

Life Cycle Assessment and Costing of an Anode-Supported SOFC with SCFA10 coating: A Modular and High-Resolution Approach

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Abstract

The sustainability of solid oxide fuel cells (SOFCs) is strongly constrained by energy-intensive manufacturing and material-related impacts. The objective of this study is to evaluate the introduction of an ultra-thin $\text{Sr}_{0.9}\text{Ce}_{0.1}\text{Fe}_{0.9}\text{Al}_{0.1}\text{O}_3$ (SCFA10) functional coating in an anode-supported SOFC, comparing it with a conventional configuration.

The study develops and applies an integrated life cycle framework combining Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and environmental LCC (eLCC). A modular, high-resolution modelling approach based on primary experimental data — including a scale-up synthesis protocol for SCFA10 — is applied to ensure a transparent inventory construction. The analysis is performed at the single-cell level under a cradle-to-gate perspective.

Environmental results indicate that the coating leads to negligible variations, with increases below 1% across all evaluated impact categories (+ 0.18% for global warming potential). The absolute contribution of the coating remains below 0.3% of total impacts, while environmental hotspots are dominated by conventional cell components and high-temperature processes. Economic results show comparable production costs (estimated at about 66 € per unit) and limited variation in monetised environmental impacts for both configurations, with a positive net present value achieved after 6–7 years under base-case conditions.

Overall, the innovative SCFA10 functional coating is found to be both environmentally and economically neutral at the manufacturing stage. While the impacts remain marginal at the production level, potential benefits are expected to emerge at the use and system integration levels.

1. Introduction

The transition towards sustainable energy systems requires technologies whose performance is evaluated beyond efficiency metrics, incorporating environmental and economic dimensions across the entire life cycle (Curran, 2017). In this context, Solid Oxide Fuel Cells (SOFCs) have emerged as a promising option due to their high efficiency and fuel flexibility (Staffell et al., 2019). However, their overall sustainability remains strongly influenced by energy-intensive manufacturing processes and complex material supply chains, which can offset potential environmental benefits (Mahato et al., 2015).

Life Cycle Thinking (LCT) approaches, particularly Life Cycle Assessment (LCA) and Life Cycle Costing (LCC), have been increasingly applied to SOFC technologies (Pehnt, 2003; Finkbeiner et al., 2010). Nevertheless, recent literature highlights persistent methodological limitations, including a scarcity of high-quality primary data, limited process-level resolution, and insufficient integration between environmental and economic modelling frameworks. In addition, previous studies consistently identify material production and high-temperature treatments as dominant environmental hotspots, underscoring the need for more detailed and transparent modelling of manufacturing processes (Naimin et al., 2026).

Within this context, a critical gap remains in the consistent evaluation of emerging material innovations at the cell level, where even small design modifications may influence both environmental burdens and cost structures. Addressing this challenge requires methodological approaches capable of linking experimental data, process modelling, and life cycle assessment within a unified and reproducible framework.

To this end, this study introduces an integrated and high-resolution framework that combines a modular life cycle modelling approach with primary data derived from experimental activities. The proposed methodology enables the decomposition of the SOFC architecture into independent functional units, enhancing transparency, reproducibility, and comparability of results. Within this framework, a scale-up synthesis protocol for the innovative ceramic material $\text{Sr}_{0.9}\text{Ce}_{0.1}\text{Fe}_{0.9}\text{Al}_{0.1}\text{O}_3$ (SCFA10) is explicitly modelled and directly embedded into both LCA and LCC analyses.

The objective of this work is to evaluate the implications of introducing an ultra-thin SCFA10 functional coating in an anode-supported SOFC cell, compared with a conventional configuration. The analysis is conducted at the cell level under a cradle-to-gate perspective and integrates LCA, LCC, and eLCC. Particular attention is devoted to determining whether the introduction of the innovative material leads to significant changes in environmental impacts and production costs at the manufacturing stage.

While the present study focuses on the manufacturing phase, future work will extend the analysis to the use phase in order to assess whether potential performance improvements can translate into additional life cycle benefits.

