel supply, fuel use during onboard electricity generation and primary energy demand for the manufacture of the diesel engine or the fuel cell system.

Figure 3-1: Life cycle energy use of case ship 1

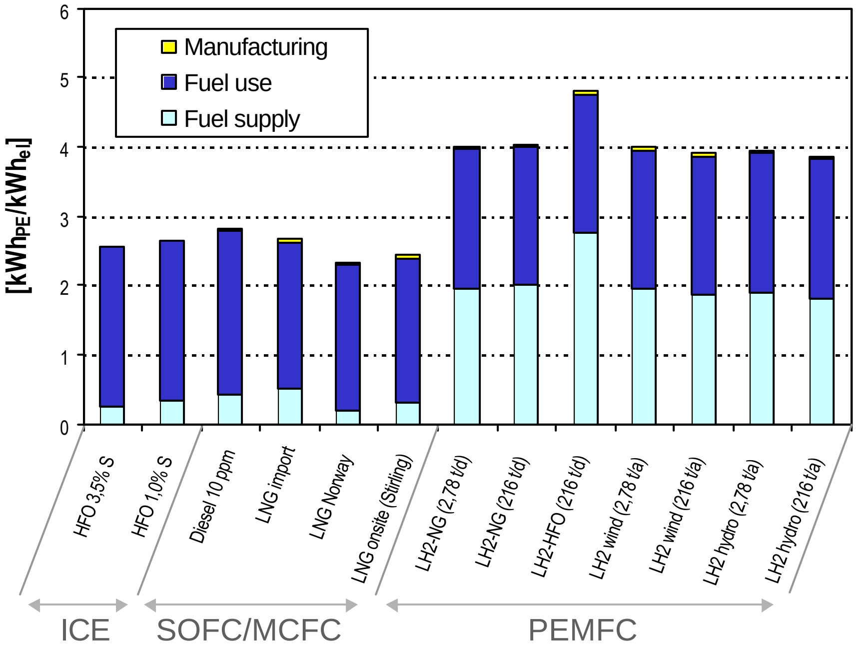


Figure 3-2 shows the life cycle CO_2, CH_4 and N_2O emissions for onboard electricity generation in terms of CO_2 equivalent including fuel supply, operation and manufacture of the fuel cell system or the diesel generator.

Figure 3-3, Figure 3-4, Figure 3-5, Figure 3-6 and Figure 3-7 show the life cycle emissions of air pollutants of onboard electricity generation.

Figure 3-2: Life cycle CO_2, CH_4 and N_2O emissions of onboard power supply in terms of CO_2 equivalent of case ship 1

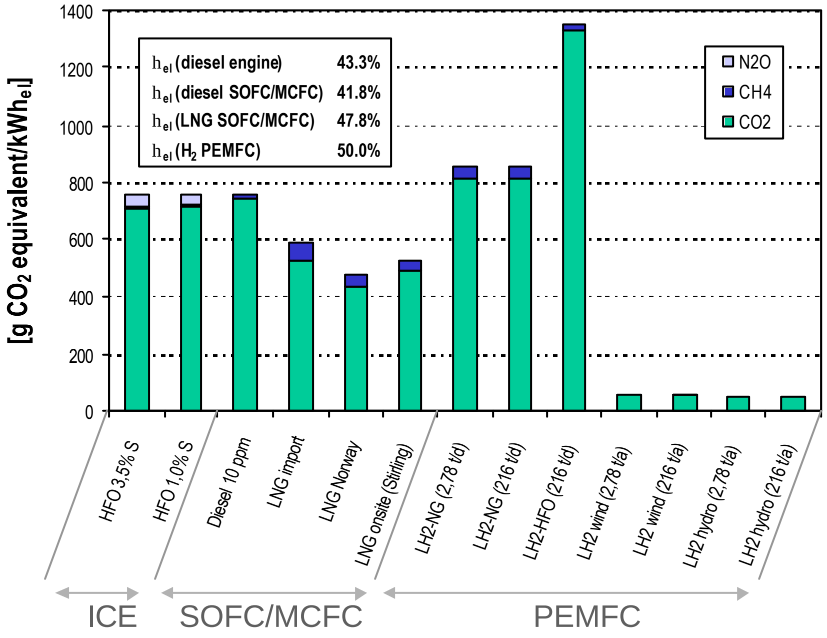


Figure 3-3: Life cycle SO_2 emissions of onboard power supply of case ship 1

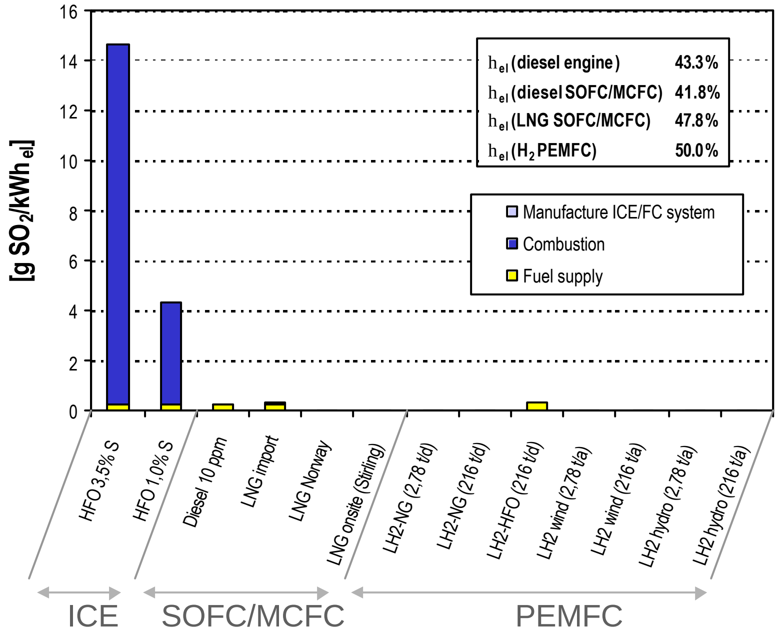


Figure 3-4: Life Cycle NO_x emissions of onboard power supply of case ship 1

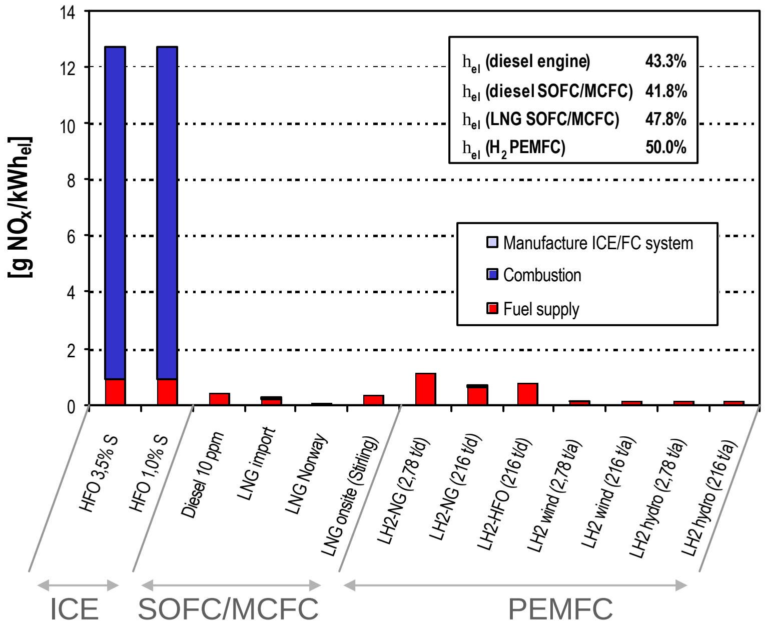


Figure 3-5: Life Cycle dust and particulate matter (PM) emissions of onboard power supply of case ship 1

