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A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application

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Abstract

The study performed a life cycle assessment (LCA) of a molten carbonate fuel cell (MCFC) plant for marine applications. The results are compared to a benchmark conventional diesel engine (DE) which operates as an auxiliary power generating unit. The LCA includes manufacturing of MCFC and DE, fuel supply, operation and decommissioning stages of the system's life cycle. As a new technology in its very early stages of commercialisation, some detailed data for the FC systems are not available. In order to overcome this problem, a series of scenario analysis has also been performed to evaluate the effect of various factors on the overall impact, such as change in power load factors and effect of recycling credit at the end of life cycle. Environmental benefits from fuel cell operation are maximised with the use of hydrogen as an input fuel. For the manufacturing stage of the life cycle, input material and process energy required for fuel cell stack assemblies and balance-of-plants (BOP) represent a bigger impact than that of conventional benchmark mainly due to special materials used in the stack and the weights of the BOP components. Additionally, recovering valuable materials through re-use or re-cycle will reduce the overall environmental burden of the system over its life cycle.

Keywords: Fuel cell; Fuel cell manufacturing; Molten carbon fuel cell; Diesel engine manufacturing; Life cycle analysis

1. Introduction

As a new and promising technology, fuel cells have increasing popularity primarily in power provision due to their pollutant free operation when hydrogen is used as a fuel. FC technology demonstrates a certain level of acceptance and use in land-base applications with different research interest on both its construction technology and operating parameters [1]. However, because of the novelty of the product and its subsequent limitations such as commercialization, scale, fuel supply issues, its use in the commercial shipping industry is currently non-existent. Nevertheless, continuously increased need for emission reduction in shipping operations provides a prospect for research efforts for addressing various maritime specific issues of the technology. In the meantime, potential benefits of the on-board FC technology should also be evaluated against its environmental impacts from manufacturing, fuel supply, and end-of-life characteristics throughout its operational life. As an integral part of new technology assessment, life cycle assessment (LCA) plays an important role in evaluating the environmental performance.

The main objective of the study is to quantify and analyse the life cycle environmental impacts of a MCFC system to be used for a power supply on-board a ship, and its comparison with a conventional marine DE as a benchmark. Due to considerably large power requirements for propulsion, the study focuses on the analysis of a conceptual MCFC against an existing DE for auxiliary power generation of a passenger ferry (case ship) for open sea operations. The main propulsion of the case ship is supplied by diesel engines.

The LCA analysis covers the energy requirements, emissions of greenhouse gases (GHG) and air pollutants during the manufacturing, fuel supply, operation, and end-of-life stages of the MCFC and the DE systems in the case ship. Greenhouse gas and pollutant emissions related to the manufacturing of high temperature FC, are analysed with conventional and sulphur-free car diesel with detailed production path from “cradle-to-gate” for each fuel.

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LCA is a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system through all stages of its life cycle [2]. The typical life cycle of a product is a series of stages originated from the extraction of raw materials, manufacturing, transport, operation, maintenance, re-use, and decommissioning. The assessment of the potential environmental impacts of the systems has been performed based on the methodological framework as outlined in the ISO14040 standard [3].

2. Fuel cell technology for ships

Fuel cell technology has been used successfully in aerospace engineering, automotives, power plants and navy ships. Although the application of fuel cell and associated R&D activities for commercial ships have been very limited, technical feasibility of using fuel cells for ship propulsion and auxiliary power has been demonstrated by the successful application in navy vessels. Following the success of navy application, rational use of energy source, demand of environment protection system viability and performance of using a commercially acceptable fuel have been the recent research interest in fuel cell development and application on commercial ships.

Among the currently available fuel cell technologies, MCFC and PEMFC are considered as the most promising options for marine applications. MCFCs operate at a high operating temperature (650 °C) with a high tolerance to air contamination and carbon monoxide, a contaminant found in the fuel. However, it is sensitive to sulphur or sulphur compounds in hydrocarbon fuels. The high temperature allows the use of non-noble catalysts. The catalysts are insensitive to certain degree of fuel contaminant which often damages other type of fuel cells, MCFCs in principle may use a range of gaseous fuels, such as natural gas, biogas or coal gas. A comparison of MCFC and PEMFC with conventional marine power systems is given in Table 1 [4].

The main challenges of applying fuel cells in marine environment are to satisfy the requirement of quick dynamic response, high power density related to weight and size, tolerance to salt air, shock resistance, quick start and load responding characteristics. Other aspects such as fuel type, efficiency, reliability, maintainability, cell life duration, marine environment pollution, anti-shock, vibration and ship motions should also be considered. Apart from the technical performance of fuel cells, capability of using commercially available fossil fuel, instead of pure hydrogen, is another challenge of fuel cells' application on commercial ships. It has been anticipated that, due to the low volumetric energy density of hydrogen, its use in fuelling FCs in commercial shipping will be limited to inland waterways and coastal waters in the future [5].

In order to make fuel cells a viable option for commercial ships, traditional marine fuels have to be considered as the first choice of fuel. This requires a fuel reformer to extract hydrogen from marine fuels by undergoing a series of chemical processes. Fig. 1a presents a fuel cell system with a fuel reformer. Fuel reforming can be performed at a centralised plant on-site at the fuelling port, or onboard ship or a combination of them. Components of the DE systems are also presented in Fig. 1b.

The development of reformer technology plays an important role in the application of fuel cells in marine applications. Currently there are two main fuel reforming concepts considered viable in marine applications. The first concept is to use conventional hydrocarbon processing techniques for the production of clean reformat for the fuel cell. In the alternative system, a high temperature metal membrane is used to separate hydrogen from the hydrocarbon fuel. Although initial analysis has shown the advantages of membrane system in efficiency and light weight, this technology is still under development. In the case of reformer, the efficiency is defined as

$$\eta_{\mathrm{ref}} = \mathrm{LHV}_{\mathrm{out}}/\mathrm{LHV}_{\mathrm{in}} \tag{1}$$

where η_{ref} is the reformer fuel conversion efficiency, $\mathrm{LHV}_{\mathrm{out}}$ the lower heating value of output product and $\mathrm{LHV}_{\mathrm{in}}$ is the lower heating value of input reactant.

Overall system efficiency is the key factor for reduced emissions from the FC. An efficient fuel processing, fuel utilisation and power conditioning are linked to the environmental effects. The overall efficiency of the system is defined as

$$\eta_{\mathrm{eff}} = \eta_{\mathrm{fp}}\eta_{\mathrm{fc}}\eta_{\mathrm{pc}} \tag{2}$$

where η_{eff} is the overall system efficiency, η_{fp} the fuel processing efficiency, η_{fc} the fuel cell efficiency and η_{pc} is the power conditioning efficiency.

3. LCA modelling

The existing auxiliary power system on the case ship consists of 3 units of diesel installation, each of 1000 kW at 900 rpm, with a specific weight range of 17.5–20.5 kg kW^{-1}. The power output of the MCFC selected for the conceptual design is 500 kW per unit.

A model of generic MCFC system was developed. Fuel cell stacks and BOP components under the study are using the state-of-the-art materials and manufacturing process technology. A LCI of this conceptual design has been established. Verification of selected materials and processes as well as energy inputs by FC manufacturers has also been performed.