2. Description of the technology

A SOFC is an electrochemical device that converts chemical energy from a fuel (such as hydrogen or natural gas) and an oxidant (oxygen) directly into electricity, heat, and water. Operating at very high temperatures (650–1000°C), it uses a solid ceramic material as the electrolyte to conduct oxygen ions. The electrolyte is typically composed of yttria-stabilised zirconia (YSZ), a material which is also the basic component of the electrodes (anode and cathode) of the cell.

In this electrochemical cell, fuel (e.g., hydrogen, natural gas) enters the anode side, while air (oxygen) enters the cathode side. At the cathode, oxygen from the air accepts electrons forming negative oxygen ions, O^{2-} . These ions travel through the solid ceramic electrolyte to the anode. On the anode side, the fuel reacts with the incoming oxide ions, releasing electrons and producing water (if hydrogen is the fuel), or carbon dioxide (if carbon monoxide is present). The electrons released at the anode travel through an external circuit to the cathode, generating direct current (DC) electricity. More details about the technology are reported in several reviews, including Singh et al. (2021), Laosiripojana et al. (2009) and Minh (2004).

Key benefits of SOFCs include high efficiency (can reach 60% or more electrical efficiency), fuel flexibility (handling various carbon-based fuels), quiet operation, and suitability for combined heat and power (CHP) production systems. Moreover, SOFCs can use hydrogen, natural gas, biogas, or even carbon monoxide, and they are tolerant to limited sulphur impurities in the fuel (Hanna et al., 2014).

However, the high working temperatures present some challenges, such as: long startup time, thermal insulation, low resilience to emergency shut down (due to the thermal stress of materials).

Like other fuel cell technologies, SOFCs are scalable: they are proposed or used in applications from small household units (kW) to large power plants (MW). Not the least, SOFCs are reversible, they can function as electrolyzers for hydrogen production from steam and electricity. In this case, they are usually named Solid Oxide Electrolyzer Cells (SOECs).

A single cell is not useful for most applications due to the low voltage, so that the cells are stacked to reach the desired voltage. Like other fuel cell technologies, a SOFC stack is obtained by coupling a number of cells with appropriate interface architecture and mechanical assembling components. Although the tubular configuration is more stable, nowadays the planar configuration is preferred to reduce stack volume and increase power density (Tonekabonimoghaddam and Shamiri, 2021).

Current addresses in SOFC research focused on: reduction of working temperature, increase of useful life, increase of the resilience to thermal cycles, development of new materials for reducing the cell production cost and reducing critical raw material use (Singh et al., 2021; Santoro et al., 2022; Vecino-Mantilla et al., 2024; Longo et al., 2023).

In the following sections, the life cycle study is centred on a SOFC having a planar configuration.

3. Methodological framework: Modular approach and material synthesis

This section describes the core methodological approach and experimental procedures adopted to overcome current limitations in the environmental and economic modelling of Solid Oxide Fuel Cells (SOFCs).

To ensure consistency and transparency, the analysis is structured around a flexible framework that integrates unit-process granularity with a defined manufacturing upscaling pathway.

Specifically, Section 3.1 delineates the modular approach used to decompose the complex multi-layer cell architecture into independent functional blocks, thereby minimising inventory uncertainties and optimizing data access. Section 3.2 outlines the step-by-step upscaling protocol implemented via solution combustion synthesis (SCS) for the production of the innovative SCFA10 ceramic powder, providing the primary technical datasets for the subsequent life cycle assessment and costing.

3.1. The modular approach

LCA of SOFCs remains challenging due to the multilayer architecture of the components, the energy-intensive ceramic fabrication processes, and the persistent scarcity of high-quality primary data. These limitations have been repeatedly highlighted in the literature, particularly with regard to ceramic material processing and high-temperature manufacturing (Karakoussis et al., 2001). Additional studies confirm that the lack of reliable process information may compromise the robustness of environmental modelling, especially during anode and electrolyte fabrication (Zhao and Brouwer, 2012). Reviews performed over the last decade further emphasise the

methodological uncertainty associated with SOFC manufacturing inventories (Longo et al., 2017). Recently, the growing focus on the sustainability of hydrogen and fuel-cell supply chains has renewed attention on these data gaps (Salim et al., 2022).