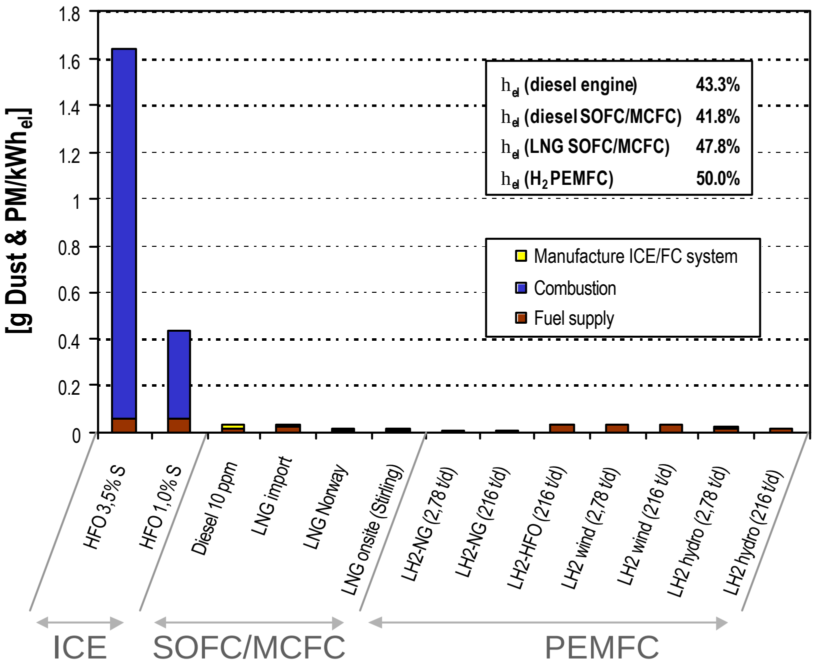


Figure 3-6: Life Cycle NMVOC emissions of onboard power supply of case ship 1

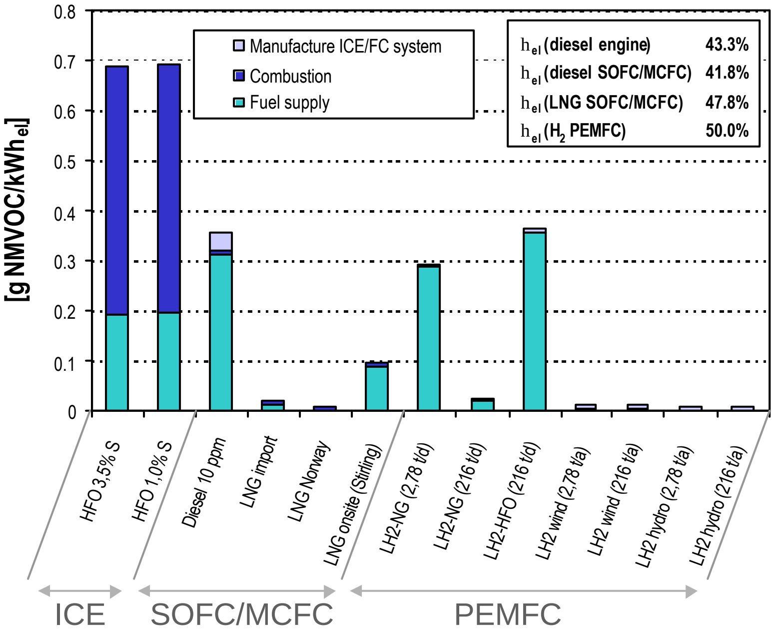
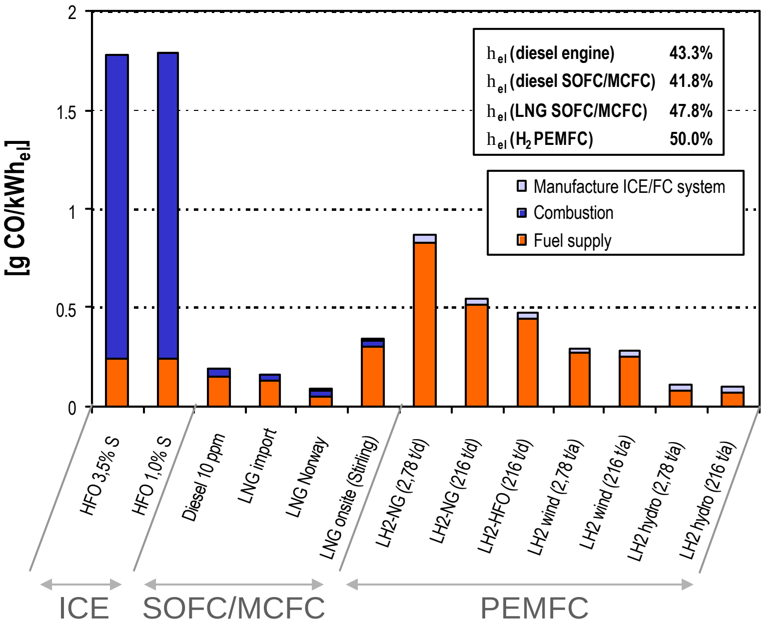


Figure 3-7: Life Cycle CO emissions of onboard power supply of case ship 1



3.2 Case ship 2

Figure 3-8 shows the total primary energy input for the different fuel/ propulsion system combinations split into fuel supply, fuel use during onboard ship operation and primary energy demand for the manufacture of the diesel engine or the fuel cell system.

Figure 3-9 shows the annual CO_2, CH_4 and N_2O emissions from the operation of one ship.

The emissions of air pollutants are shown in Figure 3-10 (SO_2), Figure 3-11 (NO_x), Figure 3-12 (dust and particulate matter (PM)), Figure 3-13 (NMVOC) and Figure 3-14 (CO). The acidification (expressed as SO_2 equivalents) and eutrophication (expressed as PO_4^{3-} equivalents) from the different pathways are shown in Figure 4-5 and Figure 4-6.

Figure 3-8: Annual life cycle energy use of case ship 2

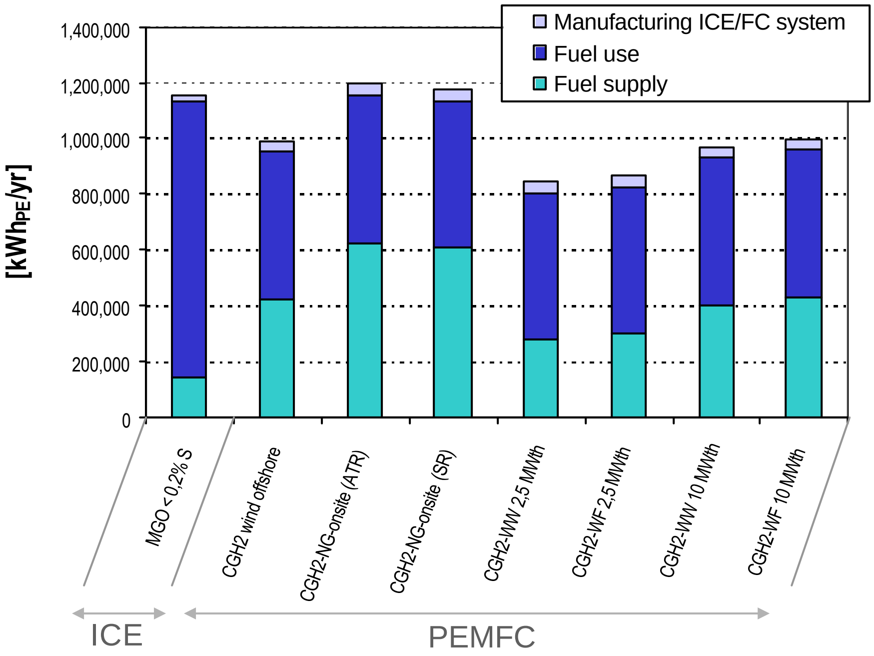


Figure 3-9: Annual life cycle CO_2, CH_4 and N_2O emissions in terms of CO_2 equivalent from the operation of case ship 2

