Exergetic, environmental and economic sustainability assessment of stationary Molten Carbonate Fuel Cells

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Abstract

In this study, exergetic, environmental and economic (3E) analyses have been performed in order to provide sustainability indicators from resource extraction to the final product of stationary power Molten Carbonate Fuel Cells (MCFC) systems (500 kW). Two environmental life cycle impact assessment methods have been selected: the ReCiPe 2016 hierarchical midpoint and endpoint, and the Cumulative Exergy Extraction from the Natural Environment (CEENE). A cost-benefit model is adopted to calculate the economic sustainability using the levelized cost of electricity (LCOE) under different sensitivity parameters. The global warming potential (GWP) is estimated to be 0.549 kg CO_2-eq/kWh while acidification (5.06e-4 kg SO_2-eq/kWh), eutrophication (9.81e-4 kg P-eq. freshwater/kWh), ozone layer depletion (4.11e-6 kg CFC-11-eq/kWh) and human toxicity (1.07 kg 1,4-DB-eq/kWh). Aggregated CEENE was estimated to be about 8.55 MJ_{ex}/kWh. Results show that majority of impacts are dominated by fuel supply, while some others are dominated by manufacturing of system. GWP is the only impact category dominated by system operation. Due to potentially high electrical efficiency, MCFC energy systems can lead to lower CEENE and improvements of global warming, fossil fuel and resource scarcity, and photochemical oxidant formation potential with respect to other conventional energy conversion systems. Advances in longer lifetimes of the MCFC stack can help trigger innovation in manufacturing processes and will lead to less resource use of electricity, metal, and minerals, thus less resource scarcity and toxicity related burdens. The baseline LCOE is calculated 0.1265 €/kWh being comparable with the Italian grid (0.15-0.16 €/kWh). The costing results indicate that the unit decreasing the system capital cost could potentially reduce the LCOE by around 25%. Advancing the use of life-cycle thinking in MCFC industry with site-specific data raise systems credibility and enables clarifying the trade-offs between the sustainability pillars, thus designing more sustainable products.

Keywords: Molten Carbonate Fuel Cells; Exergy, LCOE, LCA, Eco-efficiency

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Abbreviations

BoP – Balance of Plant; **CHP** – Combined heat and power; **CEENE** – Cumulative exergy extractions from the natural environment; **ED** – Ecosystem quality; **ELCA** – Exergetic life cycle analysis; **PMFP** – Fine particulate matter formation; **FFP** – Fossil resource scarcity; **FETP** – Freshwater ecotoxicity; **FEP** - Freshwater eutrophication potential; **FC** – Fuel Cell; **GWP** – Global warming potential; **HRSG** – Heat-recovery steam generator; **HH** – Human Health; **HTP_c** – Human toxicity potential: cancer; **HTP_{nc}** – Human toxicity potential: non-cancer; **IRP** – Ionizing radiation; **LCOE** – Levelized cost of electricity; **LCA** – Life cycle analysis; **LCI** – Life cycle inventory; **LCT** – Life cycle thinking; **METP** – Marine ecotoxicity potential; **SOP** – Mineral resource scarcity; **MCFC** – Molten Carbonate Fuel Cells; **EOFP** – Photochemical oxidant formation: ecosystem quality; **HOFP** – Photochemical oxidant formation: human health; **RA** – Resource availability; **ODP** – Stratospheric ozone depletion; **TAP** – Terrestrial acidification; **LOP** – Land use; **TETP** – Terrestrial ecotoxicity potential; **FETP** – freshwater ecotoxicity; **WCP** – Water consumption potential;

1. Introduction

The deployment of new clean technologies like fuel cell and hydrogen technologies are being considered one of the pillars of future European energy and transport systems, making a valued contribution to the transformation to a sustainable economy by 2050 [1]. Among these, the Molten Carbonate Fuel Cell (MCFC) technology offer rich potential for both electricity generation and cogeneration in an environmentally friendly fashion [2,3]. However, in this phase of early deployment, life cycle thinking (LCT) information is still required from research and development to demonstrate economic, environmental, and social sustainability in a real-world implementation, especially in the globally highly competitive environment [4].

Life Cycle Thinking (LCT) is systemic approach allowing assessment of the complex relationship of every system with its environment and identifying the most sustainable energy options across all life cycle stages [5]. In the context of LCT, Life Cycle Assessment (LCA) represents the state of the art in applications related to environmental sustainability and is considered obligatory to support hydrogen and fuel cell development [6]. The LCA comprehensively quantifies and assesses the emissions, resources consumed, and pressures on health and the environment the whole product life cycle [7]. Several studies have been undertaken to investigate the environmental performance of MCFCs through the use of LCA, in order to understand to what extent these are environmentally sound, to what extent they can be improved and what steps and components require attention [8]. Lunghi et al. [9] performed an LCA of an MCFC system using global warming, acidification potential, and energy resource depletion as criteria for the environmental performance evaluation. Raugei et al. [10] combined a classical exergy and LCA (presenting only life-cycle airborne emissions) to compare the environmental performance of an MCFC versus a gas turbine. Alkaner and Zhou [11] performed an LCA of an MCFC energy plant for marine applications compared to a benchmark conventional diesel engine using only airborne emission and four impact indicators for evaluation. Zucaro et al. [8] using a multi-impact analysis with seven environmental impact categories performed an LCA of an MCFC power system. These studies provided valuable insights, however, a gap of knowledge in most previous studies exists because of limited impact categories considered [4].

Because of the complexity of socio-ecological systems, optimizing the performance of a given process requires that many different aspects are taken into account to provide a synthetic answer to the complex and multifaceted problem of environmental impact [12]. More specifically, resource management and the minimization of the environmental impacts of energy production are becoming an issue of great significance towards the development of sustainable technologies [13,14]. An emerging trend in LCA literature shows that resources ("upstream" categories) are one of the categories of environmental impacts that need to be considered [15]. Among the "upstream" impact categories, abiotic and biotic, water resource, land use, and primary energy resources, are the most important [16]. To deal with environmental challenges, priority must be given to the studies investigating multiple impact categories to study upstream (amount of resources) and downstream (consequences of the system emissions) impact on resource use and environmental dynamics.

New methods for the accounting or impact assessment of resource use have proven to be valuable for sustainability evaluation and are increasingly developed [17,18]. Exergy, based on the second law of thermodynamics is the most powerful scientifically sound method to express physical and chemical potential and usefulness of resources, product, by-product or waste. Exergy is a thermodynamic concept, representing the maximum useful work which can be extracted from a system as it reversibly comes into equilibrium with its environment [19]. Numerous studies have been carried out on exergy analysis of MCFC systems in a simple and hybrid configuration in a range of applications using a strict thermodynamic evaluation of the systems [20–25]. Recent literature works [15,26,27] suggests that thermodynamic resource metrics such as cumulative exergy extractions from the natural environment (CEENE), cumulative exergy demand (CExD), solar energy demand (SED) and cumulative energy demand (CED) covering resource extraction to the final product can be used as a measure for the use of resources in LCA and other sustainability assessment methods. Integrating the exergy concept and the principles of life cycle assessment (LCA) leads to Exergetic Life Cycle Assessment (ELCA), which can be used as an additional environmental decision support tool toward product and overall system sustainability [26]. Resource analysis using life cycle thinking based on thermodynamic principles by means of exergy is an appropriate measure of resources consumption offering deeper insights of the performance of production processes and products [26,28]. Through the use of ELCA is possible to monitor the consumption of primary resources throughout the life cycle of a product (including renewable and non-renewable resources). The LCA-based evaluation of energetic flows and resource exploitation is essential for improving the environmental management of natural stocks and their use [29]. The ELCA should be complemented with problem-oriented (midpoint) impact categories (e.g., global warming, ozone layer depletion, eutrophication, and acidification) and damage-oriented (as damage to human health, ecosystem quality or resources) for a holistic environmental appraisal [12]. Complementary to environmental impact assessment, economic analysis is receiving increasing attention to allow energy managers and all stakeholders to make the right decisions in terms of economic and technical feasibility [30]. Henceforth, gaining a better knowledge of MCFC from complementary angles – from upstream to the downstream life cycle stages and impacts is absolutely necessary to provide a holistic sustainability assessment, thus, improving the environmental and economic efficiency of power generation and making more informed decisions.

The objective of this study is to analyze and compare the performance of a Molten Carbonate Fuel Cell power plant by means of economic, exergy-based and environmental life cycle impacts. Cumulative Exergy Extraction from the Natural Environment (CEENE) based on thermodynamics [31] was applied to calculate the life cycle's resource footprint (upstream impacts), while ecological sustainability (resource and emission-related impacts) was measured using the cutting edge LCA methodology ReCiPe 2016 [32]. For system economic viability, the levelized cost of electricity (LCOE) was quantified. The main aspects considered to be the novelty of this work are:

- A comprehensive resource-based environmental sustainability assessment is performed by means of ELCA. This advanced the scope of in respect to former LCA studies on MCFC by providing useful information about natural resource consumption. Cumulative Exergy Extraction from the Natural Environment [31] is one of the most recommended methods for resource accounting [26,33]. Resource use assessment has pinpointed the critical materials, stages and resource groups.
- The study broadens the scope with regards to environmental impacts of all previous LCA studies by generating a multi-criteria environmental profile where the inventory flows are converted to seventeen (17) harmonized impact scores on midpoint (problem-oriented) and three (3) at the endpoint (damage-oriented) level. Examples of midpoint indicators are global warming and acidification. Endpoints are defined as the final damage to the natural environment, human health, and raw material exhaustion, which are caused by the various environmental effects at midpoint level. The new version of LCA-ReCiPe method contributes to a better understanding of the environmental impacts using recent models and scientific knowledge [34].
- A techno-economic appraisal and feasibility analysis which provides reliable information of the economic competitiveness of MCFC systems.

