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Review article

Life cycle sustainability of solid oxide fuel cells: From methodological aspects to system implications

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HIGHLIGHTS

- Up-to-date Life cycle thinking literature of Solid Oxide Fuel Cells (SOFCs).
- SOFC environmental consequences and benchmarking using a life cycle perspective.
- Illustrative Eco-efficiency calculation for energy production technologies.

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ABSTRACT

This study reviews the status of life cycle assessment (LCA) of Solid Oxide Fuel Cells (SOFCs) and methodological aspects, communicates SOFC environmental performance, and compares the environmental performance with competing power production technologies using a life cycle perspective. Results indicate that power generation using SOFCs can make a significant contribution to the aspired-to greener energy future. Despite superior environmental performance, empirical studies indicate that economic performance is predominantly the highest-ranked criterion in the decision making process. Future LCA studies should attempt to employ comprehensive dynamic multi-criteria environmental impact analysis coupled with economic aspects, to allow a robust comparison of results. A methodology framework is proposed to achieve simultaneously ambitious socio-economic and environmental objectives considering all life cycle stages and their impacts.

1. Introduction

The upward trend of global energy emissions [1] and their likely multiple adverse effects compel the adoption of eco-innovative energy supply solutions to foster world transition into a paradigm of sustainability. The interest in electrochemical systems based on fuel cell (FC) technology both in the residential and in the industrial sector is exponentially increasing as an effort to increase energy security while meeting environmental objectives [2] [3].

The Solid oxide fuel cell (SOFC) is a cutting-edge technology considered as a core of future energy systems [3]. SOFCs are commonly perceived to be a pollution-free technology because combustion is avoided (virtually no acid gas or solid emissions are produced) [3], nevertheless, there is still a need for research and development not only to meet efficiency and durability, but also environmental sustainability derived from life cycle methodology because environmental impacts of any product are scattered across its lifespan [4].

Life cycle assessment (LCA) has emerged as a key tool for analyzing issues of natural resource depletion and environmental degradation from a life cycle perspective [5]. Energy-related LCA studies have rapidly progressed in later years (+361% comparing 2014 with1994) [6], and are continuously evolving due to more stringent emission standards. The environmental aspects of SOFCs have been previously described in literature [2] [7], however, analyzing the environmental trade-offs associated with one or more specific products/processes and examination of how this performance is assessed, is imperative to properly communicate

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the environmental performance, design environmental policies, and ensure appropriate comparisons between products and their successive generations. The present study follows the previous work of Mehmeti et al. [4] and concludes the description of the life cycle issues of high temperature FCs, namely Molten Carbonate Fuel Cells (MCFCs) and Solid Oxide Fuel Cells (SOFCs). The goal of this study is to review the status of LCA of SOFC systems, improve the understanding of SOFC implications in environmental consequences and compare the environmental performance of this promising technology with competitive systems. The last section of the study illustrates how environmental implications and economic performance can be integrated into an eco-efficiency index and how the eco-efficiency analysis can be applied to compare products and technologies in both aspects for a better and more transparent decision-making process. The outcomes of this study can be used as a reference review and guiding tool by researchers in the field of FCs, SOFC manufacturing companies, policy-makers and LCA practitioners when developing any LCA for SOFCs.

2. Solid oxide fuel cell systems

A solid oxide fuel cell is a high temperature fuel cell operating from 600 to 1000 °C. Thanks to this, SOFC holds many advantages such as high efficiency, fuel flexibility, environmental friendly and silent/vibration free operation [3].

SOFC generates power with efficiencies of about 40–60%, depending on plant configuration. If the heat produced is also harnessed; their overall efficiency in converting fuel to energy can be up to 90%. Moreover, they have no need for expensive catalysts as in the case of low-temperature FCs such as polymer electrolyte membrane fuel cells (PEMFC).

Table 1 presents some characteristics of a SOFC system, which comprises an anode, a cathode and an electrolyte. SOFCs typically use a solid, nonporous metal oxide (yttria-stabilized zirconia, or YSZ) as electrolyte. The anode is composed of ceramics and metals (mix $CoZrO_2$ or $NiZrO_2$ cermet), while the cathode is made from perovskite-like mixes of conducting oxides (e.g. $La0.8Sr0.2MnO_3$). Birnbaum et al. [7] gives an overview of the materials used for SOFC fabrication.

