Journal of Power Sources 308 (2016) 97–108

Contents lists available at ScienceDirect

Journal of Power Sources

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

Review article

Life cycle assessment of molten carbonate fuel cells: State of the art and strategies for the future

Andi Mehmeti [a, b, *], Francesca Santoni [a, b], Massimiliano Della Pietra [b], Stephen J. McPhail [b]

[a] *Department of Science and Technology – DIST, Parthenope University of Naples, Centro Direzionale, Isola C4, Naples 80143, Italy*
[b] *ENEA, Casaccia Research Center, Via Anguillarese 301, Rome 00123, Italy*

HIGHLIGHTS

- State of art of LCA on Molten Carbonate Fuel Cells is reported.
- Key LCA concepts, critical issues and best practices are highlighted.
- MCFC system implication to environmental impact categories is described.
- Cross-sectorial environmental analysis is performed.
- Eco-efficiency powerful tool of considering ecology and economy interactions.

ARTICLE INFO

Article history:
Received 8 October 2015
Received in revised form
30 November 2015
Accepted 7 December 2015
Available online 30 January 2016

Keywords:
Fuel cells
Power generation
Life cycle assessment
Eco-efficiency
Systemic analysis

ABSTRACT

This study aims to review and provide an up to date international life cycle thinking literature with particular emphasis on life cycle assessment (LCA), applied to Molten Carbonate Fuel Cells (MCFCs), a technology forcefully entering the field of decentralized heat and power generation. Critical environmental issues, comparison of results between studies and improvement strategies are analyzed and highlighted. The findings stress that MCFC environmental performance is heavily influenced by the current use of non-renewable energy and high material demand of rare minerals which generate high environmental burdens in the manufacturing stage, thereby confirming the prominent role of these processes in a comprehensive LCA study. The comparison of operational phases highlights that MCFCs are robust and able to compete with other mature technologies contributing substantially to airborne emissions reduction and promoting a switch to renewable fuels, however, further progress and market competitiveness urges adoption of an eco-efficiency philosophy to forge the link between environmental and economic concerns. Adopting a well-organized systematic research driven by life cycle models and eco-efficiency principles stakeholders will glean valuable information to make well balanced decisions for improving performance towards the concept 'producing more quality with less resources' and accelerate market penetration of the technology.

1. Introduction

At present, exponentially increasing demand of energy especially in fast-growing economies, and the persistence in the use of fossil energy sources, impels to investigate new sustainable energy production and conversion systems. The interest in fuel cell (FC) technology is increasing in parallel with the increases of environmental concern about global warming, which calls for a worldwide reduction of carbon dioxide (CO_2) emissions. Fuel cells (FCs) are galvanic cells, in which the free energy of a chemical reaction is converted into electrical energy (via an electrical current). Because electrical energy is generated without combusting any fuel, FCs offer multiple environmental and technical benefits, making them a vital technology towards to a low emission energy supply. A wide range of FCs exist, typically classified by either their operating temperature or the type of electrolyte [31]. High temperature FCs, such as Molten Carbonate Fuel Cells (MCFCs), are promoted as ultraclean and a favored solution suitable for

---

* Corresponding author.
E-mail address: andi.mehmeti@uniparthenope.it (A. Mehmeti).

http://dx.doi.org/10.1016/j.jpowsour.2015.12.023

stationary power generation, offering rich potential to reduce reliance on the already strained power grid, alleviating carbon footprint and providing a source of renewable energy [6,22,25,36,44]. Already there are more than 50 installations worldwide producing over 300 MW of clean electric power [64]. However, at present, sensitivity to fuel contaminants and high initial investment costs are inhibiting full market penetration [53,64].

All processes involved in a product's lifetime result in environmental impacts due to consumption of resources and corresponding emissions to the biosphere [15]. In the last decade, due to increasing environmental concerns, the ecological footprint of power generation has been considered a crucial issue among the general public, policy makers and scientists, in the light of the emissions and depletion of resources it induces. Consequently, evaluation and monitoring of energy production systems encompassing a life cycle perspective, is crucial for approaching sustainable economic and technological development. Life cycle assessment (LCA) represents one of the most important tools in the field of industrial ecology, designed to help in environmental management in the short term and sustainable development in the long term [15,19]. LCA methodology focuses on the production chain of the examined goods or service, encompassing primary energy sources, fuel production processes and developments in technology, whether in the design, manufacture or use of a product or system [20]. LCA is a cooperative effort performed by many investigators throughout the world and has proved to be useful also to analyze and evaluate the performance of FCs [1,2,42,48]. As a matter of fact, FCs are considered to be low-emission devices, but comprehensive information on the system's supply chain, service life and decommissioning have to be reported for a fulfilling assessment. The present study aims to review and analyze life cycle thinking studies (mainly LCAs) applied to MCFCs, to establish a baseline for the current environmental status and “appeal” of this incumbent multiple-generation solution from which to devise development priorities for enduring market implementation. The argumentation is carried through starting with a brief description of MCFC characteristics, an overview of LCA guidelines focusing on FCs, a critical and comparative analysis of the evaluations that were found in the scientific literature, and concludes with a summary of key findings and fresh, updated assessment tools, with recommendations on how environmental impacts can be synergistically decoupled from economic activities to allow a more effective market approach. The outcome of this study is addressed to researchers in the field of FCs, MCFC manufacturing companies, policy-makers and environmental engineers to facilitate the exchange of technical information and provide sound information for strategic decision making in the distributed and power generation sector.