To address these limitations, this study adopts a modular approach, increasingly recognised as a robust strategy to improve transparency and reproducibility in SOFC LCAs (Bargiacchi et al., 2021). This approach is based on decomposing the stack into repeatable functional units, each modelled as an individual subsystem. In this work, the base module consists of the membrane–electrode assembly (MEA) and the cathode-side bipolar plate, which ensure gas distribution, electrical interconnection and structural continuity. The stack is therefore represented as N repetitions of this module plus two terminal plates, reflecting consolidated SOFC design principles (Kawajiri and Inoue, 2016).

This modular structure allows each sub-unit – anode, cathode, electrolyte, barrier layers and bipolar plates – to be analysed independently. Such granularity is essential to accurately represent material flows, energy consumption and high-temperature profiles, which have been identified as major hotspots in several SOFC LCA studies (Gandiglio et al., 2019). Moreover, the increasing role of advanced and additive manufacturing technologies in SOFC fabrication further reinforces the need for unit-process-level modelling (Tai et al., 2019).

From a methodological perspective, the modular approach provides three main advantages:

- (1) Reduction of Life Cycle Inventory (LCI) complexity: Modularisation avoids the need to reconstruct entire industrial production chains, which are often inaccessible for emerging SOFC technologies.
- (2) Improved access to primary data: Modelling sub-units as stand-alone systems facilitates the measurement of specific process inputs (e.g., energy, mass flows, yields), reducing dependence on generic datasets (Shafie et al., 2021).
- (3) Transparent comparison between design alternatives: By keeping all parameters constant except for the anode composition, this modular approach enables a clear attribution of environmental variations when an ultra-thin SCFA10 functional coating is added.

Overall, this framework addresses fundamental structural limitations in current SOFC LCA practice, offering a flexible and updatable analytical tool capable of supporting robust environmental comparison across evolving technological scenarios.

3.2. Scale-up synthesis protocol

A scale-up protocol based on solution combustion synthesis of $\text{Sr}_{0.9}\text{Ce}_{0.1}\text{Fe}_{0.9}\text{Al}_{0.1}\text{O}_3$ was developed and successfully implemented for the preparation of 20 g of powder per batch. The SCS scale-up procedure is conveniently divided into six key steps.

Step 1. A solution was prepared, in a 3L stainless-steel beaker, dissolving in ~1L of distilled water $\text{Sr}(\text{NO}_3)_2$ (99.999% Merck – 19.6532 g), $\text{Fe}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ (99.95% Merck – 37.5173 g), $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ (99.999% Merck – 4.4806 g), and $\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$ (99.99% Merck – 3.8708 g) as metal precursors, citric acid (99.99% Merck – 79.2969 g) as a combustion fuel, and ammonium nitrate (98% Merck – 192.00 g) as additional oxidant. The precursor quantities were determined from the nominal composition and targeted powder yield. The citric acid amount was set by fixing the fuel-to-metal cations molar ratio at 2, whereas the ammonium nitrate content was calculated following propellant chemistry principles to ensure a reducer-to-oxidizer ratio (φ) of 1. An analytical balance was employed for metal precursors and citric acid, whereas a technical balance was properly used for NH_4NO_3 . **Step 2.** After the complete dissolution of all precursors named in Step 1, the pH was adjusted to 6 using ammonia solution (28% v/v, Merck). **Step 3.** The resulting aqueous solution was magnetically stirred at 80°C on a hotplate (Heidolph) for approximately 7 hours until a sol was formed. The sol was then equally divided into four 3L stainless-steel beakers. **Step 4.** The content of each of the four beakers was reheated to 80°C under continuous magnetic stirring, allowing the sol to concentrate progressively (Fig. 1a) until gel formation was achieved (Fig. 1b). **Step 5.** Subsequently, for each beaker, the hotplate temperature was raised to 350°C, after removal of the stirring bar, triggering a self-sustaining combustion reaction (Fig. 1c), that produced a black/brown powder within a few seconds (Fig. 1d). The combustion process was monitored using a K-type thermocouple connected to a PicoLog datalogger. **Step 6.** The as-burned powder obtained from each beaker was calcined separately in static air at 1000°C (10°C/min) for 5 h, followed by the subsequent combination of the resulting powders.