Fig. 1 illustrates the electrochemical reactions taking place in an SOFC single cell. The SOFC stack contains electrical interconnects - the so called bi-polar plates - which link individual cells together in series. Being essentially a ceramic assembly, SOFCs can be shaped to any geometry: three major configurations for stacking the cells together to increase the voltage and power are tubular, planar and segmented [8].

As indicated in Fig. 1, molecular oxygen at the cathode side is reduced to oxygen-ions (O_2^-) combining with two electrons each.

Table 1
General characteristics of Solid Oxide Fuel Cells.

Characteristics	Solid oxide fuel cell (SOFC)
Electrolyte	Yttria-stabilized zirconia (YSZ), doped ceria ZrO_2
Anode	Cobalt or nickel zirconia ($CoZrO_2$ + $NiZrO_2$)
Cathode	Lanthanum Strontium Manganite (LSM), Lanthanum Strontium Cobalt (LSC), Lanthanum Strontium Cobalt-Ferrite (LSCF)
Operating temperature range (°C)	600–1000
Charge carrier	O_2^-
Catalyst	Ceramics oxide
Primary fuel	Hydrogen (H_2), Natural Gas (NG), Syngas (SG), Biogas (BG), landfill gas (LFG), Methanol, ethanol, ammonia, liquid petroleum gas (LPG)
Efficiency, LHV (electrical/thermal) %	60/90

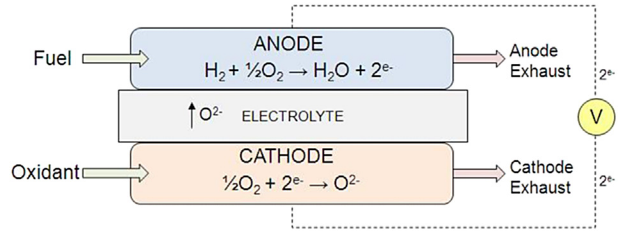

Fig. 1. Working principles of a SOFC system fueled with H_2.

These ions as a result of the reactions at both interfaces and the oxygen ion conductivity of the electrolyte are transported to the anode where they are combined with fuel (hydrogen) to produce water vapor and complete the reaction by releasing two electrons to the external circuit. SOFCs are not hampered by charging cycles (like batteries) and provide constant power as long as fuel is fed and cell temperature is maintained. During SOFC operation, values between 0.6 and 1 V per cell can be obtained, while current densities vary between 0.5 and 1 A/cm^2. Several types of fuel (Table 1) can be converted in an SOFC, however, gas quality assurance is important to eliminate contaminants (e.g. sulphur compounds, siloxanes, halogens) in order to enhance system reliability.

3. The life cycle assessment (LCA) methodological approach

Life Cycle assessment (LCA) is a multi-step versatile method used for compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its entire life cycle, i.e. from its manufacture, use, and maintenance, to its final disposal, including the raw material acquisition required for manufacturing the product [5]. Interpreting the results from LCA helps decision-makers to make a more informed decision for improving the environmental compatibility of products and services towards a net reduction of resource requirements and associated multiple types of impacts (e.g. air pollution, water pollution, land pollution), and facilitate comparisons of energy technologies, whether in the design, manufacture or use of a product or system [5] [9] [10]. Together with other decision-making tools, LCA may provide input towards the selection of one product over another.

The systematic procedure of a LCA (Fig. 2) is based on environmental management standards (ISO14040:2006 and14044:2006) and consists of four phases: goal and scope definition, life cycle inventory analysis, impact assessment, and interpretation [5].

Goal and scope definition is the first phase of an LCA, defining the purpose of the study, its scope, data quality goals, allocation procedures and functional unit/s. This stage guides the entire process to ensure that the most meaningful results are obtained and LCA is performed consistently. The inventory analysis (LCI) is an iterative process for data collection from the modeled energy systems when used to produce the functional unit. It quantifies the energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges) for every life cycle stage, media (air, water, and land), or any combination thereof [10]. The elementary flows identified in the LCI step are linked in the assessment of various potential environmental impacts in the life cycle impact assessment (LCIA) stage, composed of mandatory (classification and characterization) and optional (normalization, grouping and weighting) steps. The weighting step in the case of FC production is not recommended, because it is based on subjective assessments (e.g. economic, political or environmental considerations) rather than scientific findings; thus they can heavily influence the results and conclusions of the LCA [9].