The final outcome of the paper is to present a range of quantified indicators covering resource extraction to the final product identifying system implications (depletion of resources and downstream consequences of emissions) and provide a comprehensive sustainability viewpoint for the researchers and policymakers of MCFC technologies as an energy conversion system.

2. Methodology

2.1. Molten Carbonate Fuel Cell Systems

A simplified schematic diagram of the MCFC system is shown in Figure 1. The system under study is based on the work presented by Iora et al. [35] which consists of nine main components: a 500 kW-class MCFC stack, a catalytic burner, a fuel compressor, an air compressor, a gases re-compressor, a fuel reformer, a water pump, an inverter (INV), and a heat-recovery steam generator (HRSG). The fuel cell stack is representative of the 500 kW Ansaldo TWIN STACK.

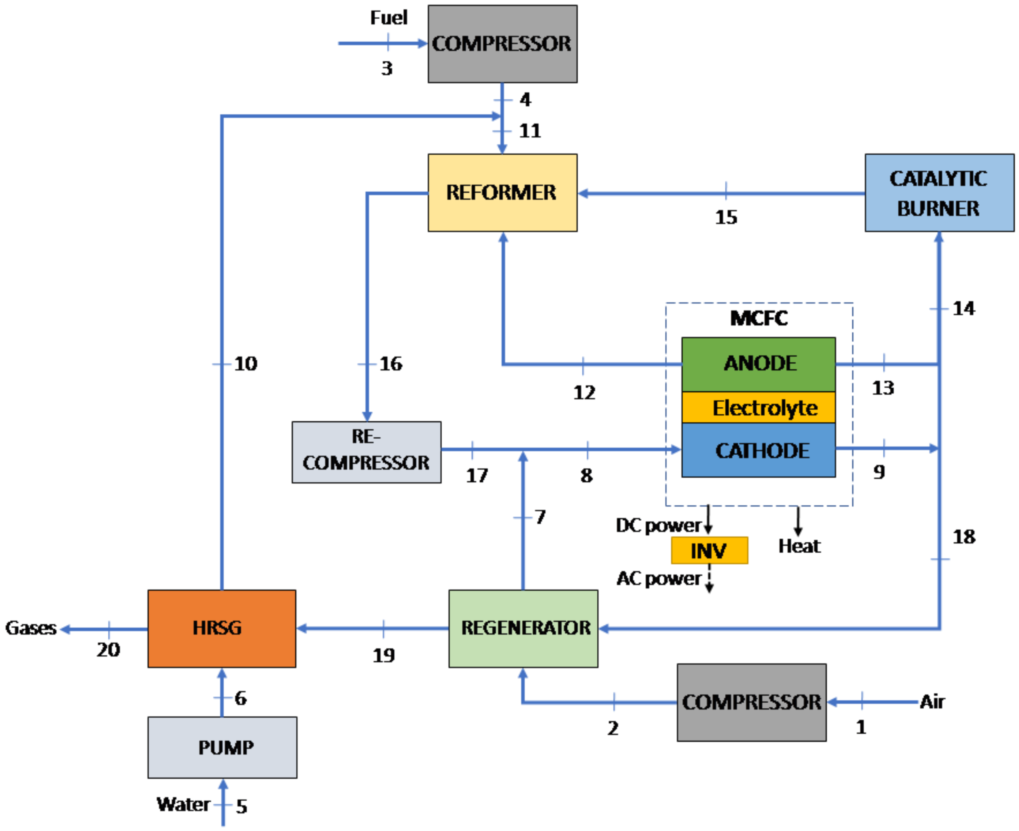


Figure 1. Simplified schematic diagram of a combined heat and power Molten Carbonate Fuel Cell plant.

The Molten Carbonate Fuel Cell (MCFC) belongs to the high-temperature fuel cells operating at 650 °C. The primary components of an MCFC are the active parts, i.e. anode, cathode and matrix (where the carbonates are soaked), and several special steel components (anodic and cathodic collectors, bipolar plates, manifold, vessel, pressure plate) required to assemble the cells into a stack and the stacks into a system [8]. The main materials (Table 1) utilized are nickel (for the electrodes), lithium aluminate (electrolyte-containing support), lithium–sodium or lithium–potassium carbonate (electrolyte), stainless steel (for secondary equipment such as the bipolar plate and gas manifolds) and chromium and/or aluminum for reinforcement and corrosion protection [36]. The balance-of-plant (BoP) includes reformer, inverter, and other minor components. A review of materials used for MCFC components is provided by Hsieh [37].

Typically referred efficiency of MCFC systems is around 47% electrical efficiency and 30-35% thermal efficiency, with an overall system energy efficiency of more than 80% [38]. Up to 50% and 52%, electrical efficiency could be obtained for regular natural gas-fueled MCFC systems. The highest electrical and overall efficiency can be reached by hybrid concepts where heat is used for generating electricity [39].

2.2 Life cycle performance modeling

2.2.1 LCA Goal and Scope definition

Figure 2 shows a simplified resource flow diagram of an MCFC value chain. In this study, a cross-scale assessment of the environmental burdens associated with MCFC system 500 kW is performed. This size was chosen because of the availability of primary data.

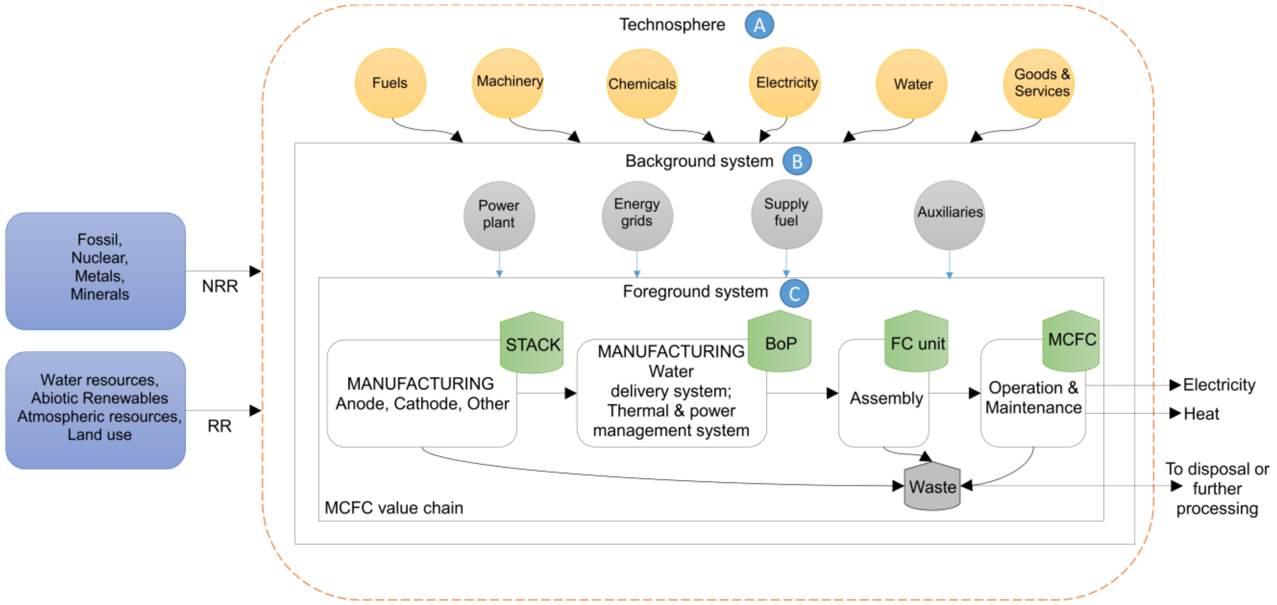


Figure 2. System boundary and process flows included in the LCA of Molten Carbonate Fuel Cell power (MCFC) systems. RR: renewable resources; NRR: non-renewable resources; BoP: Balance of plant; FC: Fuel Cell.

A cradle-to-gate (from raw materials to finished good with no use or end life considerations) study was carried out including the following stages: fuel production, MCFC manufacturing, operation, and maintenance. The system boundary is defined using a thermodynamic hierarchy at three levels (A+B+C). The level A (technosphere) includes all energy and materials conversion processes that are needed to support infrastructure processes in the background system (level B). In other words, the cradle is the natural environment. The background system supports the foreground system and its processes. It deals with almost all material and energy flows going to and coming from the foreground system. The foreground system (level C) comprises all processes related to the production (manufacturing of the anode, cathode, matrix, and electrolyte, as well as the manufacturing of the balance of plant (BoP and the start-up system) and use of the fuel cell (FC) itself and includes all the stages where direct inputs (water, energy, and other materials) are used to produce the functional unit. The functional unit is 1 kWh of electricity as produced by the MCFC system.