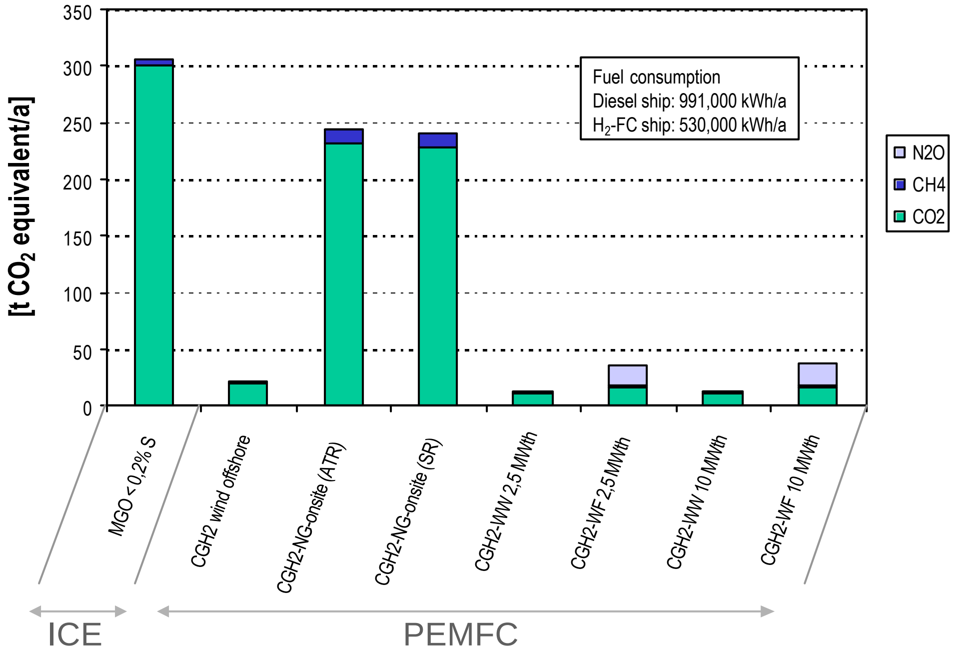


Figure 3-10: Annual life cycle SO_2 emissions from the operation of case ship 2

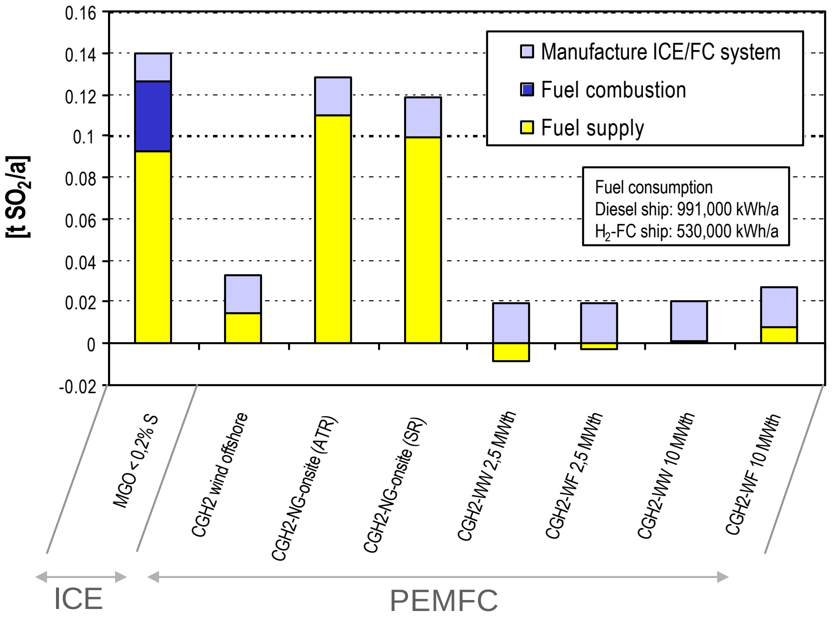


Figure 3-11: **Annual life cycle NO_x emissions from the operation of case ship 2**

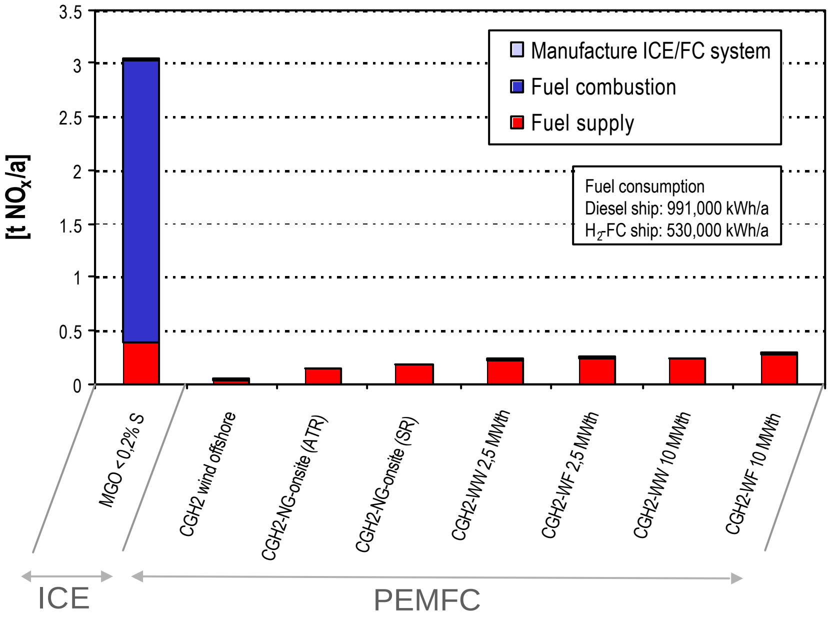


Figure 3-12: **Annual life cycle emissions of dust and particulate matter (PM) from the operation of case ship 2**