3.1. Scope of the study

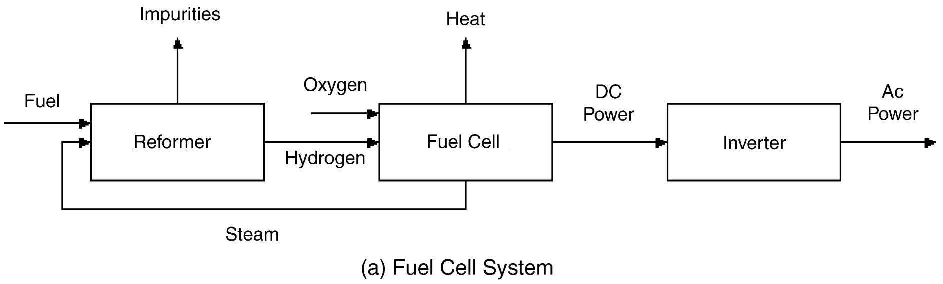
Table 2 and Fig. 2 outline the scope and boundary of the study, including the principle stages of the life cycle of the systems to be investigated.

In addition to the scope of the study outlined above, the following assumptions are made in the LCA modelling:

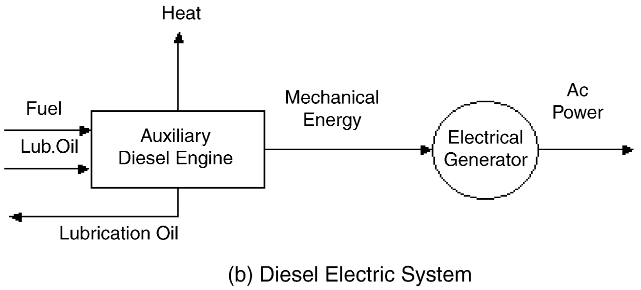
- The energy and materials input required for manufacturing equipment, i.e. capital goods used in the production of the FC system, is not considered.
- The environmental impacts associated with the transport of materials for FC manufacturing are not considered.
- The planar design of MCFC is considered.
- Annual operating duration of a single DE in the case ship is about 6000 h.

Table 1
Comparison of Marine Power Systems

Criteria	MCFC	PEMFC	Diesel	Gas turbine
NO_x, CO, HC emissions, CO_2	Very low, reduced CO_2	Very low, reduced CO_2	Medium, reduced NO_x with emulsified fuel, no CO_2 benefit	Medium, no CO_2 benefit
Power range	500–2500 kW, modular	20–2500 kW, modular	Up to 68 MW	Up to 50 MW
Noise, vibration	Low	Low	High	Medium
Thermal efficiency (%)	40–55	39–42	30–35	25–30



(a) Fuel Cell System



(b) Diesel Electric System

Fig. 1. Components of compared systems.

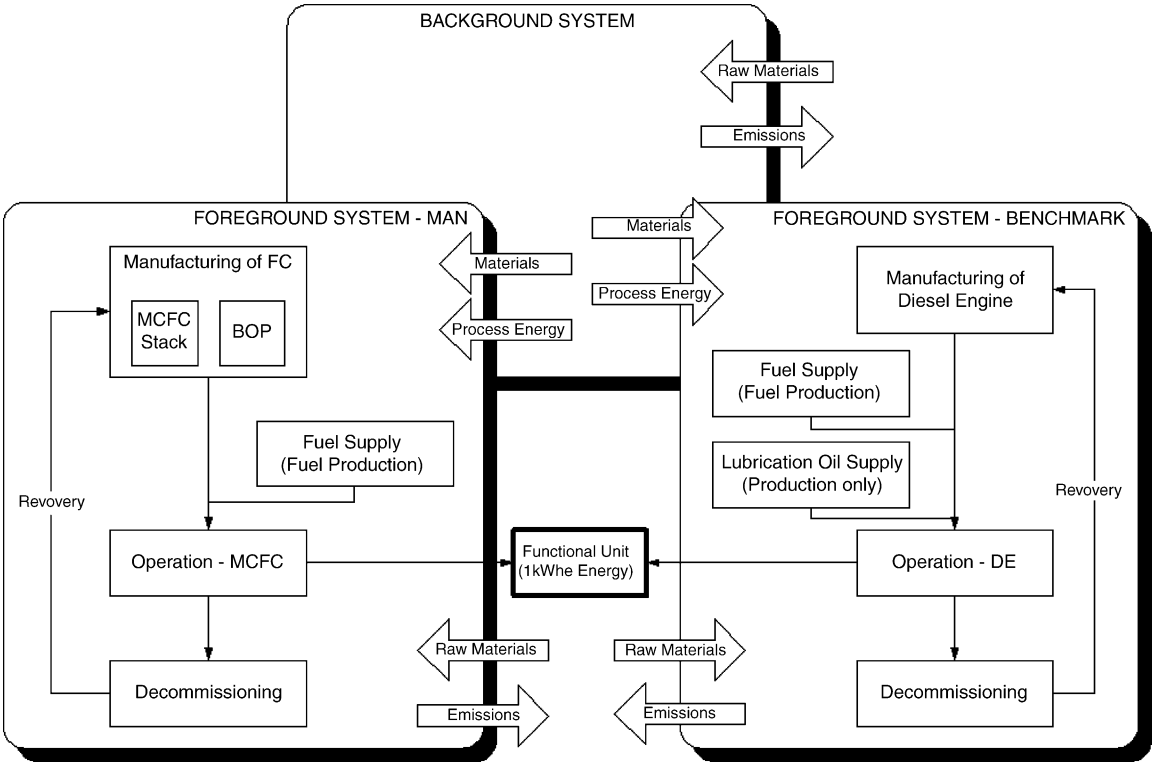


Fig. 2. System boundaries of the LCA study.

- Due to FC specific operational characteristics, annual operating duration of MCFC system is assumed to be 8700 h.
- Operating lifespan of the MCFC stack is assumed to be 43,500 h, i.e. 5 years, and that for the DE is 20 years.
- In order to compare the systems, lifetime of the MCFC system (casing and BOP) is also considered as 20 years with periodic replacement of FC stacks every 5 years, i.e. four stacks during the lifetime. Hence, the total operating hours during the 20 years of life cycle is 120,000 h for both systems.
- LCI of the fuel oil and lubrication oil supply paths are cradle-to-gate values and exclude fuel transport to ship.
- FC Stack fuel utilization coefficient = 85% [6].
- Diesel reformer efficiency = 85% [7].
- Electric generator efficiency = 98% [7].
- Specific lubrication oil consumption for = 0.7 g kWh^{-1} [8].
- Functional unit is 1 kWh of electricity generated by the system.

3.2. LCA study

3.2.1. Production of fuels

In the Case ship, as a conventional benchmark, low sulphur fuel oil (LSFO) with sulphur content 0.6% is used in the DE for auxiliary power generation. Whereas, fuel chosen for the MCFC is the low sulphur car diesel fuel ($S < 10$ ppm) since sulphur free in fuel is essential to ensure FC's performance.

Lubrication oil consumption for the same operating conditions as in auxiliary diesel engine has also been modelled in the LCA. In the input materials stage of the LCA model, cradle-to-gate values for the production of heavy fuel oil (HFO) and the low sulphur diesel oil are used from an LCA software database [9]. Input data for the production of fuel and lubricating oil is presented in Table 3.

3.2.2. Manufacturing

3.2.2.1. Diesel engine. Basic life cycle inventory (LCI) for manufacturing of a generic DE is developed on measurements data supplied from an engine manufacturer. The data cover energy inputs to the factory, including the marine diesel oil and heavy fuel oil for engine testing, and emissions from the manufacturing.