MCFCs are a typical example of a multi-functional process as their main products are electricity and heat. Allocation factors (Appendix A) based on the exergy content of products (electricity) and co-products (heat) were used to distribute the environmental burdens among each product [6]. For electricity, the conversion factor is 1. Regarding thermal energy, the conversion is performed using Carnot coefficient ($1-T_{air}/T_0$) of 0.193 calculated using an air temperature (T_{air}) of 20 °C (298.15 K) and thermodynamic mean temperature of delivered heat (T_0) of about 115 °C (383.15 K). This corresponds to an electricity and heat allocation factor of 0.87 and 0.13, respectively.

2.2.2 Life cycle inventory (LCI)

The life cycle inventory (LCI) is the phase of LCA where data are collected, the system is modeled, and the all inputs and outputs in foreground and background system are obtained. Table 1 present the cradle-to-gate input flows of raw materials and energy for each stage for the MCFC system. The compiled LCI was implemented in SimaPro software and the Ecoinvent database [40] is used to model datasets in the background system.

Table 1. Input flows of raw materials and energy for MCFC value chain (one unit 500 kW).

Input	Value	Unit	Reference
MCFC Stack material flows			
Nickel, 99.5%, at plant/GLO	2848.0	kg	[41,42]
Chromium, at RER	124.8	kg	[41,42]
Reinforcing steel, at plant/RER	4248.0	kg	[41,42]
Sheet rolling, steel/RER	4248.0	kg	[41,42]
Lithium, at plant/GLO	296.8	kg	[41,42]
Aluminum oxide, at plant/RER	551.2	kg	[41,42]
Lithium carbonate, at plant/GLO	195.0	kg	[41,42]
Sodium carbonate from ammonium chloride production, at plant/GLO	180.0	kg	[41,42]
Electricity, medium voltage, production UCTE, at grid/UCTE	108.0	MWh	[4]
Ethanol from ethylene, at plant/RER	110.0	kg	[41,42]
Isobutanol, at plant/RER	115.0	kg	[41,42]
Tetrachloroethylene, at plant/WEU	148.5	kg	[41,42]
Modified starch, at plant/RER	21.0	kg	[42,43]
Ethylene glycol, at plant/RER	18.0	kg	[42,43]
Building, multi-storey/CH	0.0	m^3	[40,42]
Building, hall steel construction/CH	0.1	m^2	[40]
Balance-of-plant (BoP) material flows			
Reinforcing steel, at plant/RER	1025.13	kg	[44]
Sheet rolling, steel/RER	1025.13	kg	[44]
Palladium, at regional storage/ RER	0.89	kg	[44]
Platinum, at regional storage/RER	0.12	kg	[44]
Aluminum oxide, at plant/RER	87.75	kg	[44]
Copper, at regional storage/RER	320.12	kg	[44]
Aluminum alloy, AlMg3, at plant/RER	274.37	kg	[44]
Glass wool mat, at plant/CH	45.96	kg	[44]
Inverter, 500kW, at plant/RER	1.00	unit/s	[40]
MCFC infrastructure			
Heating, sanitary equipment cogeneration unit 160kWe/RER/I	1.11	units	[40,42]
Construction work, cogeneration unit 160kWe/RER	4.20	units	[40,42]
Transport, passenger car/RER	2000.00	pkm	[40,42]
Natural gas, burned in industrial furnace >100kW/RER	2500.00	MJ	[40,42]
Light fuel oil, burned in boiler 100kW, non-modulating/CH	12,000.00	MJ	[40,42]
Electricity low voltage, at grid/RER	1.6	MWh	[40,42]
Building, multi-storey/CH	0.352	m^3	[40,42]
Building, hall steel construction/CH	2.118	m^2	[40,42]
MCFC Operation			
Natural gas, at Italian consumer	7.33	MJ/kWh	[42]
Water, deionised, at plant	0.7518	kg/kWh	[42]

In order to estimate the energy and mass requirements, the performance and evaluate the environmental impact of this system, a thermodynamic analysis was developed. The main assumptions that have been taken into consideration during this thermodynamic analysis are:

- Steady state operation at a load of 100 %, i.e., at design conditions.
- Natural gas is used as the feedstock.
- Water is supplied to maintain the reforming process.
- Air mixed with combustion gases is the oxidant in the MCFC.
- All the fluids are treated as ideal gases.
- Water gas shift reaction take place on the surface of the MCFC anode and at a high rate, thus in equilibrium.
- Reforming reaction on the surface of the MCFC anode was not considered by the low quantity of methane present.
- The size and other design parameters of the components were taken from [35,44,45].

  The electrochemical model considered to estimate the voltage losses is the one presented by [46].

A mass and energy balance presented by Eqs. (1) and (2), respectively, is performed by solving the set of equations resulting from the application of the conservation equations to every component and the whole system as presented in Figure 1. The particular set of equations is solved simultaneously by using the EES software v 10.091 [47] and obtained by applying the considerations given in the literature [35,48,49] and explained previously. The details of every thermodynamic state of the system are presented in Appendix A.

$$\dot{\mathrm{m}}_{\mathrm{in}} = \dot{\mathrm{m}}_{\mathrm{out}} \tag{1}$$

$$\dot{\mathrm{W}} - \dot{\mathrm{Q}} = \sum_{\mathrm{in}} \dot{\mathrm{m}}_{\mathrm{in}} \mathrm{h}_{\mathrm{in}} - \sum_{\mathrm{out}} \dot{\mathrm{m}}_{\mathrm{out}} \mathrm{h}_{\mathrm{out}} \tag{2}$$

Where:

- $\dot{m}$: mass flow entering (in) or flowing out (out) the control volume.
- h: enthalpy of the thermodynamic state.
- $\dot{W}$: power realized by or on the system.
- $\dot{Q}$: the rate of heat transfer to or from the system.

The LCI datasets for system manufacturing (stack + balance of plant) are compiled through a combination of scaled literature data [4,8,41], lab-scale data, consultation with engineers and use of data of similar products [43,44]. In the inventory, data for pre-fabrication of materials used (e.g. sheet rolling processes), energy requirement on-site and engineering services, water for manufacturing, and transport are developed using inventories for combined heat and power (CHP) technologies [40]. It is assumed that 25% of solvents used in manufacturing evaporates. MCFC stack lifetime is assumed to be five (5) years. Assuming one maintenance intervention per year, 20% (1/5) of the stack is replaced in each maintenance intervention. The use of infrastructure was defined by the unit process needed by the total amount of product generated during the lifetime of the installation.

Input (fuel, water, and air) and outputs (flue gases to the environment) during the operation phase were simulated. The gas concentration ratio between the harmful emissions and carbon dioxide (CO_2) was retrieved from company data [50]. After the service life, the MCFC is dismantled and materials are recycled, however, no environmental burdens from dismantling and recycling are considered (cut-off).

2.2.3 Life Cycle Impact assessment models and indicators

The LCIA framework adopted in this study employs two LCIA models to account for all environmental life cycle burdens, i.e. from resource consumption to the final effect on the areas of protection (ecosystem quality, human health, and natural resources). The resource consumption impacts are assessed by Cumulative Exergy Extraction from the Natural Environment (CEENE) method, while the environmental sustainability is assessed using LCA-ReCiPe 2016 methodology (both midpoint and endpoint).

Cumulative exergy extracted from the natural environment (CEENE) is a resource accounting method quantifying different types of resources per functional unit (Eq. 3) in a single unit (exergy). By multiplying the resource inputs in Table 1 with CEENE factor of the reference flow the amount of energy equivalent to each input in each process is calculated.

$$\mathrm{CEENE_j} = \sum_{\mathrm{i}=1}^{184} (\mathrm{X_i} \times \mathrm{a_{i,j}}) \tag{3}$$

Where:

- $\mathrm{CEENE_j}$ is the cumulative exergy extracted from the natural environment for a product j (in $\mathrm{MJ_{ex}}$),
- $\mathrm{X_i}$ is the factor of the reference flow i ($\mathrm{X_i}$ in $\mathrm{MJ_{ex}}$/ kg, $\mathrm{MJ_{ex}}$/MJ, $\mathrm{MJ_{ex}/Nm^3}$),
- $\mathrm{a_{i,j}}$ is the cumulative amount of reference flow i (kg, MJ, $\mathrm{Nm^3}$, $\mathrm{m^2{\cdot}a}$) necessary to obtain product j.

The CEENE model is based on global generic factors. It accounts for the depletion created by the extraction of useful exergy embedded in resources when these are extracted from their natural environment, including abiotic renewable resources, fossil fuels, nuclear energy, metal ores, minerals and mineral aggregates, water resources, land and biotic resources, and atmospheric resources [31,51,52]. A detailed explanation of CEENE method is provided by Dewulf et al. [31]. SimaPro software was used to calculate the environmental impacts using the extended version of the CEENE method [52].

The LCI flows were further converted to a number of harmonized impact scores on midpoint and endpoint level (Figure 3) using the LCA-ReCiPe 2016 [34]. The following midpoint environmental impact categories are considered: global warming potential (GWP), stratospheric ozone depletion (ODP), ionizing radiation (IRP), photochemical oxidant formation: human health (HOFP), photochemical oxidant formation: ecosystem quality (EOFP), human toxicity potential: cancer (HTP_c), human toxicity potential: non-cancer (HTP_{nc}), terrestrial ecotoxicity potential (TETP), freshwater ecotoxicity potential (FETP), marine ecotoxicity potential (MAETP), freshwater eutrophication potential (FEP), fine particulate matter formation (PMFP), terrestrial acidification (TAP), land use (LOP), water consumption potential (WCP), mineral resource scarcity (SOP) and fossil resource scarcity (FFP). At endpoint level, the area of protection impacts (human health, ecosystem quality, and resource availability) was calculated.