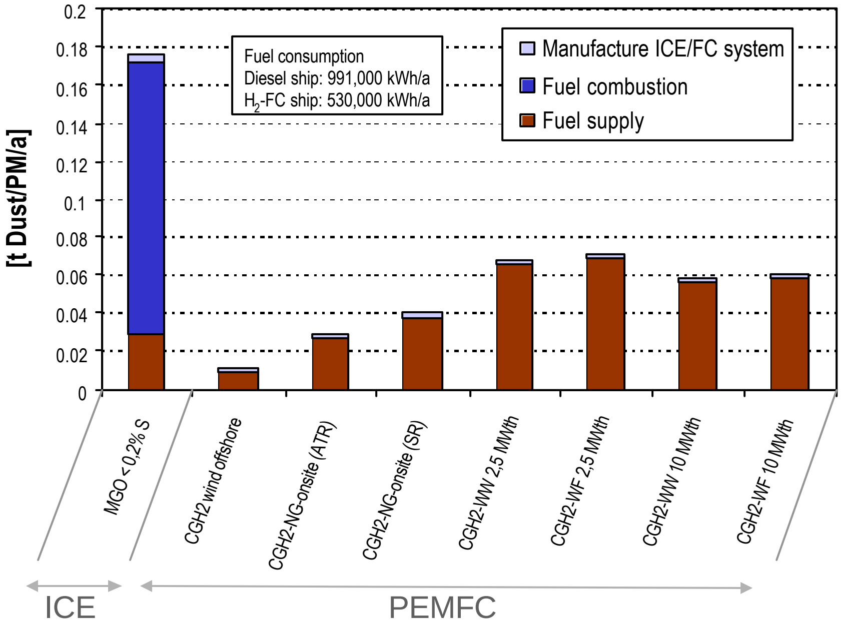


Figure 3-13: Annual life cycle NMVOC emissions from the operation of case ship 2

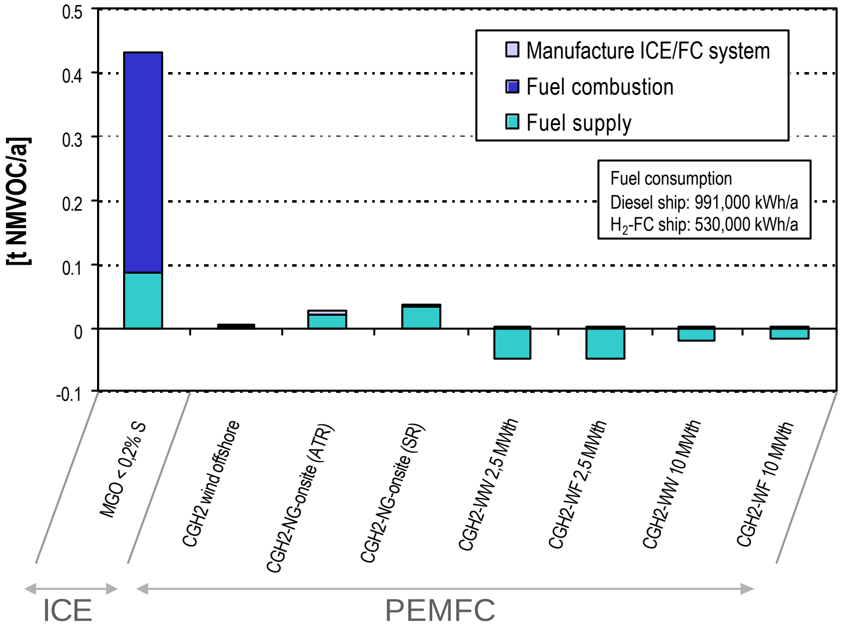
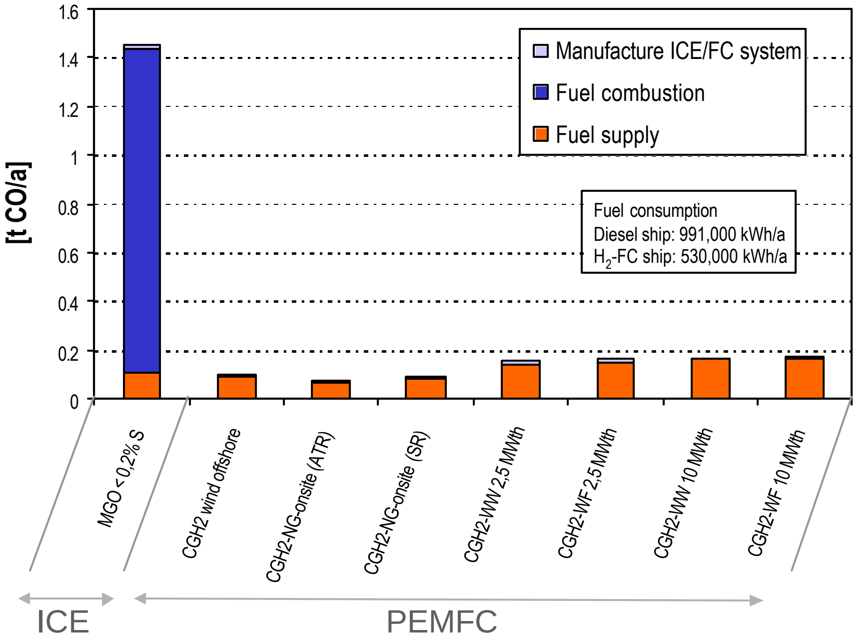


Figure 3-14: Annual life cycle CO emissions from the operation of case ship 2



4 LIFE CYCLE IMPACT ANALYSIS

An impact analysis is carried out and presented focusing on the major impacts caused by shipping: global warming, acidification and eutrophication.

These three impact categories are those where fuel cells can make an important contribution.

4.1 Case ship 1

The global warming potential (GWP) is expressed as CO_2 equivalents. The factors for the direct GWP for different greenhouse gases (GHG) relative to CO_2 are taken from [IPCC 2001]. They have an uncertainty of ±35%. The GWP factors for selected greenhouse gases are shown Table 4-1.

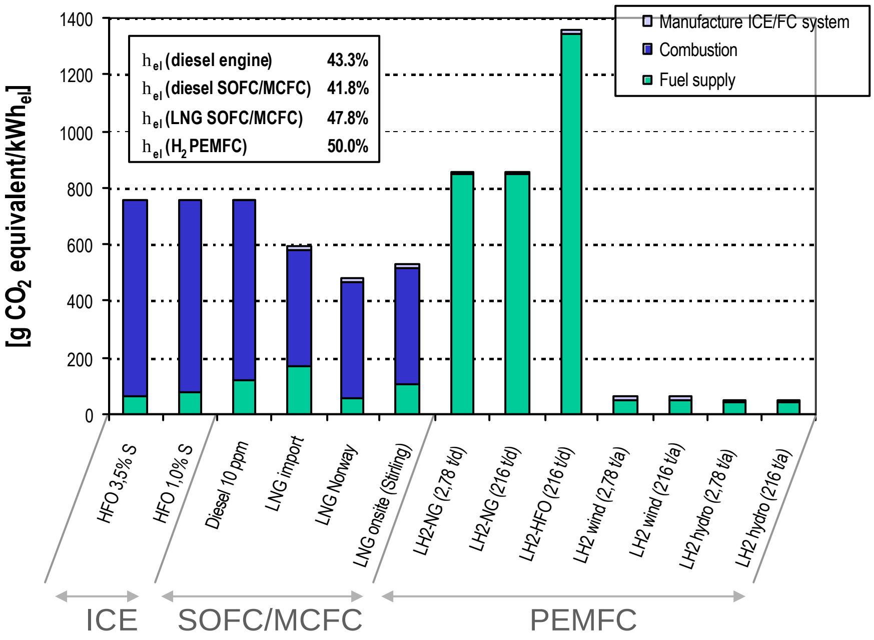
Table 4-1: Global Warming Potential (GWP) for different time horizons [IPCC 2001]

	20 years	**100 years**	500 years
CO_2	1	**1**	1
CH_4	62	**23**	7
N_2O	275	**296**	156
CF_4	3,900	**5,700**	8,900

In most life cycle analyses the factors for a time horizon of 100 years are used, which is done here as well. CO_2, CH_4 and N_2O mainly is generated by combustion processes and from agriculture (e.g. N_2O from fertilizer). CF_4 is emitted during the production of primary aluminum.

Figure 4-1 shows the life cycle greenhouse gas emissions (GHG) for onboard electricity generation including fuel supply, operation and manufacture of the fuel cell system or the diesel generator.

Figure 4-1: Life cycle GHG emissions of onboard power supply of case ship 1



For the conventional heavy fuel oil (HFO) and the reduced-sulfur HFO greenhouse gases are essentially the same as additional energy requirements for mild desulfurization are low compared to the CO_2 emissions of fuel combustion.

Sulfur-free car diesel production at the refinery has higher energy requirements than heavy fuel oil because it is a higher-value product requiring more efforts and because desulfurization to below 10 ppm is energy intensive. On the other hand, diesel has a lower carbon content per energy content than heavy fuel oil. This compensates for the higher GHG emissions is production and the slightly lower efficiency of the diesel SOFC system onboard the ship.

Liquefied natural gas (LNG) has a 29% lower carbon content per energy content than HFO. Additionally, the LNG powered MCFC fuel cell system is more efficient than the combustion engine. These two effects combine to a 22%-37% reduction in overall GHG emissions over the conventional benchmark.

LNG from Norway transported to Oslo the variant with the lowest GHG emissions because of the short transport distance. Onsite liquefaction of pipeline natural gas is higher in GHG emissions because of the lower efficiency of small-scale liquefaction machines. LNG import from “long distance”, which in the concrete case is assumed to be from Algeria, North Africa, is the highest GHG emission variant because of the long transport distance translating into higher energy requirements and higher CH_4 losses.

In spite of the fact that the efficiency of the liquid hydrogen (LH_2) powered PEM fuel cell is the highest of all systems considered here, natural gas derived hydrogen induces slightly higher GHG emissions than HFO powered systems and significantly higher GHG emissions than LNG powered systems. This is due to the energy requirements of hydrogen generation from natural gas and of hydrogen liquefaction. Hydrogen generation from HFO at the refinery has the highest GHG emissions of all variants considered here stemming from the higher carbon content of HFO and the less efficient generation process compared to natural gas steam reforming.

Hydrogen generation from renewable electricity (wind, hydro power etc.) has extremely low GHG emissions stemming from the construction of the facilities and the infrastructures.

Overall, the contribution to the GHG emissions stemming from the manufacturing of the combustion engine or fuel cell systems is negligible compared to all other contributions, even in the case of renewably produced hydrogen.

The emissions of SO_2, NO_x and NH_3 lead to the acidification of waters and soils. The acidification potential is indicated as SO_2 equivalents. No separate NH_3 balance has been made for the single steps of the life cycle. Therefore, NH_3 is not included here in the calculation of the acidification potential. The error induced by this should be small as the processes relevant here have zero or small NH_3 emissions. Major contributions to global NH_3 emissions stem from livestock farming. The acidification potential factors indicated in [Pehnt 2002] are used here (SO_2: 1; NO_x: 0.7). The results are shown in Figure 4-2.

The emissions of NO_x and NH_3 lead to a eutrophication of waters. As described in the above paragraph, NH_3 is not taken into account here. Again, the error induced by this should be small. The eutrophication potential is indicated as PO_4^{3-} equivalent. The eutrophication potential factor of NO_x is 0.13 [Pehnt 2002]. The results are shown Figure 4-3.