Table 2
Summary of the study scope

Life cycle stage	DE	MCFC
Manufacturing	Engine Block manufacturing: material inputs; production processes	FC Stack, Casing, and BOP manufacturing: material inputs; production processes
Fuel production and supply		
Fuel production	Fuel oil production; lubrication oil production	Diesel oil production
Fuel supply	N/A	N/A
Operation	Load factor = 1 (baseline scenario); LF scenarios	Load factor = 1 (baseline scenario); LF scenarios
Repair and maintenance	N/A	N/A
Decommissioning	Recycling credits for manufacturing material inputs	Recycling credits for manufacturing material inputs

Table 3
Input data for the production of fuel and lubricating oil

Substances	Outputs (free refinery values for 1 kg oil produced)			
	HFO (1.4%S)	LFO (0.2%S)	Diesel (0.05%S)	Lubricating oil
CO_2 (kg kg^{-1} fuel)	0.35109	0.3449	0.3449	0.68812
CO (g kg^{-1} fuel)	0.60928	0.64572	0.64572	0.7442
NO_x (g kg^{-1} fuel)	1.8103	1.9206	1.9206	2.1921
SO_2 (g kg^{-1} fuel)	0.84228	0.83693	0.83693	1.5602

The weight of the DE used in the study is estimated at 15.2 kg kW^{-1} (dry weight, excludes flywheel and pumps) by averaging the data from set of DEs within the similar power range (900–1500 kW) with a speed range of 900–1000 rpm from various manufacturers. Alternator weight is assumed to be 30% of the dry engine weight, and further 15% allowance (2 kg kW^{-1}) has been made for scrap and manufacturing losses.

During the testing stage of engine manufacturing, 0.350 kg kW^{-1} of marine diesel oil (MDO) and 1.886 kg kW^{-1} of heavy fuel oil (HFO) is consumed. During the manufacturing of DE, the following energy sources are used for per kW engine output: electricity from national grid = 0.0072 MWh, heating from city network (produced with coal only) = 0.0074 MWh. Energy inputs and emissions for electricity and heat are used from a LCA software database [9].

3.2.2.2. MCFC stack and components. In the study, analysis of the manufacturing of the MCFC system is divided into two sections.

The first section is fuel cell stack manufacturing. This stage includes the manufacturing of electrodes, electrolyte and interconnect with the BOP. Only limited information is available on the production of MCFC stacks.

The second stage is BOP manufacturing including the manufacture of all other components in the MCFC system, as well as the casing.

In order to overcome the problem of lack of reliable data for MCFC stacks, an alternative approach is followed. According to this, a generic MCFC system that will accomplish the requirements of the case ship auxiliary power demand is defined for the LCA study purposes, and that of the LCI is resulted by using the state-of-the-art materials and manufacturing processes. The main characteristics of the MCFC stack used in the model are:

- power density = 0.1 W cm^{-2};
- electrode area = 10,000 cm^2 (single cell).

Material weights calculated for either porous or non-porous components and other parts are net values estimated from published literature representing the best available values of an ideal production [10–12]. In order to consider production losses, a 15% of materials weight loss has been assumed. Some data is

Table 4
LCI for 1 kW MCFC cell [11]

Substance	Anode	Cathode	Matrix	Bipolar plate	Total
Electrical energy (MJ)	551.34	297.18	262.91	19.69	1131.12
CO_2 (kg)	508	214	127	8.03	857.03
CO (g)	121	45.4	25.2	37.6	229
NO_x (g)	6.17	3.77	441	5.84	457
SO_2 (g)	10.92	6.67	1.5	0.26	19.38
CH_4 (g)	423	131	36.2	0.502	590.7
NMVOC (g)	420	129	16.8	0.0343	566
VOC (mg)	–	–	–	15.5	15.5
Benzene (g)	0.895	0.31	0.031	0.0102	1.25

Table 5
Energy inputs for the manufacturing of BOP components of FC

Component	Material	Specific weight ($kg\,kW^{-1}$)	Energy inputs for manufacturing ($MJ\,kW^{-1}$)
Casing	Steel	30.6	11.2
Reformer	Steel, catalyst	60	12.9
Power conditioning system	Aluminium, purified silica, plastics, Cu	5	4.3

collected from [13–23], and the main values used in the model are presented in Table 4.

3.2.2.3. *BOP and components.*

Major BOP component weight groups are casing, reformer and power conditioning unit. In the study, specific weight values for those components are assumed 60 and 5 $kg\,kW^{-1}$, respectively [8]. Material breakdown of the BOP components and energy inputs for manufacturing process are obtained from a SOFC LCA data and presented in Table 5 [10]. Weight breakdowns for MCFC system components are summarised in Table 6 [8].

3.2.3. *Operation*

Operational profile of the case ship represents the characteristics of a typical short route shipping route. A "summer schedule" profile with two voyages per day has been selected. As shown in Table 7, the fuel consumption is calculated for three different operation modes, i.e. in port, manoeuvring and cruise.

During the operation, there is no SO_x emission from the MCFC system since the sulphur is removed before the reaction of the fuel in the stack. Other emissions specifications are taken from published literature [7,24] as presented in Table 8. A constant fuel cell efficiency of 45% is used for the conversion of factor unit between $g\,kg^{-1}$ fuel and $g\,kWh_{el}^{-1}$.

Table 6
MCFC system weight summary

System components	LCA model weights ($kg\,kW^{-1}$)
Stack	23.7
Casing	30.6
Reformer	16
Power conditioner	0.5
System weight	70.8

Table 7
The operational characteristics of fuel cells are fundamentally different compared to DE

Operation mode	Duration (h)	Aux. power (%)	Fuel consumption (kg)	
			Aux.DE (SFC = 194 $g\,kWh^{-1}$)	MCFC (SFC = 201 $g\,kWh^{-1}$)
At port	3	73	459	476
Manoeuvring	1	87	182	189
Cruise	8	84	1409	1459
Total trip	12		2051	2124

3.3. *MCFC end-of-life issues and LCA scenarios*

In contrast to the studies on potential environmental impacts of the MCFC in the operation stage, there are uncertainties in the research for its end-of-life stage. As a general rule, the hierarchy in dealing with waste at the end-of-life stage follows the order of environmentally friendliness, i.e. reuse, recycling, incineration with energy recovery and disposal.