4. State of the art

We carried out a comprehensive analysis of LCT studies, specifically focusing on LCA and LCC of SOFCs, as reported in the scientific literature. The analysis was performed in September 2025 using the SCOPUS database.

4.1. LCA and SOFC

Over the last five years, an increasing number of studies have applied LCA to the single SOFC cell/MEA—explicitly excluding the stack and system levels — to isolate cradle-to-gate manufacturing impacts. Evidence converges on three key points. (1) The main environmental hotspots are powder preparation and high-temperature processing (e.g. calcination and sintering); improved synthesis routes and scale up can markedly reduce energy consumption and greenhouse gas (GHG) emissions (Wang et al., 2023). (2) Material composition strongly drives impacts and the demand for critical raw materials (CRMs): recycling pathways for ceramic and metallic fractions offer significant potential for environmental gains and CRM savings (Sarner et al., 2022). (3) In prospective analyses, lighter cells with higher specific power — together with appropriate layout choices — lead to notable reductions in Global Warming Potential (GWP) and highlight the critical role of the anode material in the component-wise breakdown (Spreafico, 2024).

4.2. LCC and SOFC

The papers analysed conduct LCC analysis on various technologies and systems that include SOFCs. They can be grouped into three main areas. (1) Power-to-Gas (P2G) Systems and Hydrogen Production: The studies (Ding et al., 2024; Jalili et al., 2023; Ding et al., 2020; Glenk et al., 2023) focus on integrating technologies related to hydrogen and energy storage. (2) Hybrid Systems and Stationary Cogeneration: Some researchers (e.g., Arsalis, 2024; Hasanzadeh et al., 2021; Caramanico et al., 2021; Yan et al., 2021) examine the coupling of SOFCs with other fuel cells, turbines, or their application in micro-cogenerations. (3) Sector Applications (e.g., in transport): Some investigations (Guyen and Kayalica, 2024; Heidary et al., 2023; Lee et al., 2022; Rodrigues de Moraes et al., 2022; Kim et al., 2020; Salim et al., 2022) apply SOFCs or hydrogen-based systems to specific industrial sectors or vehicles.

4.3. Critical synthesis of the literature

Based on the literature review, no existing study performs a combined LCC and LCA focused specifically on production process and SOFC cell + SCFA10 components. Our study differs from the previous literature in two key aspects. (1) **Objective of the analysis:** The aim of our work is to evaluate and quantify the economic and environmental impacts and the financial feasibility of SOFC production, by comparing equivalent MEAs that differ only in their anode material. To this end, we use coherent functional units, a set of harmonised environmental indicators (climate, cumulative energy, CRM, and toxicity), and traceable process inventories for synthesis and thermal treatments. (2) **Integrated methodological approach:** We combined economic, environmental, and financial analysis through the LCC method and Net Present Value (NPV) calculations.

5. LCA: Methodology and results

The LCA was carried out according to the ISO 14040 and ISO 14044 standards and included the four classical phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (ISO, 2006a; ISO, 2006b). The study was developed to evaluate the environmental impacts associated with the manufacturing of an anode-supported SOFC and to compare a conventional configuration with an innovative architecture incorporating an ultra-thin SCFA10 functional coating deposited onto the anodic layer. The assessment specifically focuses on the environmental implications associated with the introduction of advanced functional coatings intended to improve interfacial and electrochemical properties while maintaining the conventional SOFC architecture.