Figure 4-2: **Life cycle acidification (SO_2 equivalent) of onboard power supply of case ship 1**

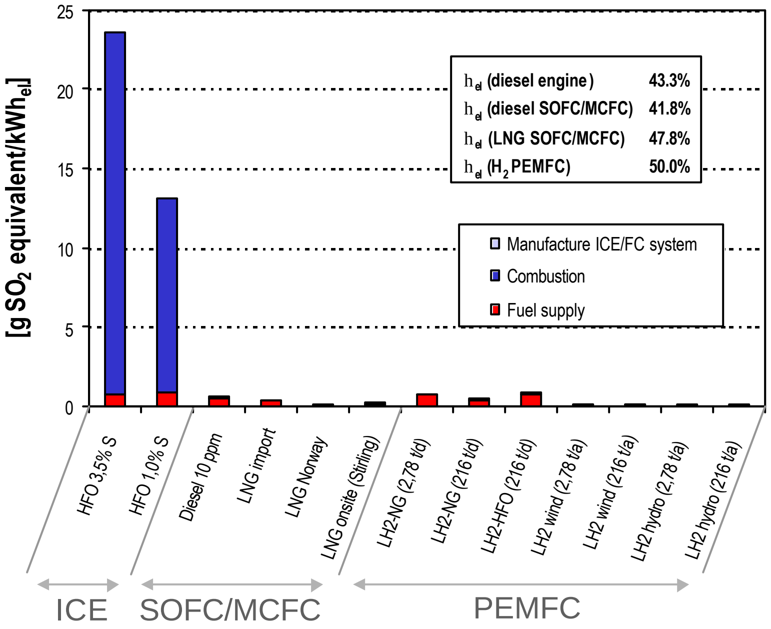
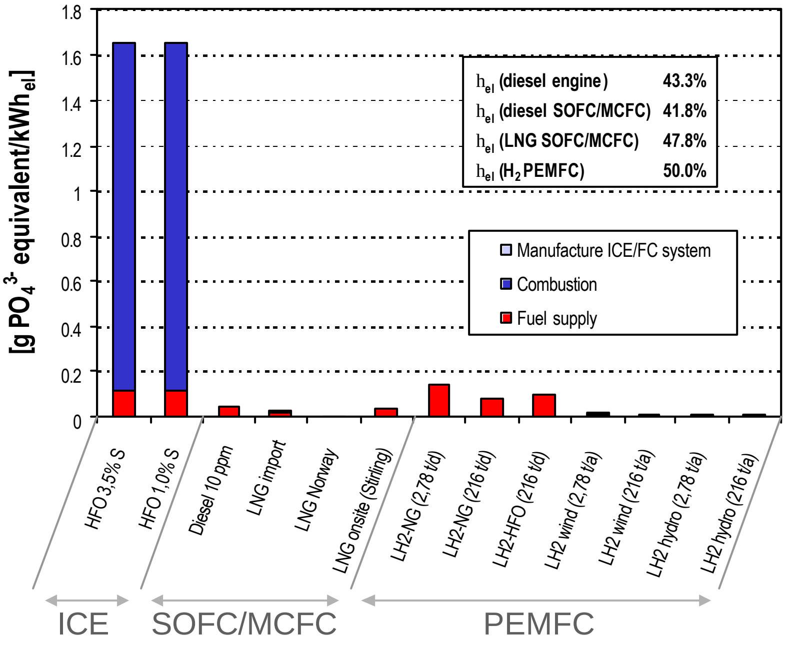


Figure 4-3: **Life cycle eutrophication (PO_4^{3-} equivalent) of onboard power supply of case ship 1**



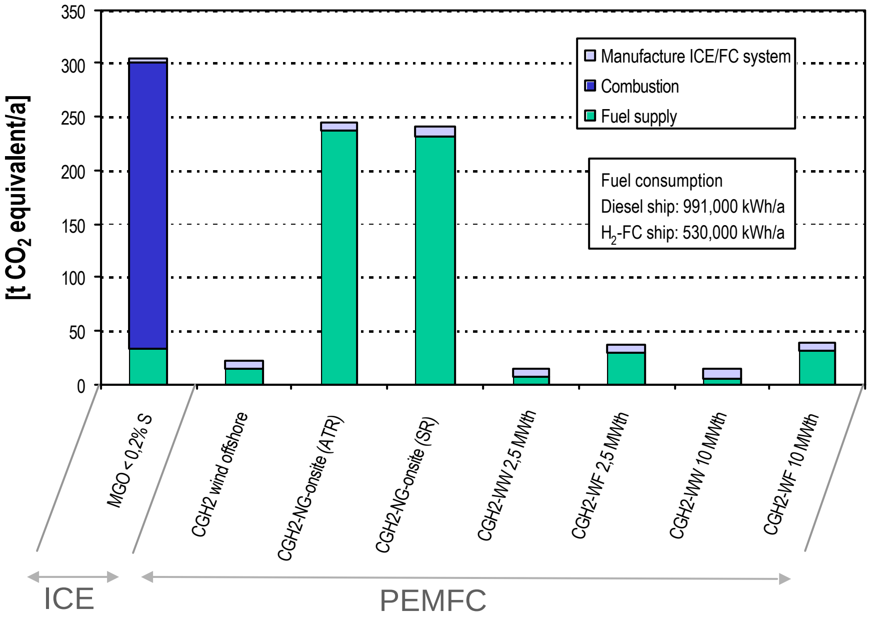
Over 90% of the acidification potential and of the eutrophication potential stem from fuel combustion in conventional engines. Impacts of fuel production and supply and of system manufacturing are very low. This is due to the high sulfur content of conventional ship fuels and the high NO_x emissions in conventional fuel combustion.

For fuel cell systems, sulfur emissions from system operation are zero because of essentially zero sulfur content in fuels used. NO_x emissions from system operation is also essentially zero because of the low operating temperatures of fuel reformers for high temperature fuel cells. Low-temperature hydrogen powered PEM fuel cells are truly zero emission. The main contribution to full fuel cycle sulfur and NO_x emissions stems from auxiliary electricity consumption in fuel production and supply.

4.2 Case ship 2

Figure 4-4 shows the annual GHG emissions of case ship 2 in terms of CO_2 equivalent.

Figure 4-4: Annual life cycle GHG emissions from the operation of case ship 2



A major difference between case ship 1 and case ship 2 is the differing operating profile of the two ship types. While in case ship 1 the onboard electricity generation is always operated close to 100% rated power, the propulsion of case ship 2 often operates at part load. While the efficiency of combustion engines is maximal at rated power and decreases towards part load, the efficiency of fuel cells is higher at part-load than at full load. Therefore, operating profiles with high part-load shares favor fuel cells.

This effect can be observed in Figure 4-4: Overall GHG emissions for natural gas derived hydrogen powering PEM fuel cells are around 20% lower than those of the conventional combustion engine powered by marine gas oil (MGO) in spite of the energy requirements of hydrogen generation from natural gas and of hydrogen compression. This is further enhanced by the lower carbon content per energy content of natural gas compared to MGO.

Figure 4-5 shows the acidification potential of case ship 2 in terms of SO_2 equivalent.

Figure 4-5: Acidification: annual life cycle SO_2 equivalent emissions from the operation of one ship (case ship 2)