Due to lack of defined end-of-life strategies from manufacturers, detailed analysis of the above could not be performed for the MCFC. At the time of the study, there is no information

Table 8
Emission characteristics of operation stage

Emission	Emission factor ($g\,kWh_{el}^{-1}$)		Emission factor ($g\,kg^{-1}$ fuel)	
	MCFC	DE	MCFC	DE
CO_2	687	698	3120	3170
CO	0.030	1.68	0.16	7.4
NO_x	0.015	13.43	0.08	57
SO_2 (=20 × (0.61)%S content)	0	2.562	0	12.2
HC (primarily CH_4)	0.075	0.53	0.40	2.4
PM	0	0.55	0	2.5

Table 9
Total life cycle emissions and environmental quantities for DE and MCFC for functional unit

Substance	DE (operating life = 120,000 h)					MCFC (operating life = 174,000 h)						
	Mnf	F.Supl	Oper.	Recycl.	Total	Mnf–stack	Mnf–BOP	Mnf–total	F.Supl	Oper	Recycl	Total
Electric energy (MJ)	1.341E−03	2.083E−01	–	−8.425E−04	1.792E−01	3.306E−02	8.082E−03	4.114E−02	3.373E−01	0.000E+00	−3.041E−02	3.480E−01
CO_2 (kg)	4.453E−04	6.859E−02	6.150E−01	−2.955E−04	6.227E−01	8.395E−02	2.866E−03	8.682E−02	1.010E−01	9.138E−01	−6.135E−02	1.040E+00
CO (kg)	2.356E−06	1.187E−04	1.436E−03	−1.792E−06	1.133E−03	5.920E−04	9.768E−06	6.018E−04	1.891E−04	4.608E−05	−4.232E−04	4.138E−04
NO_x (kg)	2.186E−06	3.527E−04	1.106E−02	−4.749E−07	1.139E−02	2.210E−05	9.169E−06	3.127E−05	5.626E−04	2.314E−05	−2.372E−05	5.932E−04
SO_2 (kg)	1.082E−06	1.645E−04	2.367E−03	−6.288E−07	1.206E−03	1.871E−03	1.851E−05	1.890E−03	2.451E−04	0.000E+00	−1.327E−03	8.084E−04
NMVOC (kg)	N/A	1.360E−03	4.462E−04	−1.021E−07	N/A	N/A	N/A	N/A	2.201E−03	7.323E−07	N/A!	2.202E−03
CH_4 (kg)	1.441E−06	5.453E−04	4.656E−04	−1.031E−06	9.878E−04	2.873E−05	4.921E−06	3.365E−05	8.829E−04	1.160E−04	−2.454E−05	1.008E−03
Acidification potential (AP) (kg SO_2 equiv.)	2.628E−06	4.146E−04	1.011E−02	−9.752E−07	9.176E−03	1.895E−03	2.492E−05	1.920E−03	6.439E−04	1.620E−05	−1.349E−03	1.231E−03
Global warming potential (GWP 100 years) (kg CO_2 equiv.)	4.761E−04	8.074E−02	6.248E−01	−3.175E−04	6.435E−01	8.516E−02	3.179E−03	8.834E−02	1.207E−01	9.163E−01	−6.247E−02	1.063E+00
Human toxicity potential (HTP) (kg DCB equiv.)	5.195E−05	2.834E−03	3.254E−03	−5.339E−05	5.923E−03	3.055E−04	2.987E−06	3.085E−04	4.439E−03	6.016E−06	−2.166E−04	4.537E−03
Photochemical oxidant potential (POCP) (kg ethene equiv.)	2.022E−07	5.686E−04	2.406E−04	−1.139E−07	7.928E−04	2.219E−05	1.223E−06	2.341E−05	9.201E−04	2.776E−06	−1.663E−05	9.296E−04

available about the end-of-life stage of the product, recycling and handling of materials afterwards for the MCFC. Cost effectiveness of the end-of-life strategies is also an area with some uncertainties. For example, in PEMFC, a study has indicated the feasibility of recycling membrane rather than reusing it [25]. Issues discussed in the report include amount of energy consumed, cost of process and purity of recycled material. Similar issues need to be considered for recycling strategies of MCFC stacks.

As other fuel cells, MCFCs normally use high value materials, such as aluminium, nickel, chromium and lithium for electrodes, stainless steel for bipolar and casing. Stainless steel is a 100% recyclable material, recycling is the most likely option for bipolar plates. Recycling of insulation materials has been reported not cost effective as they are silica-based materials [26]. Recycling of aluminium, nickel, chromium and lithium has a high economic and environmental value. However, there has been no data available for their extraction processes, energy requirements and cost-benefit.

Energy required for recycling steel requires is only 30–35% of that of manufacturing steel from the raw materials. As a comparison, an energy value of 22.4 MJ kg^{-1} to produce steel from iron ore would be reduced to about 7.35 MJ kg^{-1} for recycling option. Along with the energy saving, emissions from material production will also be reduced by the recovery of the steel and aluminium parts from the recycling stream [27].

The model of recycling in the study adopts the "system expansion and substitution method". System expansion is an ISO14041 recommended procedure to include substitution of recycled material in the system.

In general, metal products such as steel and aluminium follow an open-loop recycling scheme, which means end-of-life products are recycled into raw material, which maintains the same inherent properties as primary materials [28]. In the study, recycling system is assumed as a closed-loop recycling system where materials are continually recycled into the same product. Recycling rate of the metal components of MCFC casing and BOP is assumed as 90%. Due to uncertainties with the decommissioning process of the stack, three scenarios with different recycling rates are considered in the study:

- Recycling Scenario 1: stack recycling = 90%, BOP recycling = 90%;
- Recycling Scenario 2: stack recycling = 70%, BOP recycling = 90%;
- Recycling Scenario 3: stack recycling = 50%, BOP recycling = 90%.

In addition to the above three scenarios, the baseline scenario has also been defined with no stack or BOP recycling rates, and casing material input is assumed as secondary steel sheet from life cycle database [9] in that scenario.

The summary of recycling credit calculation used in the model is as follows.

For a 100 kg of primary metal (e.g. steel) to be used in the product system:

- 90 kg of recycled metal substitute 90 kg of primary metal input;
- 10 kg of metal is lost and land-filled.

The environmental burdens of the production of only the lost metal, i.e. 10 kg of primary metal, are charged to the MCFC manufacturing system. Burdens of the recovery operations, such as energy requirements for dismantling and transport are not available, and therefore neglected in the MCFC end-of-life model. The environmental burdens of the production of 90 kg of primary metal are charged to the next user(s) of the 90 kg of recycled metal.

4. Results analysis and discussion

Depending on interest of studies, LCA results analysis could consist of four steps, i.e. characterisation, normalisation, weighting and total effect, i.e. environmental scoring.

Characterisation is to group emission species into impact categories and multiplied by characterization factors that express their relative contribution (characterization values) of the substances. Normalisation is to compare the relative effects of different life cycle stages. With normalised values, it is possible to examine the relative contribution from each life cycle stage. Assignment of weighting factors is to analyse the normalised effects according to the relative importance of the effect.

The total environmental effect can be represented by the environmental score defined as below:

$$\text{environmental score} = A \times B \times C$$

where A represents the characterised value, B the normalised factor and C is the weighting factor.

Table 9 presents a summary of main results from characterisation for the comparative study. Due to different lifespan characteristics of the system components, breakdown of the emission factors from manufacturing stage of stack and BOP are presented separately. The stack manufacturing values in the table represents the values of 4 units to match the power output of the DE system and, each unit is assumed to have a 5 years lifespan, with a total lifetime of 20 years. The energy requirements for the materials production and manufacturing of various components of the MCFC module are presented in Fig. 3. Over the lifetime of the module in the baseline scenario, stacks with replacements represents the highest proportion of the material requirement, although single stack unit needs less energy input compared to insulation and casing components.