Consistent with recent literature on SOFC environmental assessment, the analysis was conducted at the cell level in order to isolate the contribution associated with material selection and manufacturing processes without including operational effects related to stack integration, balance of plant, or use-phase conditions (Salim et al., 2022).

5.1. Goal and Scope Definition

The objective of this study is to evaluate the environmental impacts of manufacturing an anode-supported SOFC and to compare a conventional configuration with an architecture featuring an ultra-thin SCFA10 coating on the anodic surface. The analysis assesses the environmental implications of surface engineering strategies aimed at enhancing electrochemical and interfacial properties while preserving the conventional design.

The assessment was conducted according to the ISO 14040 and ISO 14044 standards for LCA (ISO, 2006a; ISO, 2006b). A cradle-to-gate approach was adopted (Fig. 2) and the system boundaries include raw material extraction and processing, precursor synthesis, ceramic powder preparation, slurry and paste formulation, deposition processes, drying, calcination and sintering treatments, and final MEA assembly. This system boundary was selected because the manufacturing stage has been identified as one of the major contributors to

the environmental profile of SOFC technologies, mainly due to the production of ceramic materials and the energy-intensive thermal treatments required during fabrication (Mahato et al., 2015; Salim et al., 2022). The operational phase, stack integration, Balance of Plant (BoP), and end-of-life management were excluded from the present study in order to focus exclusively on manufacturing-related impacts and ensure direct comparability between the investigated cell configurations.

This approach is consistent with recommendations provided by Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and Environmental Footprint (EF) methodological frameworks for the environmental assessment of fuel cell technologies (Bargiacchi et al., 2022; Andreasi Bassi et al., 2023). The functional unit (FU) was defined as one manufactured anode-supported SOFC single cell.

Both configurations were characterised by identical geometry, active area, manufacturing route, and operating purpose. Consequently, the environmental differences observed between the two systems can be directly attributed to the introduction of the SCFA10 functional coating.

5.2. Life Cycle Inventory (LCI)

The LCI was developed using a modular bottom-up modelling approach, in which each MEA layer, namely the anode, electrolyte, barrier layer, cathode, and SCFA10 functional coating, was modelled as an independent foreground process. This approach enabled the environmental contribution of each component to be quantified separately and facilitated the identification of environmental hotspots within the cell architecture.

Foreground inventory data were derived from laboratory-scale experimental activities, technical datasheets, and dedicated process questionnaires. The inventory included information on precursor composition, material formulations, solvent-to-solid ratios, deposition parameters, thermal treatment conditions, and electricity consumption associated with each manufacturing step. Particular attention was devoted to ensuring consistency between the material inventory and the actual fabrication procedures adopted during cell preparation. Background data were sourced from the Ecoinvent v3.8 database, ensuring technological consistency and geographical representativeness for the selected processes and energy carriers (Ecoinvent Association, n.d.).

The modelling activities were performed using SimaPro 9.6.0.1 software. Multifunctionality was addressed, where relevant, through process subdivision or system expansion. Whenever allocation procedures were required, the selected allocation criteria were applied consistently with ISO recommendations and Fuel Cells and Hydrogen (FCH) methodological guidelines (Bargiacchi et al., 2022; Andreasi Bassi et al., 2023). Data quality was evaluated considering technological, geographical, and temporal representativeness, as well as data completeness and reliability. Particular emphasis was placed on the use of primary experimental information for foreground processes, while secondary datasets were selected from the most representative available database sources.

Where appropriate, data quality indicators and uncertainty information available within the Ecoinvent database were considered during the interpretation of results (Ecoinvent Association, n.d.; Bargiacchi et al., 2022). The proposed SOFC configuration differs from the reference cell through the introduction of an ultra-thin SCFA10 functional coating deposited onto the anodic surface. Due to its limited thickness (approximately 2 μm), the additional material inventory associated with the coating remains extremely small compared with the total mass of the cell. Consequently, the manufacturing route of the coated configuration remains substantially identical to that of the conventional SOFC, with only the additional coating preparation and deposition steps being included in the inventory model.