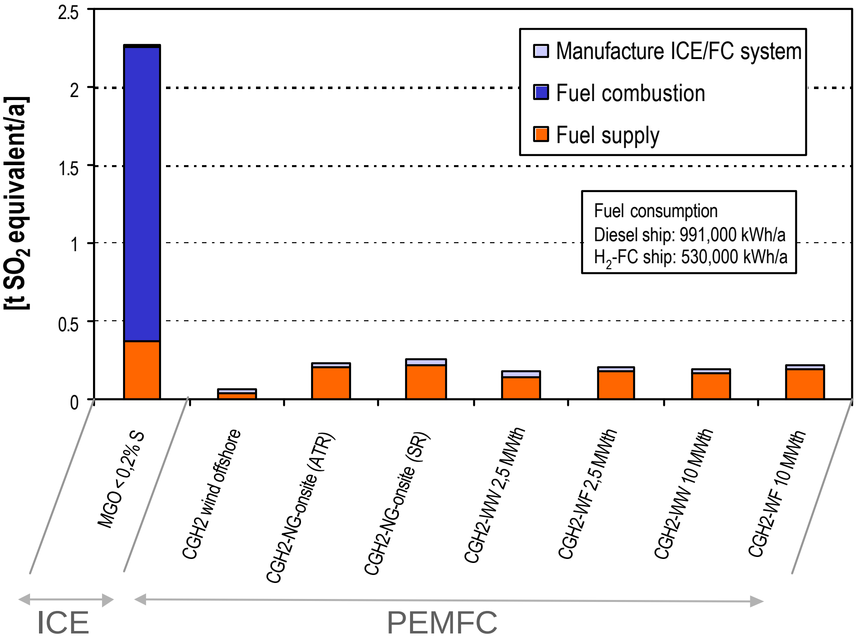
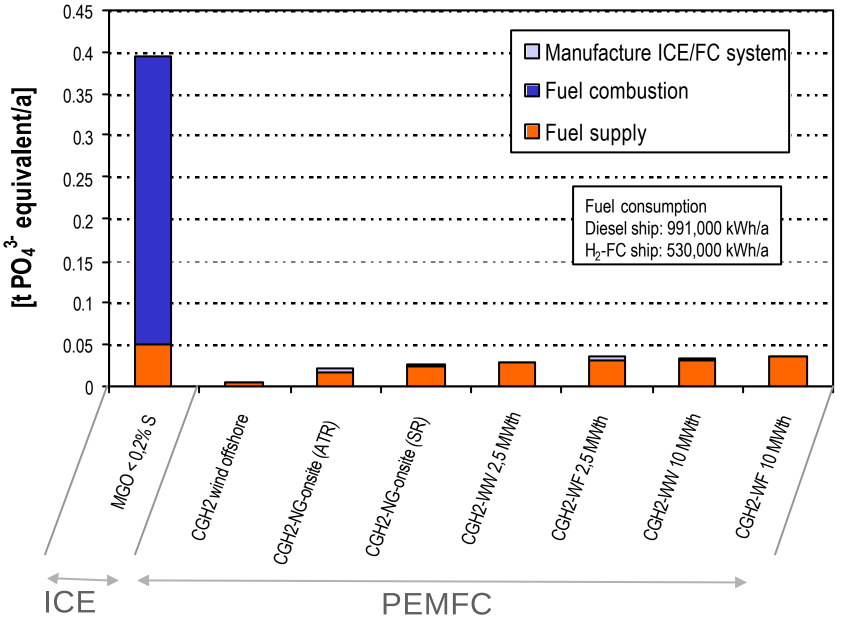


Figure 4-6 shows the eutrophication potential of case ship 2 in terms of PO_4^{3-} equivalent.

Figure 4-6: Eutrophication: annual life cycle PO_4^{3-} equivalent emissions from the operation of one ship (case ship 2)



The giant share of the acidification potential and of the eutrophication potential stem from fuel combustion in conventional engines. Impacts of fuel production and supply and of system manufacturing are low. To a certain extent this is due to the sulfur content of the conventional ship fuel and to a large extent to the high NO_x emissions in conventional fuel combustion.

For fuel cell systems, sulfur and NO_x emissions from system operation are zero. The main contribution to full fuel cycle sulfur and NO_x emissions stems from auxiliary electricity consumption in fuel production and supply.

5 COST ANALYSIS OF FUELS

Fuel production and supply costs depend on various factors, not the least important being the industrial context. The conventional fuels are well-established and available at all ports. The same will be true for advanced conventional fuels such as reduced-sulfur HFO or sulfur-free car diesel, which will be introduced to the road transport markets on a broad scale in Europe starting in 2005 and which will therefore be in principle also available for ships. Natural gas is also widely available, though not in all parts of Europe. It is definitely not available at all ports, and in liquefied form it is only available at selected spots of Europe. Hydrogen is available at few locations in Europe. Both LNG and LH_2 can be made available to ships, but they are definitely not established ship fuels.

At present, hydrogen is a chemical commodity, not a transport fuel. The industrial context of hydrogen fuel does not exist and consequently all cost projections have to be based on a future industrial scenario. Assuming niche markets for hydrogen only, production and supply costs will not be significantly different from today’s high prices of this chemical commodity supplied by industrial gas companies to the various small industrial consumers.

In a scenario of large scale introduction of hydrogen as transport fuel, costs will be significantly lower than today for applications such as passenger cars, as the commercial and logistic structures will be entirely different. For large ship applications infrastructures will be similar to today’s structures of captive hydrogen production and consumption. Very large amounts of hydrogen will be produced near the point of consumption. Today these are refineries or ammonia plants, in the future these may include ports.

For the present analysis, the following assumptions have been made for the cost estimates for a time frame of 2010 and beyond:

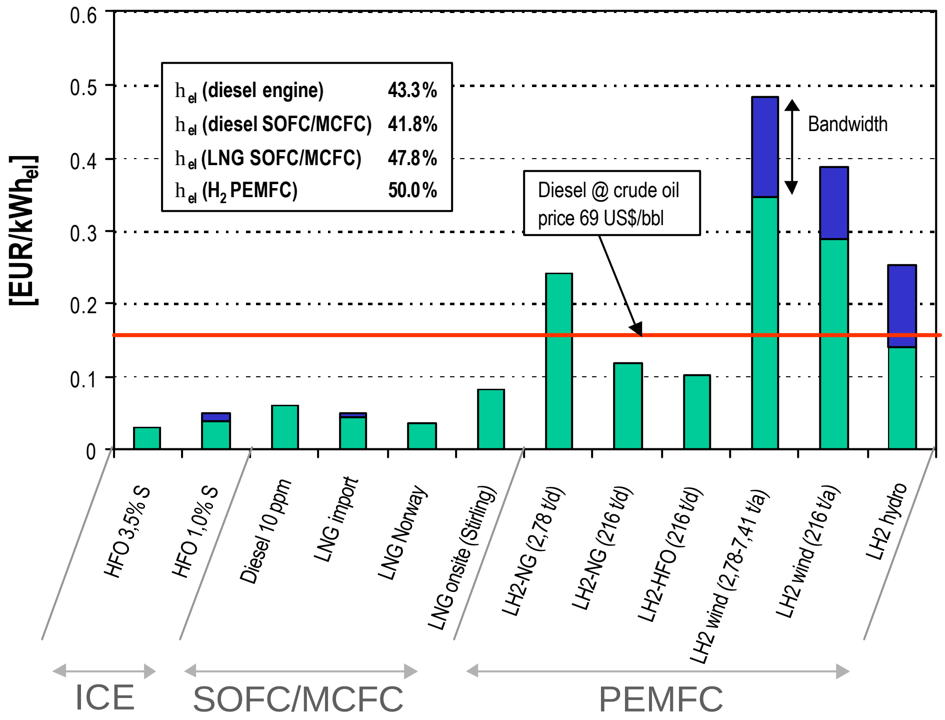
- For conventional HFO market prices have been used as the benchmark based on crude oil prices of 20-25 US-$ per barrel.
- For reduced-sulfur HFO additional costs for desulfurization based on [Beicip 2002] have been applied to HFO market prices.

- For sulfur-free car diesel market prices have been assumed based on crude oil prices of 20-25 US-$ per barrel. In order to span the historical crude oil prices, a red line indicating diesel costs calculated on the basis of a crude oil prices of 69 US-$/bbl, the annual average price in 1981 in real terms of 1995, are included in Figure 7.
- For LNG, different pathways have been analyzed. For LNG from remote locations and from Norway, market prices at import terminals have been used. These were cross-checked by full cost calculations for new installations giving consistent results. Onsite natural gas liquefaction was based on natural gas prices in Germany. For the rest of the supply chains (transport, storage etc.), cost calculations were made.
- For LH_2 from heavy fuel oil at the refinery and for LH_2/ CGH_2 from natural gas full cost calculations have been made based on low price assumptions for HFO and based on German gas prices, respectively.
- For LH_2/ CGH_2 from renewable electricity, full cost calculations have been made based on industry electricity prices in Iceland for hydro power and based on a full cost calculation for offshore wind power, respectively.
- For CGH_2 from biomass, full cost calculations have been made based on waste wood prices and wood farming costs from various literature sources.

As a result of the cost analysis production and specific supply costs relative to the energy content of the fuel have been calculated. As there are, however, relatively strong differences in the fuel consumption of the various systems, costs have been translated into electricity production costs. Figure 5-1 and Figure 5-2 present costs of electricity supply induced by the fuel; costs of power units, fuel storage etc. onboard the ships are not included.