Comparisons of the contributions of each lifecycle stage to each impact category between DE and MCFC are presented in Figs. 4 and 5, respectively. It can be seen that the operation stage is the major contributor to global warming effect in both systems since hydrocarbon-based fuels are used during operation of the both systems. Fuel supply stage has a great impact on photochemical oxidant potential. Compared with the manufacturing

Table 10
Normalisation and weighting factors

Category	Normalised factor	Weighting factor
Acidification potential (AP) (kg SO_2 equiv.)	0.0088496	10
Carcinogenic substances (EI 95) (kg PAH equiv.)	91.743	10
Eutrification potential (EP) (kg phosphate equiv.)	0.026178	5
Global warming pot. (GWP 100 years) (kg CO_2 equiv.)	7.63E−05	2.5
Heavy metals (EI 95) (kg Pb equiv.)	18.416	5
Ozone depletion pot. (ODP, catalytic) (kg R11 equiv.)	1.0799	100
Photochemical oxidant potential (POCP) (kg ethene equiv.)	1.0352	25
Winter smog (EI 95) (kg SO_2 equiv.)	0.055866	2.5

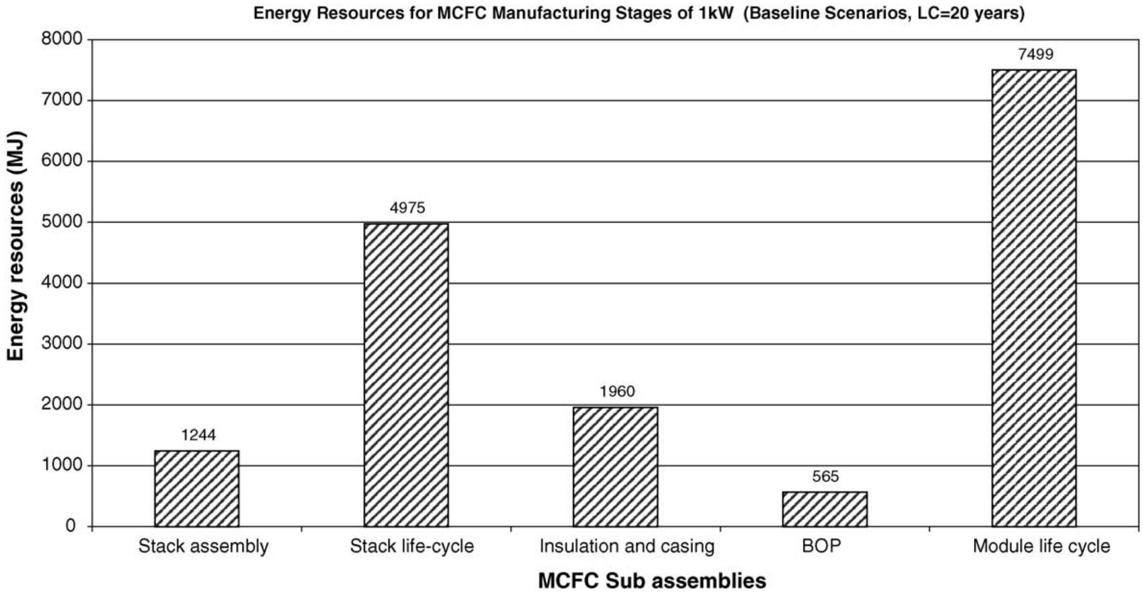


Fig. 3. Energy requirements for MCFC module manufacturing and materials production (life cycle = 20 years).

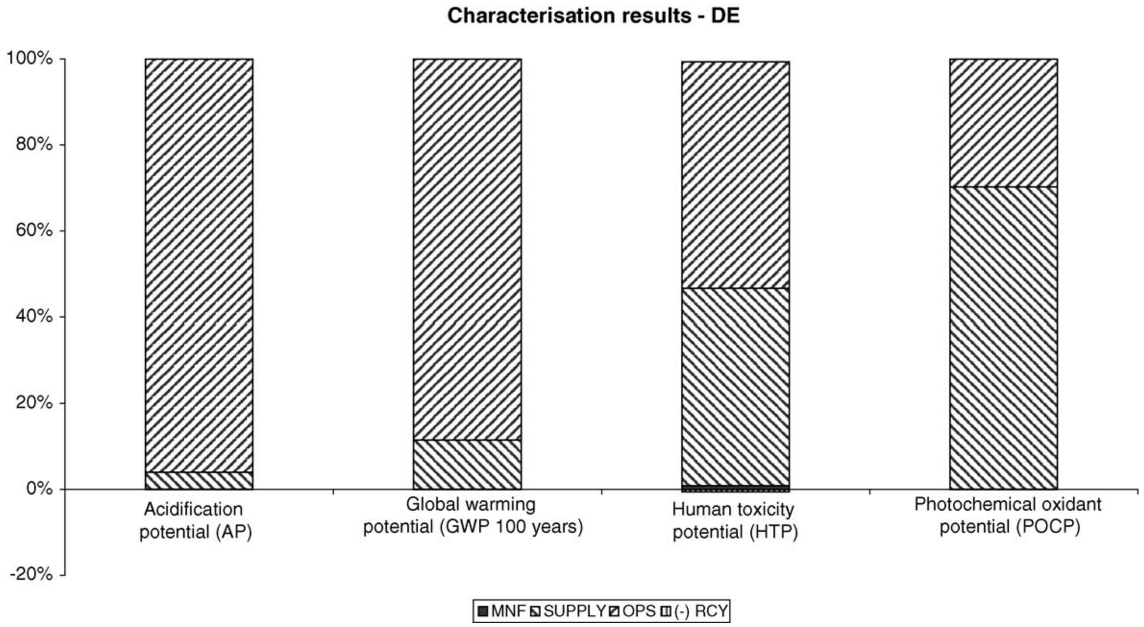


Fig. 4. Characterisation results for DE.

stage of DE, MCFC has a substantial contribution to acidification potential due to emissions of NO_x and SO_2 produced from cradle-to-gate production of the stainless steel casing. With the recycling of steel casing at the end-of-the life, the amount of impact will be reduced. Results of normalisation and weighting factors analysis are presented in Table 10.

The total environmental scores of per functional unit for each life cycle stage of DE and MCFC are shown in Fig. 6. It is apparent that the emissions from the operation of DE make its operation stage of the biggest environmental score contributing to GWP100 and acidification potential. For the fuel supply stage, MCFC has a slightly higher score than that of DE due to the high fuel consumption of MCFC.

4.1. Results for scenario analysis and parametric studies

A sensitivity study of environmental effects change with system parameters has been performed. The following presents the results of sensitivity studies with factors of power load, MCFC efficiency and recycle credit. Values for each environmental burden, i.e. emission factors and quantities, are then debited from the baseline values of the systems' life cycle.

4.1.1. Power load factor

A high environment profile in operational stage of the case ship exists at the lower loads of DE. The efficiency of diesel fuel reformer is not available. However, it is valid [6,7] to calculate