The production processes associated with the investigated SOFC configurations are schematically represented in Fig. 3a for the reference cell and Fig. 3b for the coated configuration.

5.3. Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment (LCIA) was performed using the ReCiPe 2016 Midpoint (H) methodology implemented in SimaPro 9.6.0.1. ReCiPe 2016 was selected because it represents one of the most widely applied and scientifically robust impact assessment methods currently available for the environmental evaluation of energy systems and advanced electrochemical technologies (Huijbregts et al., 2017).

The midpoint approach was adopted to provide a detailed and transparent assessment of the environmental mechanisms associated with SOFC manufacturing, avoiding the additional uncertainties typically introduced by endpoint aggregation. The method includes a comprehensive set of impact categories covering climate change, ozone depletion, ionizing radiation, particulate matter formation, acidification, eutrophication, ecotoxicity, human toxicity, land use, mineral resource scarcity, fossil resource scarcity, and water consumption.

Characterised results were first evaluated to quantify the absolute environmental burdens associated with each impact category. Subsequently, normalisation was performed using the World 2010 normalisation factors provided within the ReCiPe framework. The normalised results were used to facilitate cross-category comparison, identify the dominant environmental mechanisms, and support the interpretation of environmental hotspots within the investigated SOFC configurations (Huijbregts et al., 2017). The application of both characterisation and normalisation levels provides complementary information. Characterisation results quantify the absolute contribution of each impact category, whereas normalisation allows the relative importance of different environmental mechanisms to be evaluated within a common reference framework.

This combined approach is consistent with current LCA practices for fuel cell technologies and advanced ceramic systems and supports a more comprehensive interpretation of the environmental profile of the investigated SOFC architectures (Mahato et al., 2015; Salim et al., 2022). To further support the interpretation of results, a hotspot analysis was carried out by disaggregating the contribution of the individual cell components and manufacturing stages to the overall environmental impacts. This analysis enabled the identification of the processes and materials responsible for the largest environmental burdens and provided additional insights into the environmental relevance of the SCFA10 functional coating.

5.4. Interpretation of results

The LCIA results indicate that the introduction of the SCFA10 functional coating produces only marginal environmental variations compared with the conventional SOFC configuration. Overall, the environmental profile of the modified cell remains substantially comparable to that of the reference architecture, confirming that the additional coating process introduces only limited environmental burdens at the manufacturing stage.

The ReCiPe 2016 midpoint characterisation results indicate that the introduction of the ultra-thin SCFA10 functional coating leads to a slight increase across all investigated impact categories compared with the conventional SOFC configuration (Table I).