2. Molten carbonate fuel cell systems

The Molten Carbonate Fuel Cell (MCFC) belongs to the high-temperature FCs. In the MCFC, carbonates (Li_2CO_3, K_2CO_3) are used as electrolyte. The electrodes consist of nickel (Ni) materials. The anode of the MCFC is made of Ni, typically alloyed with Chrome (Cr) or Aluminium (Al) for microstructural stability, and the cathode is made of in-situ lithiated nickel oxide [18]. The basic configuration of a MCFC system is presented in Fig. 1. MCFCs are well described in literature [7,24,64,70].

A MCFC consists of an ion-conducting electrolyte matrix, two electron-conducting electrodes and an electrically conductive gas separator and distribution plate. The electrochemical reactions occurring in the cell are illustrated in Fig. 1. On the anode side of the cell each reacting hydrogen (H_2) molecules reduce the carbonate (CO_3^{2-}) ions to carbon dioxide (CO_2) releasing electrons and generating electrical power. On the cathode side new (CO_3^{2-}) ions are formed by combining the CO_2 of the anode exhaust and the oxygen from the air with the electrons taken from the outer load circuit thus closing the chemical and electrical loops.

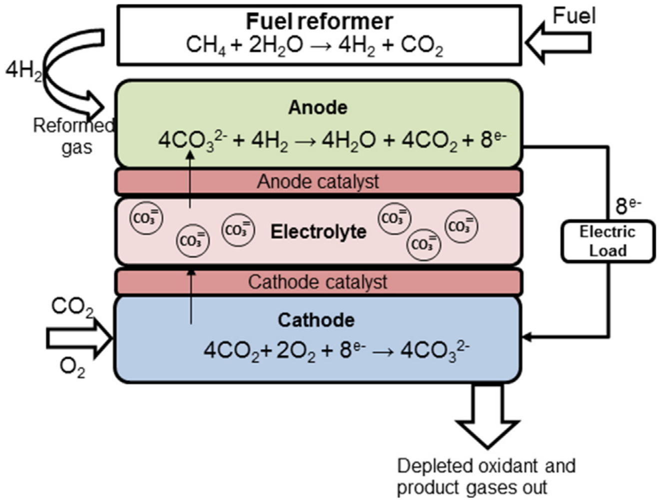

Fig. 1. Operating principle of the Molten Carbonate Fuel Cell when H2 from steam reforming is employed as fuel.

Table 1 presents characteristics of a MCFC system. A MCFC operates at 650 °C. This high operating temperature allows overall thermal efficiency on the inlet primary energy of 90%, of which up to 48–49% is electric power. Considering that the efficiency of FCs is relatively scale-and load-independent, these values are among the highest achievable for the scale of plants characteristic of distributed generation (kW-MW scale), as is illustrated in Fig. 2.

The MCFCs may be fueled with any gaseous form of H_2 (and carbon), generating steam (and CO_2) as end-products. Environmental benefits depend largely on where the H_2 or hydrocarbon fuel is sourced from (fossil, renewable, byproduct, etc.). Due to lack of infrastructure, and the enduring high cost of H_2 as an energy vector, more conventional fueling (natural gas, ethanol, etc.) can accelerate the implementation of MCFCs in the overall energy infrastructure, thus immediately increasing primary energy efficiency and supporting a better security of supply [63]. To-date, a strong interest is shown towards the use of secondary fuels such as biogas (BG), syngas from coal and waste gasified biomass. These fuels are all hydrocarbon mixtures, which can be employed in high-temperature FCs without need for further fuel processing equipment such as external reformers. This reduces cost compared to low-temperature FC systems that require pure H_2. However, while fuel flexibility is a great advantage for MCFCs, a gas clean-up step is needed to abate harmful contaminants (like particulate, hydrogen-sulphide, halogenated hydrocarbons, siloxanes) in the fuel gas to assure better FC performance and durability [3,69]. Summary of MCFC tolerance to impurities at indicative levels is integrated in Table 1, whereas the capability of applying various fuels to MCFCs is discussed from Watanabe et al. [66].

The main problems of MCFCs relate to the degradation of the cell components over long operating periods. This is due to the fact that the materials employed must withstand from 20.000 to 40.000 h at 650 °C in the presence of a molten salt under reducing or oxidizing conditions. In addition, the electrodes degrade because the Ni from the electrodes enters the melt (metallic Ni precipitation into the electrolyte matrix) and causes short circuits, making advances in life time and degradation necessary [52]. However, thanks to their