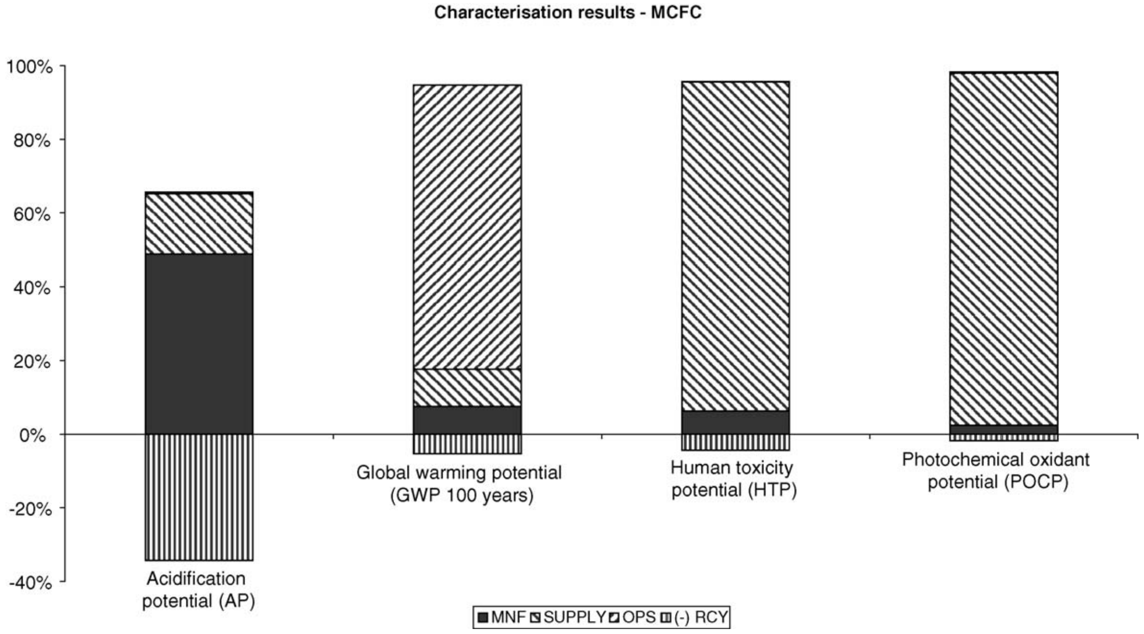


Fig. 5. Comparison of characterised results for MCFC.

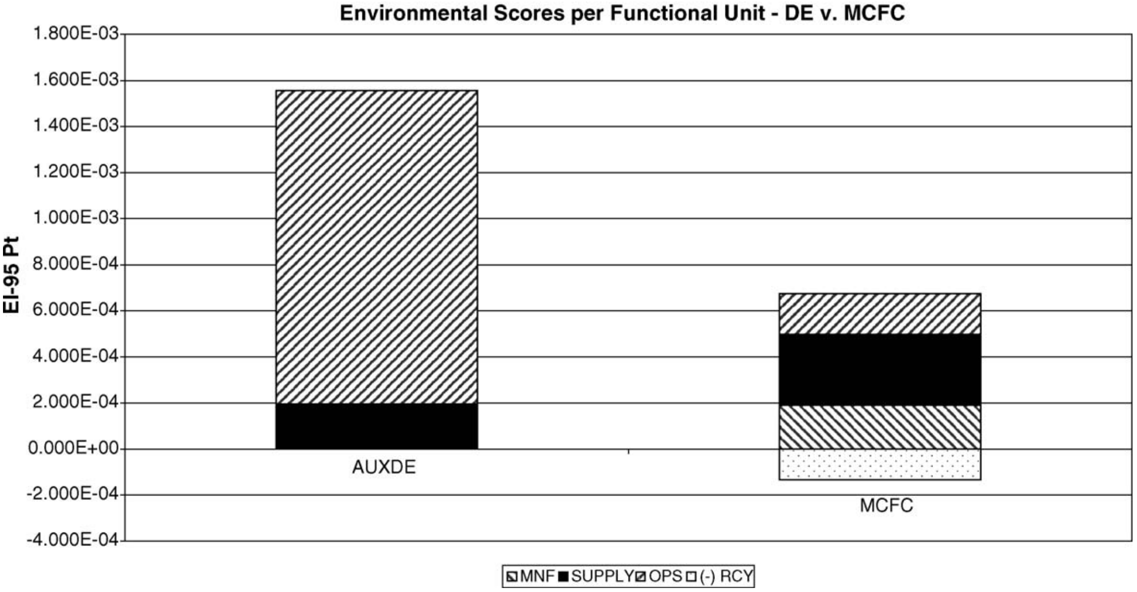


Fig. 6. Environmental scores (EI-95) per functional unit.

the specific fuel consumption for a high temperature MCFC based on the fuel utilisation rate of SOFC, i.e. 85%. A comparison between FC and DE's specific fuel consumption (SFC) against the load factors is presented in Fig. 7. According to a previous study [6], MCFC have higher efficiencies under partial load conditions.

Table 11 presents the baseline results of part load SFC simulation, sensitivity of various emission factors and environmental quantities are analysed for the entire life cycle for both DE and MCFC. The results are presented in a comparison with the baseline values of 100% load factor. According to results, over the entire life cycle of the MCFC, NO_x and CH_4 have the biggest sensitivity to operational load factor changes.

4.1.2. *MCFC efficiency factor*

The effect of the MCFC efficiency on environmental performance is analysed by changing the specific fuel consumption

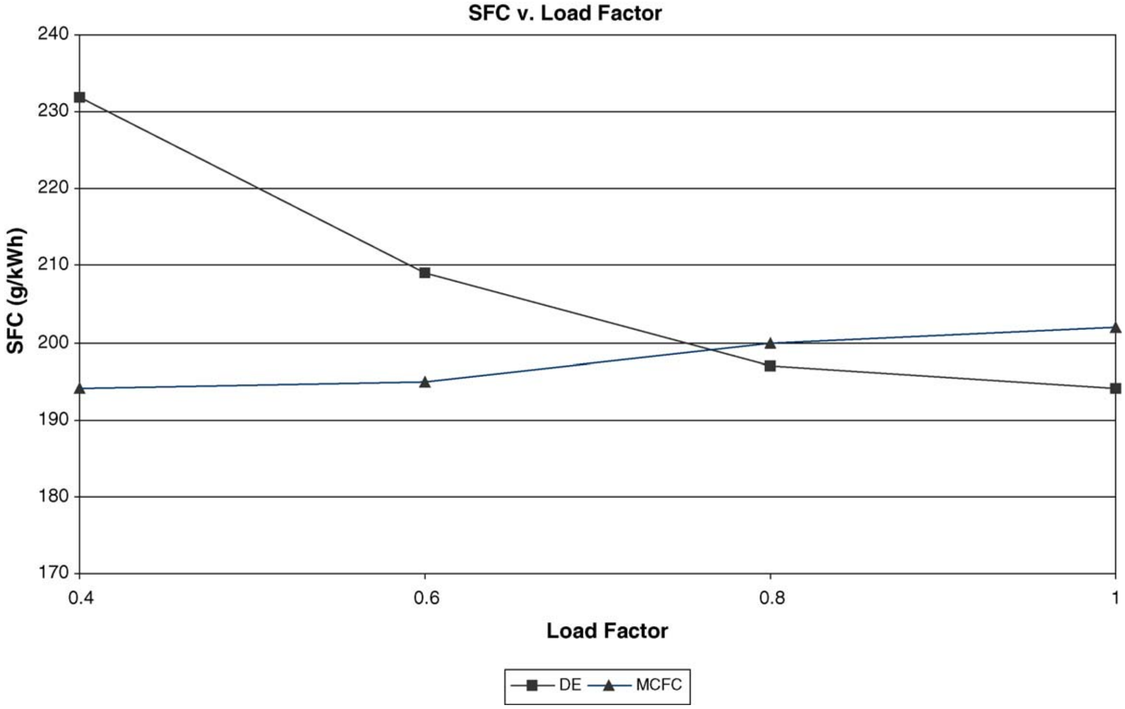


Fig. 7. Effect of power load.