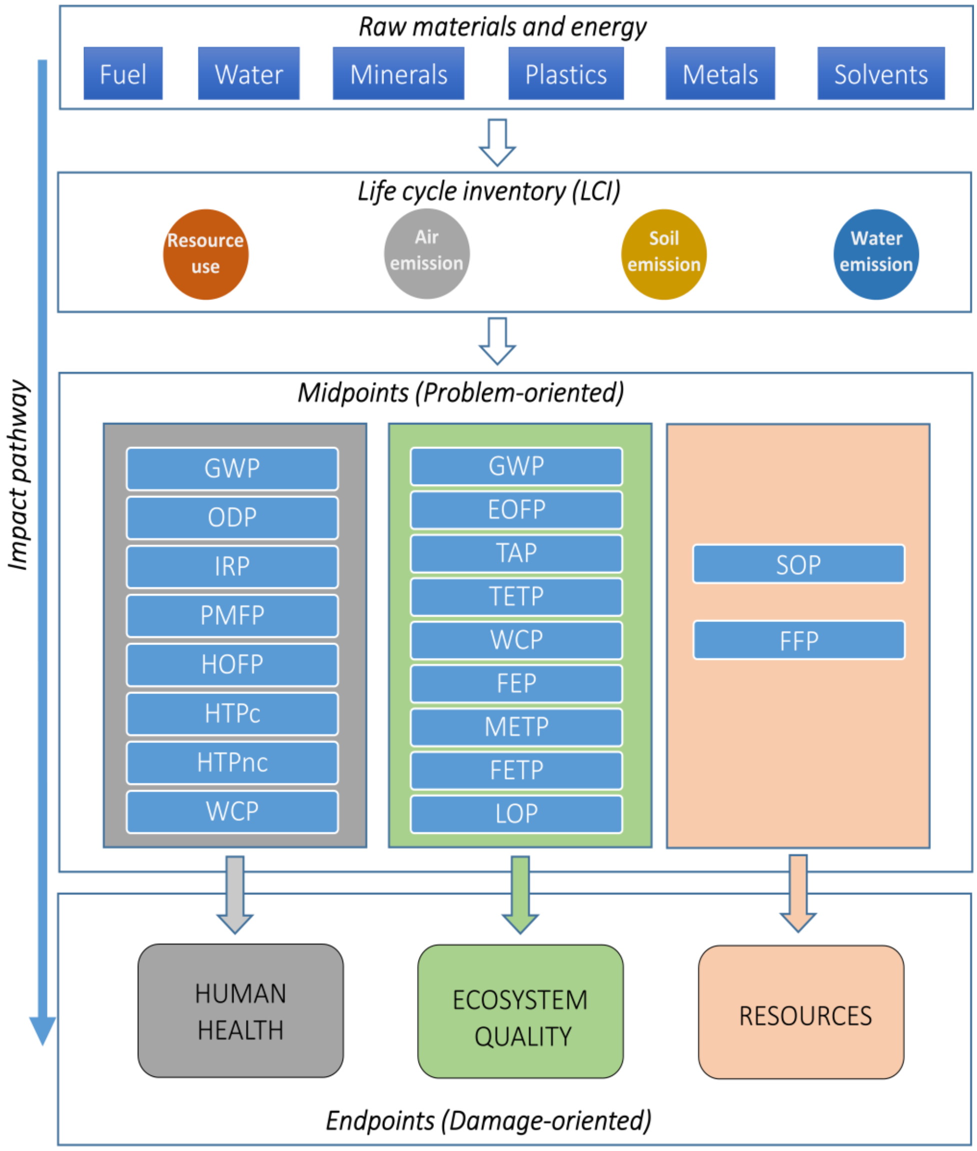


Figure 3. Schematic steps from life cycle inventory to midpoint and endpoint environmental impact category with ReCiPe 2016 model.

The impact of water use on human health, the impacts of water use and climate change on freshwater ecosystems, and the impacts of water use and tropospheric ozone formation on terrestrial ecosystems as novel damage pathways are included in the assessment.

2.3 Economic analysis

For comparing energy supply technologies from an economic point of view, the levelized cost of electricity (LCOE) is frequently applied [53]. The LCOE is a life-cycle cost concept that includes all physical assets and resources required to deliver one kilowatt-hour (kWh) of electricity (Table 2).

Table 2. Metrics used to characterize Levelized cost of electricity (LCOE).

Metric	Equation	Notes
Levelized cost of electricity (LCOE)	$LCOE = \frac{\alpha \cdot I + OM + F}{E}$	A - is the capital recovery factor (CRF); I - Investment cost; OM - Net annual operation and maintenance costs; F- annual fuel cost; E- electricity
Capital recovery factor (CRF)	$CRF = \frac{r}{1-(1+r)^{-L_T}}$	r - is the weighted average cost of capital (WACC); L_T is the project duration (in operation); i - is the interest rate over the construction loan
Investment cost (I)	$I = \frac{C}{L_B} \cdot \sum_{t=1}^{L_B} (1+i)^t \cdot \left(1 + \frac{d}{(1+r)^{L_T}}\right)$	C - is the capital costs, excluding finance cost for construction (‘overnight cost’); d - represent the decommissioning cost.
Net annual operation and maintenance costs (OM)	$OM = FOM + (VOM - REV + d_{\vartheta})$	FOM - fixed net annual operation and maintenance costs; VOM - variable net annual operation and maintenance costs; REV - variable byproduct revenues
Electricity (E)	$E = P \cdot FLH$	P - plant capacity; FLH - number of (equivalent) full load hours
Annual fuel costs (F)	$F = FC \cdot \frac{E}{\mu}$	FC - fuel costs per unit of energy input; μ - conversion efficiency (in lower heating value - LHV)

In this study, the economic sustainability is analyzed calculating the LCOE using the fuel cells Cost of Renewable Energy Spreadsheet Tool (CREST), a cash flow model [54]. The CREST is an Excel-based tool which allows estimating the LCOE accounting for different cost-based incentives. Costs and other economic data considering the operating parameters of each equipment are based on current industry trends (Table 3).

Table 3. Installation cost of MCFC system and associated components [23,55–60].

Equipment	Investment cost
MCFC	$ 1,300,000.00
Auxiliary device MCFC	$ 130,000.00
Compressor	$ 4,964

Re-compressor	$ 6,764
Catalytic burner	$ 179,369
Reformer	$ 92,253
Total	$ 1,713,353

3 Results and discussion

In the following paragraphs, the results of the are presented and discussed. Results are reported as follows: (i) Inventory data (material and energy input/output) during one-year operation (ii) Resource consumption assessment by ELCA using the Cumulative Exergy Extraction from the Natural Environment method (CEENE) method; (iii) Midpoint and endpoint impact assessment results using LCA-ReCiPe 2016; (iv) Comparison of MCFC life cycle performance with other energy conversion systems; (v) The levelized cost of electricity (LCOE).

3.1 MCFC system operation inventory

The simulation results are presented in Table 4 (data are given as annual averages). All the inventory structure and detailed flow results for every system are available in Appendix A. The electrical efficiency and the total (energetic) efficiency of the overall system are calculated to be 44% and 77%, respectively. The net produced power is calculated to be 423 kW. Using an availability factor of 90% this corresponded to 3.34-gigawatt hour (GWh) of net electricity production. The annual mass of carbon dioxide (CO_2) amounted to 1.71E+06 kg CO_2-eq corresponding to 0.51 kg CO_2-eq/kWh. The values fit very well with values reported from fuel cell energy company [50] reporting a value of 0.445 kg CO_2-eq/kWh. There is a wide range of corresponding values reported in literature: 0.552 kg CO_2-eq/kWh [10]; 1.02 kg CO_2-eq/kWh [11]; 0.4861 kg CO_2-eq/kWh [61], 0.44 kg CO_2-eq/kWh [62]. Lower CO_2 emissions per unit of the power supply can be realized with higher plant efficiencies and application of CO_2 capture and storage (CCS) technologies. The pollutant emissions, such as nitrous oxide (NO_x), sulfur dioxide (SO_x) or carbon monoxide (CO), are very low. The emissions of NOx and SOx correspond to approximately 15 and 0.15 kg/year, respectively. In pure hydrogen operation, these are zero [39].

