Energy Conversion and Management 168 (2018) 276–287

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

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

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ARTICLE INFO

Keywords:
Molten Carbonate Fuel Cells
Exergy
LCOE
LCA and ELCA
Eco-efficiency

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). The levelized cost of electricity (LCOE) under technology cost and performance parameters was calculated to analyze the system from the economic point of view. 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.

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

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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

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https://doi.org/10.1016/j.enconman.2018.04.095
Received 1 November 2017; Received in revised form 24 April 2018; Accepted 25 April 2018
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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]. 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). 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]. 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

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