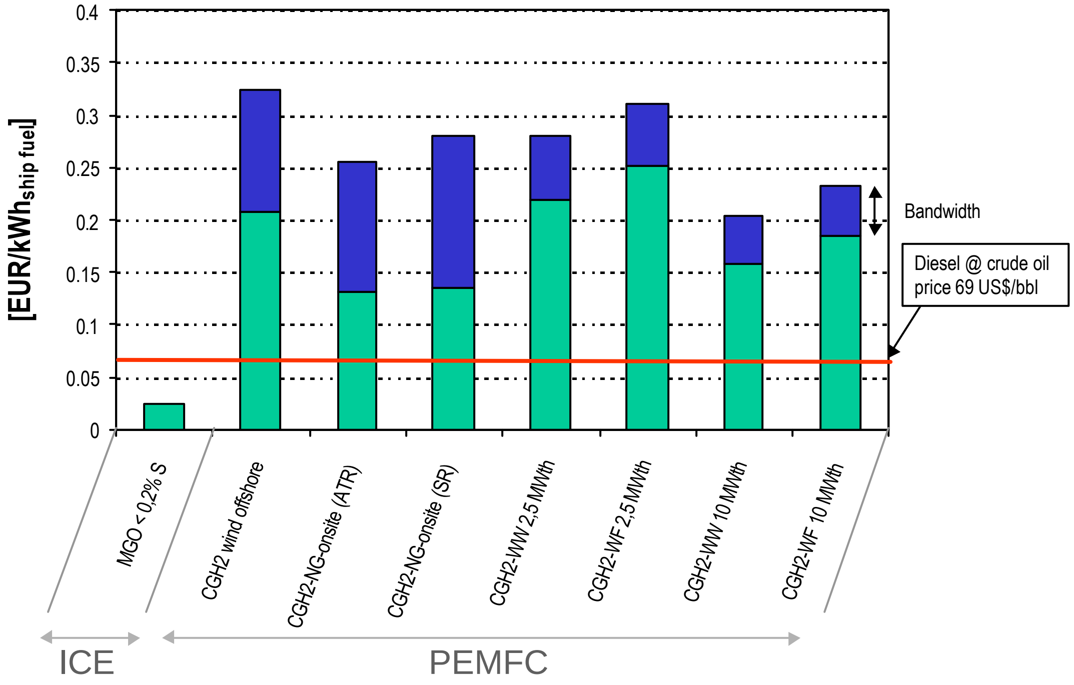
For many of the fuel production and supply paths several variants have been calculated resulting in the bandwidths presented in Figure 5-1 and Figure 5-2 [LBST 2004]. Hydrogen liquefaction costs for example depend heavily on the size of the liquefaction plant. The upper end of the costs results from small installations only supplying one ship of the case ship 1 type. The lower end is achieved assuming large plants supporting several ships or one ship and a number of other large-scale customers.

Figure 5-1: **Costs of electricity supply onboard case ship 1 based on crude oil prices of 20-25 US-$ per barrel; costs of power units, fuel storage etc. onboard the ships are not included**



For case ship 2, synergies with hydrogen filling stations for road transport have been assumed for the lower end of the costs. Here, learning curve effects for the construction of 1,000 hydrogen filling stations are taken into account, while the upper values assume the costs of the “first” filling station. For offshore wind power, installation costs and electricity transport costs have been varied. For the biomass gasification units of different sizes, the “first” unit has been assumed for the higher end of the costs, and the 20th unit has been assumed for the lower end.

Figure 5-2: **Annual fuel costs of case ship 2 based on crude oil prices of 20-25 US-$ per barrel; costs of power units, fuel storage etc. onboard the ships are not included**



6 PORTFOLIO PRESENTATION OF COSTS AND GREENHOUSE GAS EMISSIONS

A portfolio presentation of the main results of the present analysis includes costs and GHG emissions of all options in one graph. This allows to easily judge each option compared to the benchmark with respect to the two major aspects.

Figure 6-1 presents this portfolio presentation for case ship 1, Figure 6-2 for case ship 2. In order to span the historical crude oil prices, diesel costs calculated on the basis of a crude oil prices of 69 US-$/bbl, the annual average price in 1981 in real terms of 1995, are included in the figures.

Figure 6-1: Portfolio presentation of fuel costs (based on crude oil prices of 20-25 US-$ per barrel with indicative diesel price based on 69 US-$/bbl) versus greenhouse gas emissions of the various fuel/ electric generating system options for case ship 1

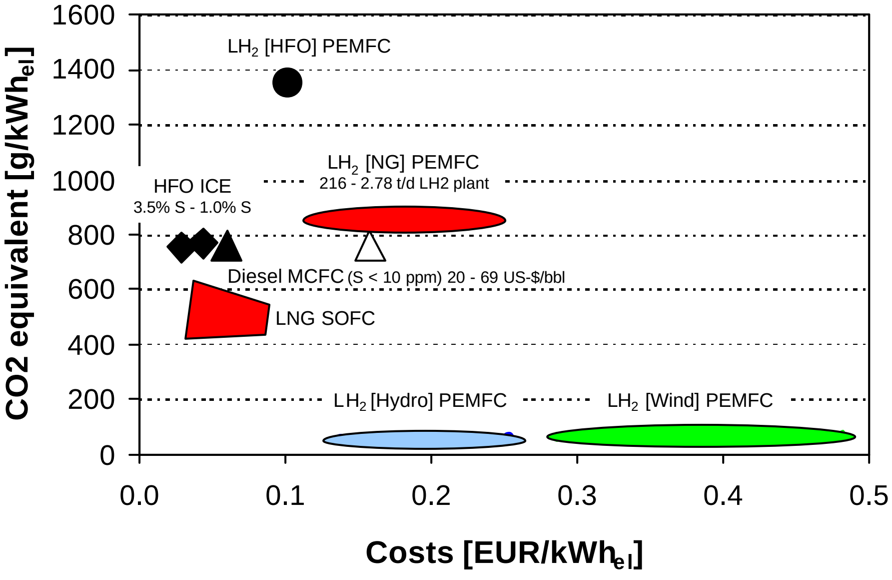
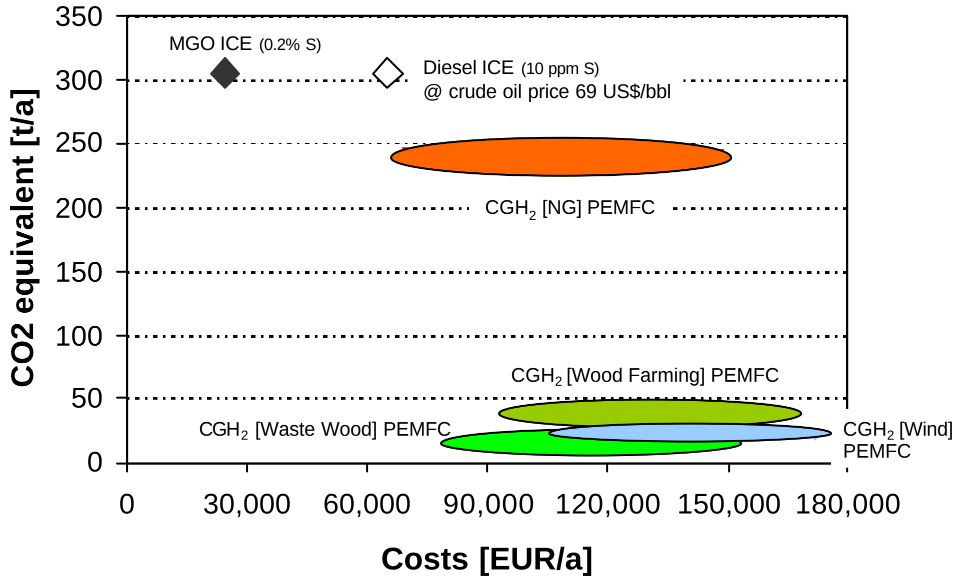


Figure 6-2: **Portfolio presentation of annual fuel costs (based on crude oil prices of 20-25 US-$ per barrel with indicative diesel price based on 69 US-$/bbl) versus greenhouse gas emissions of the various fuel/ propulsion system options for case ship 2**



7 LIFE CYCLE INTERPRETATION

7.1 Limitations and open issues

This study integrating the results of several sub-studies in the FCSHIP project is the first Life Cycle Analysis including all stages of fuel cells onboard ships.

It has several limitations and shortcomings, which limit its explanatory power and at the same time indicate areas of further studies.