Table 11
Summary results of sensitivity analysis of the systems for different scenarios (% variance from BL scenarios) for functional unit

Substance	DE			MCFC							
	Load factor scenarios			Load factor scenarios			Efficiency scenarios		Recycling credit scenarios		
	lf = 0.4	lf = 0.6	lf = 0.8	lf = 0.4	lf = 0.6	lf = 0.8	−20% SFC	+20% SFC	Stack = 90%, BOP = 90%	Stack = 70%, BOP = 90%	Stack = 50%, BOP = 90%
CO_2	19.57	7.73	1.55	−3.82	−3.34	−0.96	−19.11	19.11	7.09	5.57	4.04
CO	19.58	7.73	1.54	−1.89	−1.65	−0.47	−9.42	9.42	64.71	50.56	36.42
NO_x	19.58	7.73	1.54	−3.89	−3.40	−0.97	−19.44	19.44	4.56	3.85	3.13
SO_2	19.58	7.73	1.54	−0.91	−0.80	−0.23	−4.57	4.57	79.67	62.14	44.61
CH_4	19.54	7.71	1.54	−3.91	−3.42	−0.98	−19.54	19.54	2.93	2.38	1.82
AP	19.58	7.73	1.55	−1.76	−1.54	−0.44	−8.78	8.78	66.98	52.29	37.60
GWP 100 years	19.57	7.72	1.54	−3.82	−3.35	−0.96	−19.11	19.11	7.06	5.55	4.04
HTP	19.55	7.72	1.54	−3.85	−3.36	−0.96	−19.23	19.23	5.84	4.56	3.27
POCP	19.53	7.71	1.54	−3.92	−3.43	−0.98	−19.59	19.59	2.23	1.76	1.29

values with a plus and minus of 20% from the base SFC values for different operation modes as described in Table 7. According to the results shown in Fig. 8, the biggest change from the baseline scenario is the POPC values. About 19.7% reduction has been noted for the 20% reduction of SFC. Since the MCFC efficiency scenario is directly related with operational life cycle stage, fuel supply and operational emissions are the main factor in the results. The lowest change has been noted for the SO_2 emissions (−6%) and acidification potential (−10.6%) in the same scenario.

4.1.3. Recycling credit

Results of this part study present recycling substitutions and their credits to the system. Under this recycling scenario, net burden of the MCFC materials manufacturing is difference between the debits and credits.

Rates of change in various emission values for recycling credit scenarios are presented in Table 11. Comparison of environmental burdens over the life cycle of MCFC materials manufacturing and recycling credits are presented in Table 12.

The results show that CH_4 has the highest sensitivity to the MCFC stack recycling rate, scoring at 80%, 62%, 45%, respectively to the three scenarios over the total life cycle. This indicates an improvement potential on overall emission compared to the baseline scenario values. The magnitude of the improvement potential is effected by emission species, particularly, CH_4 emission rate during the production of aluminium which is major material in BOP components. The sensitivity of NO_x over the three scenarios is of a similar magnitude to CH_4, i.e. 65%, 51% and 30%, respectively. In terms of environmental quantities, GWP100 is of the biggest change with the change of

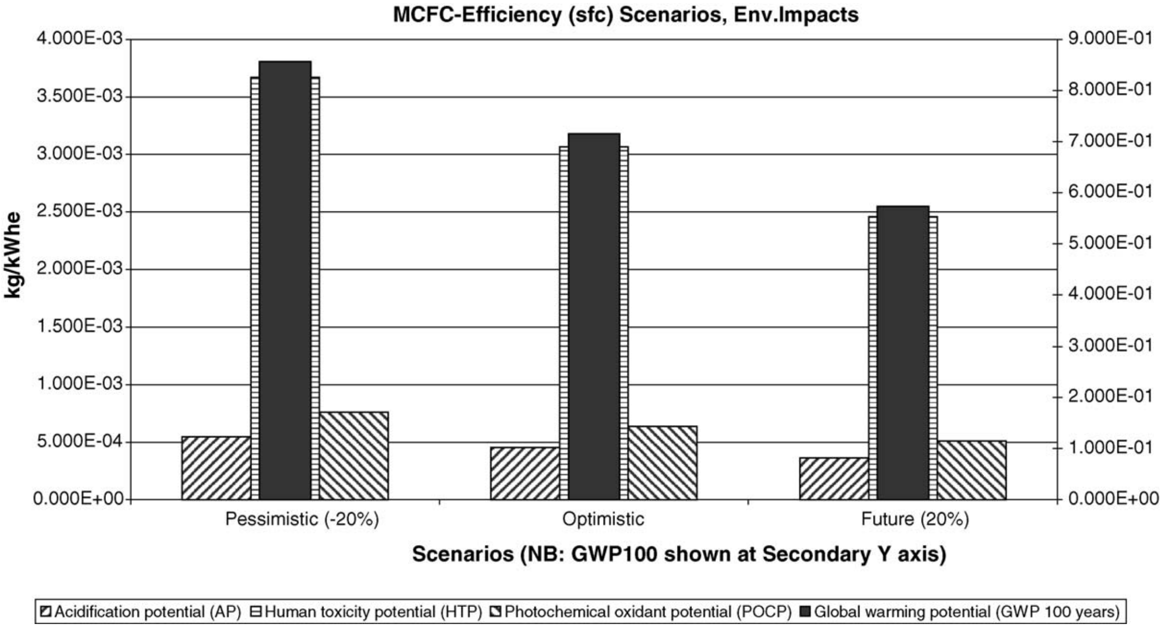


Fig. 8. Effect of changing MCFC efficiency on environmental quantities.

Table 12
Comparison of environmental burdens over the life cycle of MCFC materials manufacturing and recycling credits

Component	Manufacturing with recycled input material					System expansion (manufacturing with recycled input and recycling substitution)				
	Stack Assy (4×)	Casing	BOP	System (20 year)	Diesel Eng (PS)	Stack Assy (4×)	Casing	BOP	System (20 year)	Diesel Eng (PS)
Material	Steel sheet, stainless steel	Stainless steel	Steel sheet, aluminium		Steel sheet	Steel sheet, stainless steel	Stainless steel	Steel sheet, aluminium		Steel sheet
Unit weight (kg kW^{-1})	45.3	35.8	16.5	97.6	15.2	−38.8	−28.9	−15.4	−83.1	−13.7
Energy required (MJ kW^{-1})	4553.4	1923.4	484.3	6961.1	579.4	−1287.4	−1734.0	−436.0	−3457.3	−364.5
CO_2 emissions to air (kg)	304.6	198.4	32.9	535.9	53.4	−88.0	−178.7	−29.7	−296.3	−35.5

recycling rates, i.e. 67%, 52% and 38% improvement potentials, respectively.

5. Conclusions and recommendations

In the study, an assessment of life cycle environmental performance of a MCFC as an onboard auxiliary power system in comparison with a DE has been performed. The analysis includes manufacturing of the main components of the DE, MCFC stack and BOP, production of fuels, onboard operation and decommissioning aspect at end-of-life of the systems.

The low environmental impact of hydrogen fuelled fuel cells as a means for reducing pollutant emissions compared to burning of hydrocarbon-based fuels in diesel engines is evident and has been reported in various literatures. The study focused on LCA of fuel cells fuelled with diesel oils.

One of the challenges of fuel cell applications on commercial ships is the capability of using commercially available fossil fuel, instead of pure hydrogen. It has been anticipated that conventional liquid fuels, such as diesel oil or methanol will be a long-term solution for fuel cell application onboard ships. This solution requires a fuel reformer to extract hydrogen from marine fuels. Although a fuel cell with a reformer emits very small amount of pollutants to air, there is no significant difference between the environmental impacts of fuel production and supply for both MCFC and DE. Even though, emissions from the production and supply of fuels are significantly low compared to that from the operation stage of MCFC and DE.