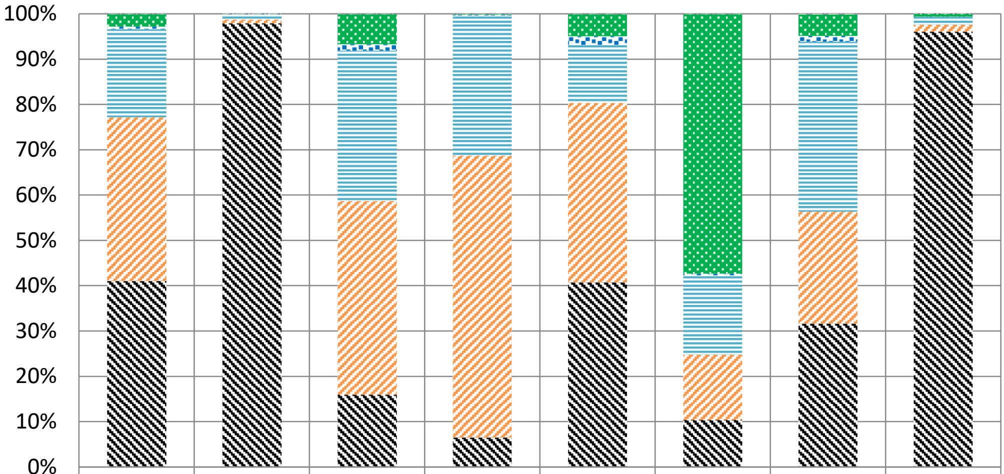
The MCFC technology offers significantly lower emissions rates compared to other heat and power systems such as reciprocating engine, micro-turbine, and gas turbine [38]. During the one-year operation of the system, 948 GJ of thermal energy is produced as a by-product.

Table 4. Normalized input-output flows for MCFC system in one-year operation.

Description	MCFC	Unit
Electrical efficiency	44	%
Thermal efficiency	77	%
Average capacity factor	90	%
Net power production	423.6	kW
Auxiliary system consumption	35.5	kW
Voltage	0.761	Volt
Current density	1,350	A/m^2
Fuel consumption	622	t/year
Water consumption	2,511	t/year
CO_2-gases	1,705	t/year
H_2O-gases	4,125	t/year
N_2-gases	26,213	t/year
NOx-gases	15	kg/year
SOx-gases	0.15	kg/year
Electricity production	3,340.17	MWh/year
Gross heat available	3402.75	GJ/year
Net thermal energy recovery	948	GJ/year

3.2 Life Cycle Impact Assessment - CEENE

In this section, we discuss the exergy-based performance analysis of MCFC systems quantified by the CEENE method. For simplicity, the results for stack and balance-of-plant (BoP) manufacturing are given in the supplementary information (Appendix A). Figure 4 presents the quantified CEENE scores for a single unit of energy produced from MCFC systems encompassing a cradle-to-gate approach. The numerical results show that impacts vary across resource categories. To generate 1 kWh of electricity an MCFC system will need approximately 8.85 MJ_{ex} over the life cycle where about 96% of aggregated CEENE impact (~8.496 MJ_{ex}) is attributed to the fuel supply. As can be seen in Figure 4 the fossil fuels resource group are by far the most important one in the energy chain. Another important resource impact category is nuclear energy. The CEENE assessment shows that energetic resources consumption produces the largest share of depletion impact, followed by metals and by mineral resources. The use stage is considered the one with the largest share of potential impact with respect to water resources where on-site water use (linked to reforming) contributed to more than 50% of water use.



	Abiotic renewable resources	Fossil fuels	Nuclear energy	Metal ores	Minerals (and mineral aggregates)	Water Resources	Land and biotic resources	Aggregated CEENE
⁘ Maintenance	1.63E-05	4.72E-04	5.21E-05	3.57E-06	1.60E-06	2.24E-05	2.54E-05	5.94E-04
▩ MCFC operation	1.17E-03	6.34E-03	4.24E-03	1.41E-05	9.73E-05	4.26E-02	8.95E-04	5.53E-02
⁙ Water supply	2.36E-04	3.72E-03	8.65E-04	1.00E-05	3.95E-05	2.99E-04	2.49E-04	5.42E-03
≡ Mfg. BoP	8.09E-03	9.62E-02	2.12E-02	2.57E-03	2.58E-04	1.30E-02	7.14E-03	1.49E-01
▨ Mfg. Stack	1.51E-02	7.35E-02	2.73E-02	5.17E-03	7.99E-04	1.07E-02	4.70E-03	1.37E-01
▧ Fuel production & supply	1.71E-02	8.46E+00	1.02E-02	5.37E-04	8.22E-04	7.71E-03	6.02E-03	8.50E+00

Figure 4. The aggregated contribution of life-cycle phases to the CEENE footprint for different resource categories for 1 kWh of electricity.

What can be evinced from Figure 4 is that the high demand for metal ores, minerals, and nuclear energy are needed in the manufacturing stage, where production of anode contribute to the most to these resource impacts (see Appendix A for a detailed assessment). This is due to more energy intensive processes and a large amount of nickel, chromium, and electricity employed in energy chain. The highest impact comes from stack manufacturing because FC stack lifetime is too short and results in higher energetic cost and thereby resource footprint. For the BoP, inverter, and reformer are marked as the most impacting. Nevertheless, during the entire fuel cell lifespan, manufacturing and disposal processes contribute not more than 5% to total CEENE score. Similar conclusions have been drawn in previous research on LCA literature of Molten Carbonate Fuel Cells [4]. To reduce the resource depletion environmental impacts, construction material saving should be achieved but also materials with lower footprints could be used in order to substitute materials with higher ones. Therefore, future research should focus on process optimization, i.e. optimize resource usage and/or substitute renewable materials for non-renewable ones are the key factors toward eco-innovative MCFC products.

3.3 Life Cycle Impact Assessment - ReCiPe 2016

Table 5 summarizes the cradle-to-gate numerical results of the environmental impacts of MCFC energy production. Results show that majority of categories are dominated by fuel supply, while some others are dominated by manufacturing of stack and BoP. The manufacturing phase is extremely relevant for toxicity potential indicators (human-HTP, marine-METP, and freshwater-FETP), metal resource scarcity (SOP), water consumption (WCP) and land occupation (LOP). The large impact is generated by valuable metals (steel, nickel, copper, iron, chromium, aluminum and their production chain) used for the construction of the cell, stack as well as for BoP (Appendix A). This is partly due to the low lifetime of the stack: it has to be exchanged during the lifetime of the total system. Consequently, the contribution of maintenance is strongly dependent on the periodical catalyst and stack replacement, which is directly related to the achievable service lifetime of the MCFC. In a similar analysis, Staffell et al. [63] estimated that for 10 years of operation for solid oxide fuel cells (SOFC) and considering multiple stack exchanges the carbon footprint was 2.9 times greater than if only one stack was required.

The BoP manufacturing significantly affects ozone depletion (ODP), ecotoxicity related categories (METP, FETP, and TETP), and mineral resource scarcity (SOP) due to the material (mainly palladium) needed for the reformer. For the BoP, other significant contributions are caused by inverter made of copper and nickel. Such observations were found to be similar to Rillo et al. [43]. Other components were of a less relevance. Replacing materials for the reformer or use of "green" hydrogen can substantially decrease or even withdraw reformer impacts [8].

Table 5. Midpoint and endpoint environmental impact indicators for MCFC system using ReCiPe 2016 impact assessment method.

Impact category	Unit	MCFC (unit/kWh$_{el}$)
Midpoint environmental indicators (Problem-oriented)		
Global warming potential (GWP)	kg CO_2-eq	5.49E-01
Stratospheric ozone depletion (ODP)	kg CFC-11-eq	4.11E-06
Ionizing radiation (IRP)	kBq Co-60 to air-eq	3.28E-03
Photochemical oxidant formation: human health (HOFP)	kg NO_x-eq	2.12E-04
Fine particulate matter formation (PMFP)	kg PM2.5-eq	1.35E-04
Photochemical oxidant formation: ecosystem quality (EOFP)	kg NO_x-eq	2.33E-04
Terrestrial acidification (TAP)	kg SO_2-eq	5.06E-04
Freshwater eutrophication potential (FEP)	kg P-eq. to freshwater	9.81E-06
Terrestrial ecotoxicity potential (TETP)	kg 1,4-DB-eq	4.71E-05
Freshwater ecotoxicity potential(FETP)	kg 1,4-DB-eq	9.86E-04
Marine ecotoxicity potential (METP)	kg 1,4-DB-eq	1.52E-03
Human toxicity potential: cancer (HTP$_c$)	kg 1,4-DB-eq	2.76E-02
Human toxicity potential: non-cancer (HTP$_{nc}$)	kg 1,4-DB-eq	1.05E+00
Land use (LOP)	m^2 × year annual cropland	2.30E-04
Mineral resource scarcity (SOP)	kg Cu-eq	6.12E-04
Fossil resource scarcity (FFP).	kg oil-eq	1.87E-01
Water consumption potential (WCP)	m^3 of water consumed	8.54E-02
Endpoint environmental indicators (Damage-oriented)		
Human Health (HH)	DALY	1.46E-06
Ecosystem quality (ED)	Species × year	2.81E-09
Resource availability (RA)	USD2013	6.67E-02

Fuel supply phase results to be responsible for a relevant share for the analyzed impact categories of photochemical oxidant formation (both human health and ecosystem quality), fine particulate matter formation (PMPF), terrestrial acidification (TAP), and fossil resource scarcity (FFP). Among the seventeen midpoint impact categories, MCFC system operation mainly affects global warming potential (GWP) accounting for nearly 80% of the total GWP. Similar figures were estimated by Gerboni et al. [39] highlighting the importance of carbon dioxide (CO_2) emission (main contributor to GWP) during the operation phase. In general, the state-of-the-art literature confirms that the system operation dominates the GWP impact category [4,64].

The production of the infrastructure of MCFC system has almost no significance for the GWP.