Nevertheless, the magnitude of these variations remains extremely limited, indicating that the additional environmental burden associated with the coating is negligible when compared with the overall environmental profile of the cell. Regarding climate-related impacts, Global Warming Potential increases from 10.972 to 10.992 kg CO₂ eq, corresponding to an increase of approximately 0.18%. Similar trends are observed for Stratospheric Ozone Depletion, which rises from $5.140 \bullet 10^{-6}$ to $5.164 \bullet 10^{-6}$ kg CFC-11 eq (+0.48%), and Ionizing Radiation, which increases from 1.250 to 1.252 kBq Co-60 eq (+0.16%). Categories associated with atmospheric emissions exhibit comparable behaviour, with Ozone Formation affecting Human Health increasing from 0.01810 to 0.01814 kg NO_x eq (+0.19%), Fine Particulate Matter Formation from 0.01057 to 0.01059 kg PM_{2.5} eq (+0.20%), and Ozone Formation affecting Terrestrial Ecosystems from 0.02028 to 0.02031 kg NO_x eq (+0.18%). A similar pattern can be observed for resource-related categories. Fossil Resource Scarcity increases from 3.577 to 3.583 kg oil eq (+0.18%), while Mineral Resource Scarcity rises from 0.03789 to 0.03798 kg Cu eq (+0.23%). Water Consumption also shows a very limited increase, from 0.2062 to 0.2066 m³ (+0.18%). These results suggest that the additional material and energy requirements associated with the SCFA10 coating do not substantially affect resource use throughout the manufacturing stage. Particular attention should be devoted to toxicity-related categories, which represent some of the largest absolute impacts among those investigated. Terrestrial Ecotoxicity increases from 71.35 to 71.50 kg 1.4-DCB eq (+0.22%), Freshwater Ecotoxicity from 0.7516 to 0.7537 kg 1.4-DCB eq (+0.27%), and Marine Ecotoxicity from 0.9934 to 0.9961 kg 1.4-DCB eq (+0.27%). Similarly, Human Carcinogenic Toxicity increases from 1.081 to 1.084 kg 1.4-DCB eq (+0.21%), while Human Non-Carcinogenic Toxicity rises from 8.847 to 8.870 kg 1.4-DCB eq (+0.26%). Although these categories exhibit the highest absolute values, the relative differences between the two configurations remain extremely small. Among all investigated categories, Marine Eutrophication exhibits the highest relative increase, rising from $2.158 \bullet 10^{-4}$ to $2.169 \bullet 10^{-4}$ kg N eq (+0.52%). Freshwater Eutrophication increases from $2.248 \bullet 10^{-3}$ to $2.252 \bullet 10^{-3}$ kg P eq (+0.22%), while Terrestrial Acidification rises from 0.02967 to 0.02973 kg SO₂ eq (+0.20%). Despite these increases, the absolute variations remain negligible and do not alter the overall environmental behaviour of the system. Overall, the characterisation results demonstrate that the environmental profile of the modified SOFC remains substantially comparable to that of the reference cell. The introduction of the SCFA10 coating systematically increases the impacts in all categories; however, the observed variations never exceed 1% and are generally confined to the range of 0.2–0.5%. Considering the extremely limited thickness of the coating (approximately 2 µm), these results indicate that the additional environmental burdens associated with precursor synthesis, coating preparation and deposition remain marginal compared with those generated by the conventional ceramic materials and manufacturing processes constituting the SOFC architecture.

5.4.1. Normalised results and hotspot identification

To facilitate the interpretation of the environmental profile and identify the most relevant environmental mechanisms, the ReCiPe 2016 midpoint characterisation results were further analysed through normalisation using the World 2010 normalisation factors provided within the methodology. The normalised results for both SOFC configurations are reported in Table II, while a graphical comparison is presented in Fig. 5. The normalisation analysis reveals that both cell configurations exhibit a remarkably similar environmental profile, with no substantial changes in the ranking of impact categories following the introduction of the SCFA10 functional coating. This finding confirms that the additional coating does not significantly modify the environmental behaviour of the system and that the same environmental mechanisms remain dominant in both configurations.

Among the investigated categories, Human Carcinogenic Toxicity emerges as the most relevant normalised impact, with values increasing only slightly from 0.1050 for the reference cell to 0.1052 for the coated configuration. Freshwater Ecotoxicity and Marine Ecotoxicity represent the second most significant environmental mechanisms, exhibiting normalised values of approximately 0.03 and 0.023, respectively.

The predominance of these categories indicates that toxicity-related impacts play a central role in the overall environmental profile of the analysed SOFC architectures. A second group of relevant impact categories includes Terrestrial Ecotoxicity, Fossil Resource Scarcity, Freshwater Eutrophication and Ionizing Radiation, whose normalised values range between approximately 10^{-3} and 10^{-2} . These categories contribute less significantly than the toxicity-related indicators but still represent non-negligible environmental mechanisms associated with the production of ceramic materials, metallic precursors, and energy-intensive manufacturing processes. Conversely, categories such as Stratospheric Ozone Depletion, Marine Eutrophication, Land Use, Mineral Resource Scarcity and Water Consumption exhibit comparatively lower normalised scores. Although these impacts are present, their contribution to the overall environmental profile remains limited when compared with the dominant toxicity-related categories (Tab. II).