The study shows that the manufacture of MCFC including stack and BOP components, supply of materials and energy for the production contributes significantly to environmental impact compared to that of DE for the same functional unit. Although the impact of a single stack unit presents an insignificant environmental load, replacement of stack after its 5 years operational life, even retaining the BOP components, results in a higher impact of stack manufacturing over the MCFC system life cycle, i.e. 20 years. The technological developments should be forecasted and incorporated for a better practice of reducing the environmental impacts during manufacture stage of the components. Any effort in the reduction of material weight through the introduction of alternative materials and manufacturing processes will directly improve the environmental performance of the manufacturing. Although proven materials and processes are normally adopted in the industry, potential benefits of using their alternatives have been reported in literatures. The vast numbers of variants to choose from have presented difficulties in the modelling study.

The utilisation rate of materials in manufacturing, rework and scrap rates are important factors to improve the environmental performance of MCFCs since the study has shown a high correlation among the weight, rate of material used and the resultant environmental burdens. As a result, reduction of environmental impacts of the MCFC manufacturing can be achieved through optimisation of design parameters.

Based on results of the study the following recommendations for future R&D are made.

The fuel reforming process combined with factors such as FC utilisation coefficient, electric converter and transform efficiencies that govern the overall efficiency of the MCFC system has a significant impact on the results of environment performance and their variations, yet those are the factors liable to improve with the development of FC technology. Environmental impact of onboard sulphur removal via a fuel reformer is also an area, which needs a further investigation.

Comprehensive life cycle inventories including the weight breakdown of stack and BOP components of MCFC systems are required for further detailed studies. Due to the early stage of system development and commercial confidentiality reasons, reliable data is currently difficult to obtain. Materials used for fuel cells are generally unconventional materials. Fuel cell manufacturing processes involve consumption of a range of solvents and chemicals, which have potential impacts on the environment. Unfortunately, such data and the extent of their environmental impacts are not available. Environmental impacts during raw-materials production, manufacturing and operational stages have not been extensively studied.

LCA of fuel cells is subject to major periodic maintenance operations in every 5 years, i.e. stack assembly replacements. The removed stack assembly, including metals and electrolyte matrix, can be further disassembled for recovery of valuable components and materials. It is evident that valuable resources could be recovered and reused at the end-of-life, however, material recovering would also require process energy, and may consume chemicals. Directly associated with material supply, recycling and re-use of components is an important factor in reducing environmental impact in the life cycle of the fuel cell. However, in contrast to status of the current development activities in the technology, end-of-life cycle and material recovery issues have not been given an adequate consideration in the industry and research.

Due to the technology is under its early development stage, commercial production of MCFCs has not been established. Therefore, manufacturing process and material specifications and available data are mainly referred to data and experiences obtained from the development and production of MCFC units at a small scale. With an increase in market demand and technology development, a series of commercial production will be in place. This will lead to a significant reduction in energy requirements and emissions in manufacturing, as well as the life cycle costs.

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References

[1] B. Bosio, et al., Industrial experience on the development of the MCFC technology, J. Power Sources 74 (1998) 175–187.

[2] Life Cycle Assessment (LCA), A Guide to approaches, experiences and information sources, Environmental Issues Series No. 6, European Environment Agency, 1998.

[3] EN-ISO 14041, Environmental Management, Life Cycle Assessment, Goal and Scope Definition and Inventory Analysis (ISO 14041:1998), October 1998.

[4] Marine Fuel Cell Market Analysis, CG-D-01-00, USCG Research & Development Centre, Washington, DC, September 1999.

[5] G. Würzig, G. Filip, Fuel Cell Technology in Marine Applications, HYFORUM 2004, Beijing, China, May 25–28, 2004.

[6] D. Brevik, Simulation of high temperature fuel cells as auxiliary generators in RO/RO passenger ferries, FCSHIP, DTR-3.3-MT-02.2004.

[7] Z. Bazari, Evaluation of Fuel Cell Ship Efficiency and Emissions, FCSHIP, DTR-4.3-LR-02.2004.

[8] Figari et al., Conceptual design of a FC electric generator for RO-RO passenger ferry vessel, DTR-3.2-FC-05.2003, Report Submitted by UNIGE and FC, May 2003.

[9] GaBi4, Software and Database for Life Cycle Engineering, PE Europe GmbH and IKP University of Stuttgart, January 2003.

[10] V. Karakousis, et al., The environmental impact of manufacturing planar and tubular solid oxide fuel cells, J. Power Sources 101 (2001) 10–26.

[11] P. Lunghi, R. Bove, Life cycle assessment of a molten carbonate fuel cell stack, Fuel Cells 3 (4) (2003) 224–230.

[12] P. Lunghi, et al., LCA of a molten carbonate fuel cell system, J. Power Sources 137 (2004) 239–247.

[13] C. Yuh, al. at, Status of carbonate fuel cell materials, J. Power Sources 56 (1995) 1–10.

[14] D.E. Erickson, Low cost MCFC anodes, in: Proceedings of the Fuel Cells '96 Review Meeting, VW, 1996.

[15] V.S. Batra, et al., Development of alpha lithium aluminate matrix for MFCF, J. Power Sources 112 (2002) 322–325.

[16] T. Fukui, Synthesis of CoO/Ni composite powders for molten carbonate fuel cells, J. Am. Ceram. Soc. 84 (1) (2001) 33–235.

[17] C.C. Ibeh, Polyolefin Binders in MCFC electrolyte matrix support, Research Topic Summary http://www.pittstate.edu/services/nsfreu/bullet3.htm.

[18] Y.-S. Kim, H.-S. Chun, Sintering characteristics of a porous Ni/Ni_3Al anode for MCFC, J. Power Sources 84 (1999) 80–86.

[19] S. Birk, Pressure effects on the performance of in-lab developed and fabricated MCFC electrolyte matrix support with polyolefin-based binders, Formal Report for PSUNSF-REU Programme, 1998.

[20] H. Morita, Performance analysis of MCFC using a Li/Na electrolyte, J. Power Sources 112 (2002) 509–518.

[21] L.A. Salam, et al., Optimisation of thermoelectric green tape characteristics made by the tape casting method, Mater. Chem. Phys. 62 (2000) 263–272.

[22] F. Li, et al., Optimisation of non-aqueous nickel slips for manufacture of MCFC electrodes by tape casting method, Mater. Res. Bull. 37 (2002) 1907–1921.

[23] Z. Ma, et al., Modelling the transport processes within multi-channel MCFC, Int. J. Hydrogen Energy 28 (1) (2003) 85–97.

[24] Lloyd's Register, Marine Exhaust Emissions Research Programme, London, 1995, p. 51.

[25] C. Handley, et al., Impact of the European Union vehicle waste directive on end-of-life options for polymer electrolyte fuel cells, J. Power Sources 106 (2002) 344–352.

[26] Microtherm Thermal Insulation, http://www.microtherm.uk.com/faq.html.

[27] Environmental Declaration No. 36, based on lifecycle inventories ISO 14040 and ISO 14041, Hot-rolled sheet steels, reels and strips Rautaruukki Oyj, Raahe Steel Mill, Helsinki, 1999.

[28] International Aluminium Institute, Year 2000 Aluminium LCI Report, March 2003.