The MCFC in operation phase also affects terrestrial acidification (TAP), photochemical oxidant formation: ecosystem quality (EOFP), and photochemical oxidant formation: human health (HOFP), due to the released nitrous oxide (NO_x) and sulfur oxide (SO_x), however, they have a negligible contribution.

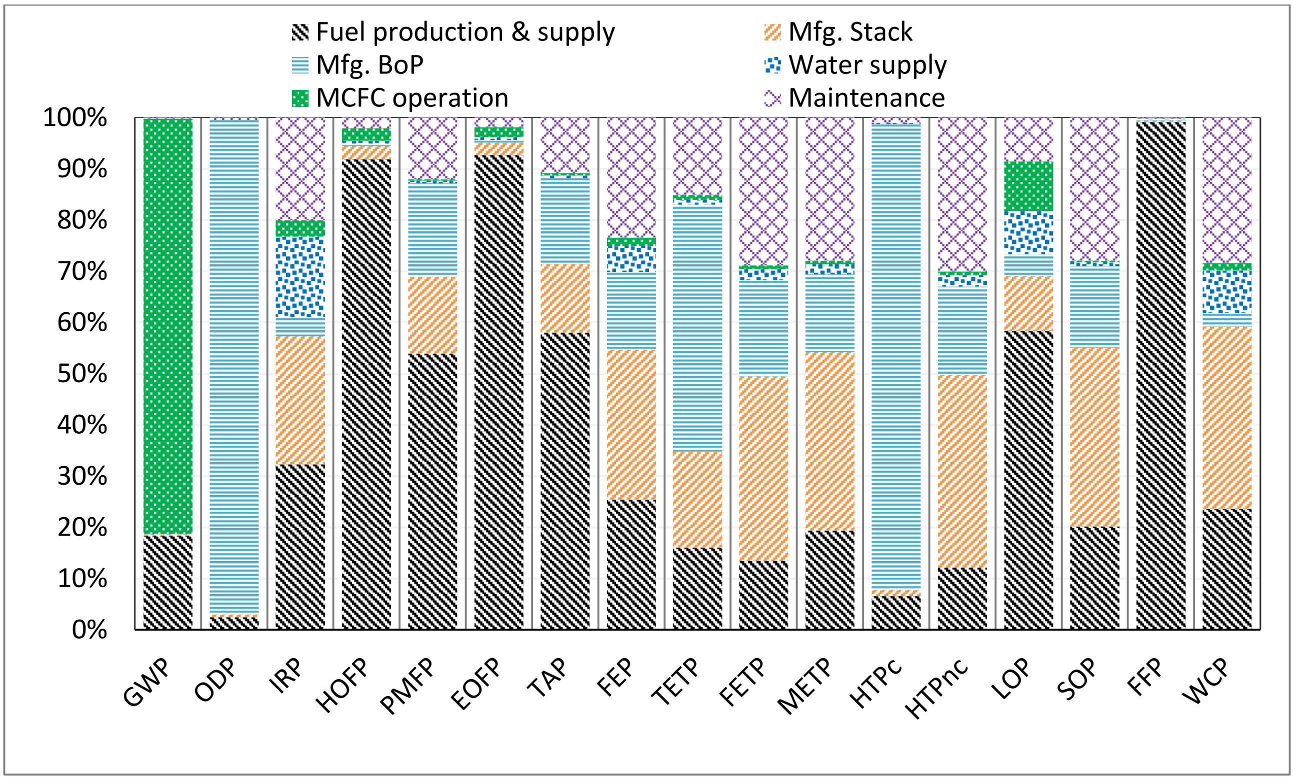


Figure 5. ReCiPe 2016 midpoints and shares according to life-cycle phases for 1 kWh of electricity. Abbreviations: Global warming potential (GWP); Stratospheric ozone depletion (ODP); Ionizing radiation (IRP); Photochemical oxidant formation: human health (HOFP); Fine particulate matter formation (PMFP); Photochemical oxidant formation: ecosystem quality (EOFP); Terrestrial acidification (TAP); Freshwater eutrophication potential (FEP); Terrestrial ecotoxicity potential (TETP); Freshwater ecotoxicity potential (FETP); Marine ecotoxicity potential (METP); Human toxicity potential: cancer (HTP_c); Human toxicity potential: non-cancer (HTP_{nc}); Land use (LOP); Mineral resource scarcity (SOP); Fossil resource scarcity (FFP); Water consumption potential (WCP).

Ecological impacts resulted from global warming potential (GWP), and other midpoint categories (Table 5) are associated with one or more of the damage categories (Human Health–HH, Ecosystem Quality–ED, and Resource availability–RA) as depicted in Figure 3. For human health impacts, the impacts are attributed to stack (31.5%), MCFC operation (28.6%), maintenance (25.2%), fuel supply (13.1%), and remaining to other stages. For the ecosystem quality impact category MCFC operation accounts for 44.4% of impacts, stack production for 15.2%, maintenance for 12.3% and the rest of natural gas supply with 23% share. For damage to resource almost whole environmental impacts are caused due to natural gas supply, affecting greatly fossil fuel category. The production of energy by an MCFC system is of environmental relevance due to GWP impact category, which greatly influences endpoint impact categories of human health and ecosystem quality.

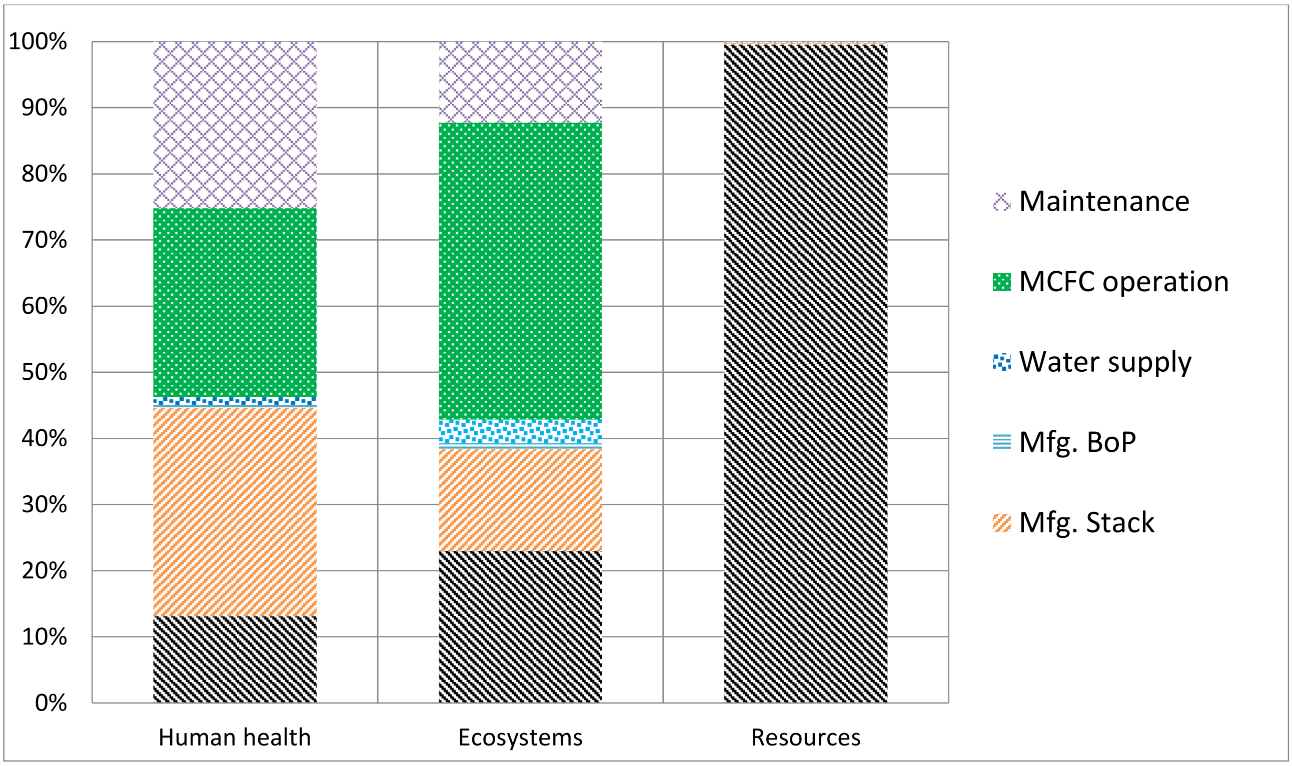
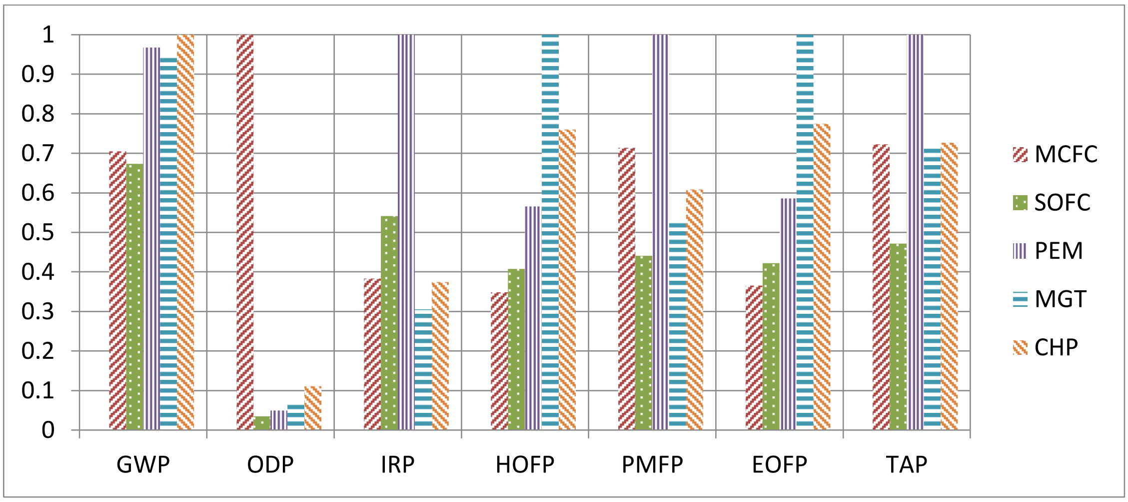


Figure 6. ReCiPe endpoints and shares according to life-cycle phases for 1 kWh of electricity.