- Some potential alternative fuels for fuel cells have not been considered here. Most prominent examples are ethanol, plant oil, fatty acid methyl esters (FAME), synthetic fuels (e.g. Fischer-Tropsch diesel from natural gas or biomass) and methanol.
- Availability potentials have not been analyzed, neither for fossil fuels nor for renewable fuels. For strategic decisions of future fuel options, this aspect may prove essential for some fuel options.
- Available data on fuel cell manufacturing are rather limited, restricting exactness and the reliability of this analysis of this stage. In addition, the assessment of future technology advances is difficult as fuel cells in general are not yet in a stage of commercial availability. Commercial MCFC prototypes for stationary applications are available, but not suitable for marine applications due to excessive weight and volume. SOFC technology is some years behind, being developed for stationary applications mainly. PEM fuel cells being developed mainly for automotive applications and small stationary applications. First fleets of demonstration fuel cell vehicles are emerging at present.
- Development activities of fuel cells for marine applications are very limited thus far in Europe. Significant assumptions on technology adaptations for marine applications had to be made. This includes assumptions on weight and volume as well as on performance (efficiency, capability of following power demand etc.).
- The analysis is limited to two case ship types (large passenger ferry, small commuter ferry) and two applications (hotel load, propulsion). Even though this should span a large portion of the entire spectrum with

respect to environmental impacts, there a large number of other ship types and potentially further applications, which might be more promising commercially. Environmental impacts and cost issues of other ship types and applications cannot easily be derived from the present analysis.

- The cost analysis should be extended to include a sensitivity analysis, especially in view of highly volatile and potentially further rising fossil fuel prices.

7.2 Conclusions

The conclusions drawn here have to be seen in the light of the limitations discussed above.

It has to be emphasized that only a full Life Cycle Analysis, including fuel supply and ship operation, gives meaningful results. Supply-only results give misleading conclusions as emissions of fuel supply and fuel use have to be added, and because differences in the efficiencies of the onboard conversion technology (engine versus fuel cell) give different weight to fuel supply emissions even if the same fuel is chosen.

Because of the operational profile, the rated power and the difference in efficiency between the conventional engine and the fuel cell, case ship 2 is similar to a city bus. Not astonishingly, GHG emission and cost estimates are similar for both applications.

Case ship 1 on the other hand is rather similar to a long-haul truck: Power requirements are close to 100% over long periods of time, and the efficiency at rated power of the conventional engine and the fuel cell are comparable.

Fuel cell efficiencies assumed here are rather conservative values which have already been demonstrated in prototype systems. Fuel cells have the potential for further efficiency improvements, which would translate into further reductions of greenhouse gas emissions for fossil based fuels. The efficiency improvement potential is especially high for hybrid systems combining fuel cells with gas turbines.

7.2.1 Emissions

Fuel cells reduce pollutant emissions (SO_2, NO_x, particulate matter etc.) and related environmental impacts (acidification, eutrophication) drastically independent of the fuel chosen. Only SO_2 emissions of a small ship (case ship 2) are not reduced by natural gas derived hydrogen if the European electricity mix is used for auxiliary power and for hydrogen compression as assumed here. Using for example the German electricity mix would reduce SO_2 emissions by more than a factor of two.

Greenhouse gas emissions can be reduced using natural gas fuel for high temperature fuel cells by 25% to 40% in the onboard power supply of a large ship (case ship 1). In this application, natural gas derived hydrogen does not reduce GHG emissions. Tapping the full fuel cell efficiency potential in the future would result in greenhouse gas emission reduction also through the use of natural gas derived hydrogen. GHG emissions are reduced to almost zero by using renewable hydrogen.

Because of the significantly higher efficiency of the fuel cell compared to the conventional engine in a small ship (case ship 2), even natural gas derived hydrogen reduces GHG emissions by 20%. GHG emissions are reduced to almost zero by using renewable hydrogen.

7.2.2 Economics

Ship fuels are exempt from taxes. Therefore, conventional ship fuels are extremely sensitive to variations in crude oil prices. In real terms of 1995, annual average crude oil prices over the last three decades have ranged from 12 to 69 US-$ per barrel [WETO 2003].

Reducing the sulfur content of heavy fuel oil from the average 2.5% in the EU to 1.0% would entail additional costs of 50 to 90 EUR per ton; in 2002, prices for high sulfur heavy fuel oil were around 140 to 145 EUR/t.

At oil prices of 20-25$/bbl (current prices are around 40$/bbl), only liquefied natural gas supplied to a large ship (case ship 1) is in the range of cost competitiveness to conventional or reduced-sulfur ship fuels. At historically high oil prices, fossil-based hydrogen and eventually renewable hydrogen become cost competitive.

Liquefied natural gas fuel is close to competitiveness with conventional fuels at oil prices of 20-25 $/bbl, depending on the LNG supply path. Depending on the efficiency advantage of fuel cells compared to conventional engines, LNG becomes competitive.

Fossil hydrogen based on natural gas or heavy fuel oil is more expensive at current oil prices, but becomes competitive in large ships (case ship 1) at historically high oil prices. Natural gas based hydrogen supplied to a small ship (case ship 2) comes close to competitiveness at historically high oil prices. Here, further cost reductions are required. These may be achieved by supplying multiple ships on the same spot leading to economies of scale in the hydrogen production and supply facility.

Renewable hydrogen is significantly more expensive at oil prices assumed here, but comes close to competitiveness in a large-scale scenario at historically high oil prices in large ships (case ship 1). Renewable hydrogen supplied to a small ship (case ship 2) comes close to competitiveness at historically high oil prices. Here, further cost reductions are required. These may be achieved by supplying multiple ships on the same spot leading to economies of scale in the hydrogen production and supply facility, and eliminating/ reducing the need for expensive hydrogen pipelines.

7.3 Recommendations

Based on the Life Cycle Analysis and cost analysis results several recommendations for improving cost effectiveness and further reduction of the environmental impacts of fuel cell ships are made.

Reductions of sulfur emissions with related acidification impacts are reduced by using reduced-sulfur or sulfur-free fuels independent of the conversion technology considered (combustion engine or fuel cell). Fuel cells require sulfur-free fuels for direct use or for reforming into hydrogen-rich gases. Using sulfur-containing fuels for reforming would require a technical complexity onboard the ship which seems prohibitive. The first and most cost effective step, which to a certain extent is done by the European commission and by IMO at present, is the drastic reduction of sulfur levels in conventional marine fuels.

Reforming systems have extremely low NO_x emission levels with related low acidification and eutrophication impacts. In general, fuel production and supply also has very low NO_x emission levels. Even though options for the reduction of NO_x emissions of conventional ship propulsion and electricity generating systems have not been studied here a conclusion by analogy from stationary and automotive applications is that advanced conventional technology (exhaust gas treatment, internal measures) is the first and most cost effective means of NO_x emission reduction. For some fuel supply paths using relatively large amounts of auxiliary electricity (e.g. compressed hydrogen from natural gas or wood) NO_x emissions stemming from combustion processes for electricity generation are relatively high, even though still factors smaller than current NO_x emissions from ship operation.

For large ship applications greenhouse gas emission reductions can only be achieved through natural gas fuel or renewable energy derived hydrogen as ship fuel at the fuel cell efficiencies assumed here. As large ship engines are very efficient, both fuel cells and internal combustion engines powered by natural gas probably allow for similar GHG emission reductions (natural gas powered combustion engines have not been analyzed here). Potential future efficiency improvements of fuel cells would result in further greenhouse gas emission reductions using fossil based fuels. Depending on the crude oil prices, costs of LNG are similar to slightly higher. Consequently, a cost efficient means of reducing GHG emissions from large ships would be the establishment of liquefied natural gas as marine fuel.

In small ships and boats, greenhouse gas reductions can be achieved by natural gas or renewable energy derived hydrogen powered fuel cells. Costs of hydrogen are high as long as single ships are supplied. Providing hydrogen fuel to a fleet of ships or to additional consumers such as fuel cell road vehicles (e.g. city buses) will most probably allow for significant cost reductions.

The above listed issues show that fuel cells are not the most immediate solution to environmental impacts of ship activities. It has to be emphasized, though, that fuel cells have the potential to intrinsically eliminate all environmental impacts caused by gaseous emissions at the same time. Therefore, from an environmental perspective, the development of fuel cell technology for marine applications is strongly recommendable. Dedicated developments of marine fuel cells will allow to exploit the full potential of the technology. Important synergies with stationary applications (large ships) and automotive applications (small ships and boats) should be used.

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