3.4 Comparative LCA of power generation

The key question, raised among stockholders is whether MCFC technology is significantly better than conventional technologies. A comparative LCA of various energy production is included in this study with inventories available from Ecoinvent database (Reference). In this way, the alternative systems are ranked according to their respective performance. Energy options differ in the nature and scale of their environmental impacts and there is no energy technology as a perfect solution. In terms of operational performance, MCFCs are robust and able to compete with other mature technologies contributing to positive environmental impact and carbon footprint reduction, especially due to the high energy conversion efficiency. A high efficiency is translated into reduced fuel consumption and corresponding emissions [65]. As Figure 7 shows, for indicators which mainly depend on operation phase (e.g., GWP and CEENE) fuel cell systems show a superior performance. As regards MCFC they are penalized by their high use or rare-earth materials which greatly affected the impact categories depending on manufacturing stage (impacts in terms of extraction and processing, affecting mineral resource scarcity, toxicity related impact categories, water depletion, and ionizing radiation). This study calculates unusually high impacts of the manufacturing process, however, our assessment is effected by great uncertainty in the manufacturing stage. Hence more detailed data collection, with focus on obtaining information from manufacturers and facilities will greatly increase the representativeness and the value of the results [43]. The challenge of assessing emerging technologies such as high-temperature fuel cells with LCA has been described in the scientific literature [4,43,64]. It should be noted that the LCA studies inevitably have large variability, depending on the inventory data (experimental vs. generic), modeling approaches (i.e. system boundaries allocation method selected) and depend on a large number of parameters of the system operation (geographic and climate conditions, fuel quality, efficiency, voltage, etc.).



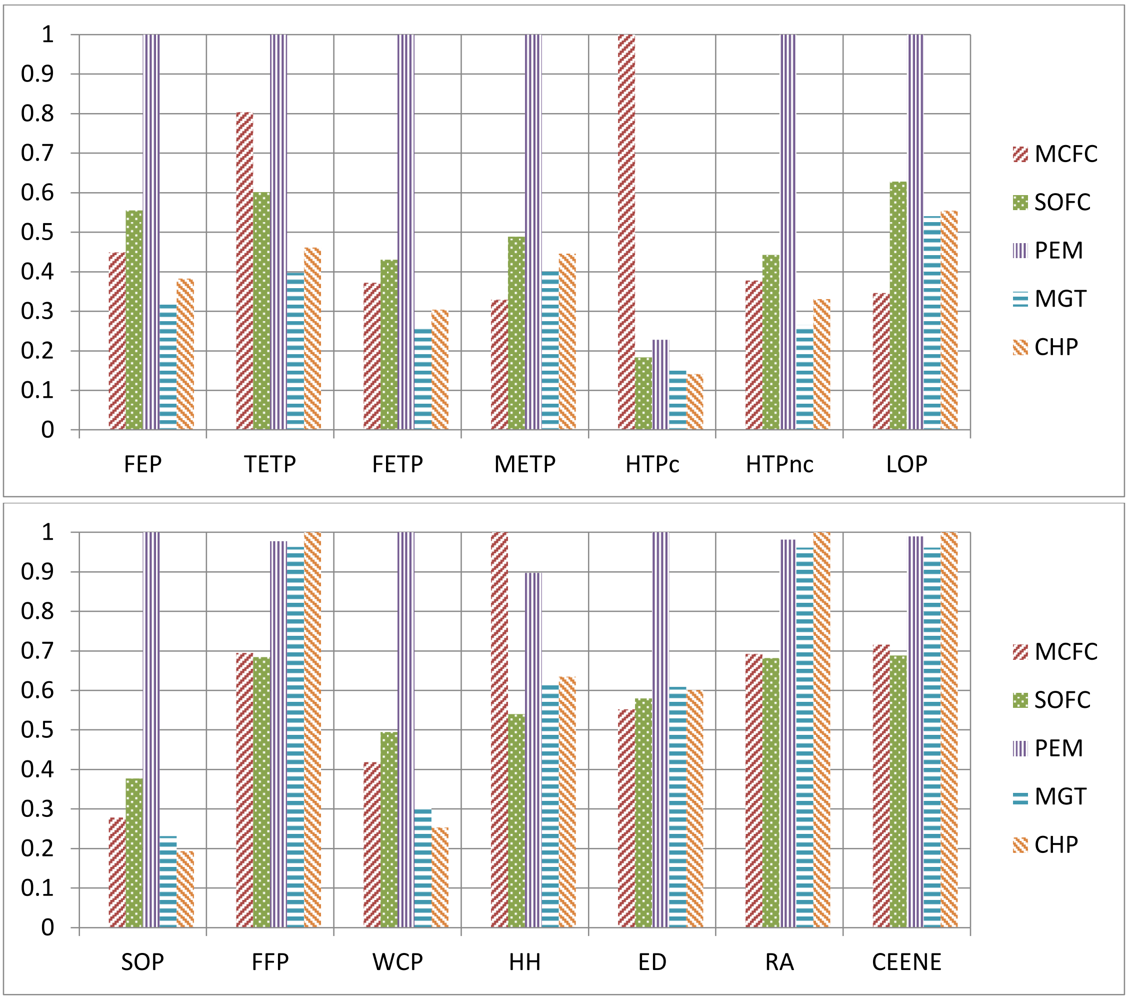


Figure 7. Comparative life-cycle impact assessment of power generation technologies. Normalized to the highest impact with values in Appendix A. Abbreviations: Global warming potential (GWP); Stratospheric ozone depletion (ODP); Ionizing radiation (IRP); Photochemical oxidant formation: human health (HOFP); Fine particulate matter formation (PMFP); Photochemical oxidant formation: ecosystem quality (EOFP); Terrestrial acidification (TAP); Freshwater eutrophication potential (FEP); Terrestrial ecotoxicity potential (TETP); Freshwater ecotoxicity potential (FETP); Marine ecotoxicity potential (METP); Human toxicity potential: cancer (HTP$_c$); Human toxicity potential: non-cancer (HTP$_{nc}$); Land use (LOP); Mineral resource scarcity (SOP); Fossil resource scarcity (FFP); Water consumption potential (WCP); Human health (HH), Ecosystem quality (EQ); Resource availability (RA); Cumulative exergy extractions from the natural environment (CEENE).

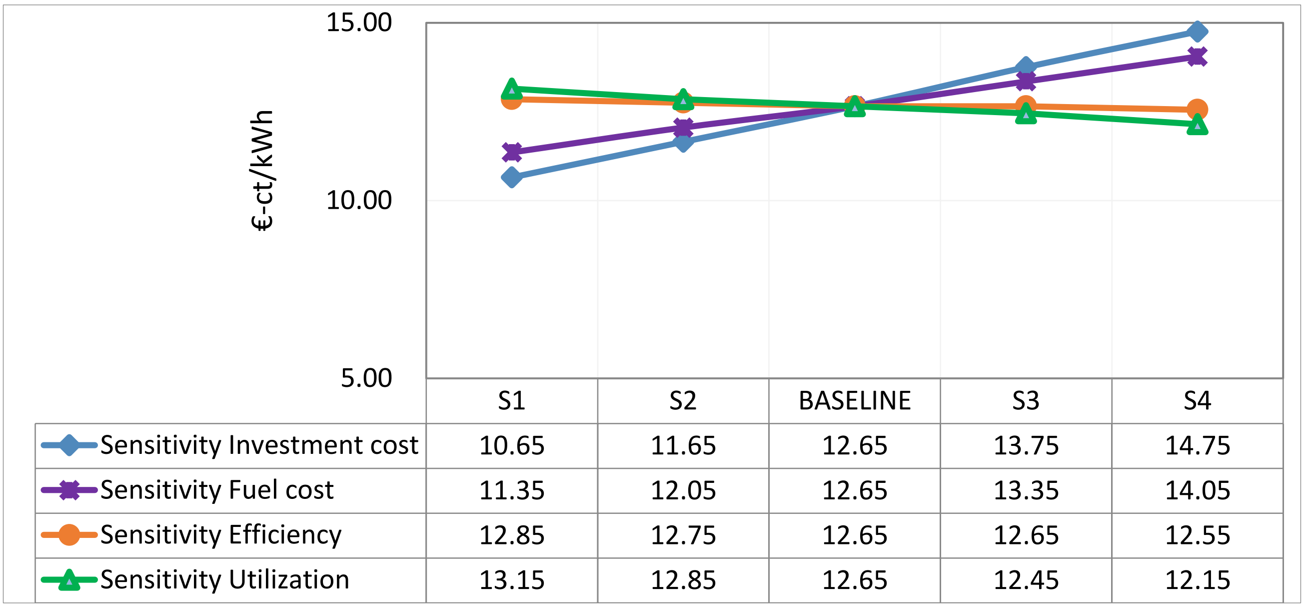
MCFC technology is not yet fully commercialized, nonetheless, is increasingly used in stationary power generation from small to multi-megawatt baseload power plant applications. Different steps of development are considered to intervene in the future configurations: increase in lifetime endurance of components, upscale of power output, increase of efficiency and material reduction [39]. Optimization of system manufacturing advances in longer lifetimes of the stack and spent stack recycling would, therefore, be highly beneficial to the overall environmental performance of

MCFC since they are significantly affected by input nickel and electricity. Further, with relatively higher reductions of the overall environmental impact can be achieved in the manufacturing using clean and alternative energy sources of electricity in the manufacturing. For a single unit of energy generation shifting from fossil-based (e.g. coal-generated electricity) to renewable (solar and wind), for example, a significant GWP reduction could be achieved. Other significant advantages could be obtained with a higher share of renewable-based energy input in electricity mix since solar and wind do not produce atmospheric emissions (NO_x, SO_x, and particulate matter-PM) that increase eutrophication, acidification, photochemical, and respiratory effects. Lee et al. [66] compared different sources of electricity input in the manufacturing of SOFC systems showing that contribution of the manufacturing stage to the overall environmental impact can vary in the range from 32% to 170%, depending on the energy mix used for electricity generation.

MCFC power plants are flexible in fuel input and energy output including natural gas and renewable biogas. The EU targets “20-20-20” related to renewable energy is forcing the EU countries to be fossil fuel independent. An option, which will be assessed for the future FC systems is the possibility to supply MCFC with fuel originating from the renewable source. Renewable biogas from food biomass, biomass, wastewater treatment plants and landfills provide a long-term outlook for reliable on-site power generation delivered in an environmentally friendly manner. In terms of resource consumption, the biogas is more favorable than the natural gas, with a 22% lower exergy input required to produce 1 kWh. While natural gas demand more fossil fuel energy, biogas demand more minerals, metal ores and land resources due to a more complex infrastructure chain. Nevertheless, natural gas has much higher total CEENE score than biogas or syngas fuels due to noticeable impacts in terms of fossil fuel energy requirements. However, the diffusion of natural gas-fueled MCFCs will continue to grow since the use of natural gas as a fuel is supported by the great advantage of not needing a dedicated new infrastructure. Thus, due to the higher electric efficiency natural gas MCFC completely disconnected from the fossil fuels group.

3.5 Levelized cost of electricity (LCOE)

Apart from the environmental performance, the economic sustainability was analyzed calculating the levelized cost of electricity (LCOE) with data presented in section 2.3. The baseline LCOE was calculated 12.65 ¢/kWh. The LCOE of MCFC technology varies according to the power plant specifications and fuel prices. Hence, a sensitivity analysis was performed to study the influence of specific investments (±50%), full load hours (±5%), fuel costs (±50%) and efficiency (±10%) with respect to their influence on the LCOE (Figure 8).



	S1	S2	BASELINE	S3	S4
Sensitivity Investment cost	10.65	11.65	12.65	13.75	14.75
Sensitivity Fuel cost	11.35	12.05	12.65	13.35	14.05
Sensitivity Efficiency	12.85	12.75	12.65	12.65	12.55
Sensitivity Utilization	13.15	12.85	12.65	12.45	12.15

Figure 8. Effect of different parameters to LCOE of plant configurations. (Note: Unsubsidized figures; Analysis assumes 50% debt rate at 5% interest rate and 40% equity at 12%).

The LCOE from MCFC systems vary from 10.65 to 14.75 ¢/kWh. Lazard's LCOE consulting report [67] estimated a range from 9.8 to 17.4 ¢/kWh. The sensitivity analysis shows that reduction of investment cost and acceptable natural gas cost can lead to competitive LCOE also with renewable power generation systems. Kost et al. [68] estimated that LCOE from photovoltaic plant (PV) was under 0.120 €/kWh for all PV power plant types at the considered irradiation range of 1450 – 2000 kWh/(m²a), while the LCOE for wind power was 0.045 and 0.107 €/kWh (onshore, with specific investment cost between 1000 and 1800 €/kW) and 0.119 to 0.194 €/kWh (onshore, with specific investment cost between 3500 and 4500 €/kW). The LCOE from an MCFC system is competitive with the Italian grid electricity price for industrial users, reported by EUROSTAT [69] about 0.161 €/kWh for 2015 and 0.153 €/kWh for 2016, respectively. The costing results indicate that the unit decreasing the system capital cost could potentially reduce the LCOE by around 25%. The potential for lower energy and operating costs is assumed to be the main cost advantage of MCFCs. A reasonable natural gas price will maintain a competitive LCOE, while a likely increase in gas cost will shift the economic advantages towards renewable energy carriers [39]. Furthermore, technical optimization of MCFC systems (e.g. decreasing the fuel utilization factor and decreasing cell voltage) will result in improved system economics [70]. The MCFC is still not competitive with conventional power generation systems, however, because MCFCs are not yet fully commercialized they have still a right cost-performance trade-off for market take-up while mature technologies, probably will remain at the current price level [71]. Today the LCOE from MCFCs is already at a very low level and will only decrease in the future since the shipments of MCFC fuelled with natural gas is increasing continuously, with a predominance of the Asian and North American markets. This has led to a strong competitive area and reduction of production costs are currently undercutting 3000-5000 €/kW, targeting prices lower than 1000 €/kW by 2020. It is estimated that with suitable production volumes, investment cost can decrease from 30% at 500 units per year up to 60% at 100k units per year, thus becoming also cost-competitive with currently widely used energy technologies [72]. Indeed, fuel cell systems are already competitive compared with central generation in some countries as demonstrated by McPhail et al. [65]. The installation of a CHP plant can reduce energy costs, but for full-fledged market penetration in this field, much depends on the relative costs of fuel (mainly natural gas) and the price that can be obtained for the electricity sold, which in turn are site-specific. Thus, competitiveness in the economic sense is achievable with appropriate support policies and economics. From an international experience it has been demonstrated that if government subsidy is provided at 50% of system cost, FC can offset the initial investment through energy saving in around 3 to 5 years, thereby successfully capitalizing on superior performance in terms of efficiency, emissions, and economics. It is highlighted that a modest reduction in the range of 3 to 4 cents/kWh will result in significant market penetration without the necessity of government subsidies [73]. For MCFCs a potential income is also expected from emission trading according to very low emissions since their CO_2 reduction potential source-to-user is highly attractive. Moreover, versatile properties of MCFC to be adapted and integrated with high-temperature solar energy sources for hydrogen production for water and CO_2 electrolysis in molten carbonate electrolytes represent great opportunities in developing a future and sustainable molten carbonate technology for advanced applications in various sectors of the energetic field [74].

4 Conclusions

A multi-impact assessment combining resource-driven and emission-driven environmental life cycle assessment and economic criteria was performed in this study for stationary Molten Carbonate Fuel Cells (MCFCs) to provide a new integrated vision and quantified indicators of the sustainability performance of such technologies. A resource-driven exergetic life assessment (ELCA) was performed to quantify the resource footprint using Cumulative Exergy Extraction from the Natural Environment (CEENE) method. The CEENE analysis revealed that manufacturing of MCFC system is of high importance for individual resource categories, however, over the entire fuel cell lifespan, such processes would account for less than 5 % of the total CEENE score. The total depletion impacts were driven by energetic resources consumption (natural gas supply) where the fossil fuel dominates the aggregated CEENE. The analysis further extended to seventeen midpoints (problem-oriented) and three endpoints (damage-oriented) indicators using LCA-ReCiPe 2016 indicated the need for alternative renewable energy sources and process optimization in manufacturing, alternative materials, and their recycling. The majority environmental impacts in manufacturing were driven by the stack, influenced by the anode where the nickel and electricity consumption were the largest contributors. The comparison with main competitors (internal combustion engines and microturbines) in the field shows that due to its operating characteristics of

MCFC the system operates with lower environmental impacts, especially for those related to fuel consumption.

Molten Carbonate Fuel Cells are still in commercialization phase, hence, achieve of more eco-innovative MCFC needs to be handled, importantly, with low-cost solutions, preferably amenable to large-scale production. In this way, the advantage in overall efficiency and low environmental impact of the MCFC compared with conventional technologies will be supported by a competitive price tag, making up the delay in one leap and leaving the road open for a challenging future where high quality is obtained with minimal waste and at an acceptable cost. This study should be continually updated and improved as new technology parameters and life cycle assessment methodologies become available. By conducting life cycle oriented analysis continuously, environmental hot spots and bottlenecks of future technological designs – based on technology forecasting studies or learning curve studies may be identified. This information can be used together with other factors to optimize these processes. The application of harmonized and robust multi-criteria analysis will evaluate significant implications for environmental and economic sustainability, thus, generating eco-efficient MCFC products.

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