The comparison between the two configurations further highlights that the introduction of the SCFA10 coating produces only marginal variations in the normalised results. For all impact categories, the observed increases remain below 1%, confirming that the environmental contribution of the additional functional layer is negligible relative to the overall impacts associated with SOFC manufacturing. Most importantly, the coating does not alter the hierarchy of environmental hotspots, which remains essentially unchanged between the conventional and modified cells. Overall, the normalisation analysis confirms that the environmental performance of both SOFC configurations is governed by the same impact mechanisms (Fig. 4). The addition of the ultra-thin SCFA10 layer therefore does not introduce new environmental criticalities but rather results in a very limited increase of impacts while preserving the overall environmental profile of the reference technology. These findings suggest that any future assessment of the coating strategy should primarily focus on its potential electrochemical and durability benefits rather than on manufacturing-related environmental concerns.

5.4.2. Hotspot analysis

To further investigate the environmental relevance of the additional SCFA10 functional layer, a hotspot analysis was performed by disaggregating the contribution of the main SOFC components to the most representative impact categories identified through the normalisation analysis. The results are summarised in Table III.

The hotspot analysis confirms that the environmental profile of the coated SOFC cell remains predominantly governed by the conventional cell architecture. In particular, the anodic layer emerges as the main contributor to several impact categories, accounting for approximately 47.5% of the total Global Warming impact, 41.2% of Human Carcinogenic Toxicity, and 47.7% of Fossil Resource Scarcity. These results highlight the environmental relevance of the materials and manufacturing processes associated with the NiO–YSZ anode, which represents one of the most resource- and energy-intensive components of the cell. A different contribution pattern is observed for ecotoxicity-related categories. Freshwater Ecotoxicity and Marine Ecotoxicity are more evenly distributed among the cathode, electrolyte and barrier layer, which contribute approximately 27–28% of the total impact each. This behaviour suggests that the environmental burdens associated with these categories are not driven by a single dominant component but rather originate from the combined contribution of several ceramic layers and their associated precursor production routes. The results also demonstrate that the environmental contribution of the SCFA10 coating remains extremely limited. Across all analysed categories, the contribution of the coating ranges from approximately 0.18% to 0.27% of the total impact. The lowest contributions are observed for Global Warming and Fossil Resource Scarcity (0.18%), while the highest values are associated with Freshwater and Marine Ecotoxicity (0.27%). Even in these cases, however, the contribution of the coating remains negligible when compared with those associated with the conventional cell components. From an environmental perspective, these findings indicate that the introduction of the SCFA10 layer does not alter the hierarchy of the main environmental hotspots. The dominant contributions remain associated with the conventional MEA layers,

particularly the anode and, for specific impact categories, the cathode, electrolyte and barrier layer. Consequently, the environmental profile of the coated configuration continues to be primarily determined by the production of ceramic materials and by the manufacturing processes required for cell fabrication. The hotspot analysis therefore provides additional evidence supporting the conclusions derived from both characterisation and normalisation results. Although the introduction of the SCFA10 coating leads to a measurable increase in all impact categories, its contribution remains below 0.3% of the total environmental burden and is insufficient to significantly affect the overall environmental performance of the SOFC cell. The environmental implications of the coating can therefore be considered marginal within the adopted cradle-to-gate perspective. Overall, the results indicate that future efforts aimed at reducing the environmental footprint of SOFC manufacturing should primarily focus on optimising conventional cell components and manufacturing stages, particularly those associated with ceramic material production and thermal processing. In contrast, the environmental burden introduced by the SCFA10 functional coating is negligible, suggesting that its implementation should be evaluated mainly in relation to the potential improvements in electrochemical performance, interfacial stability and long-term durability that it may provide.

5.4.3. Assumptions and limitations

The results presented in this study should be interpreted considering the assumptions and limitations associated with the adopted methodological framework. First, the environmental assessment was performed according to a cradle-to-gate approach and therefore focuses exclusively on the manufacturing stage of the SOFC cell. Consequently, the use phase, stack integration, Balance of Plant (BoP), maintenance requirements, and end-of-life management were excluded from the system boundaries. While this approach is appropriate for evaluating the environmental implications of introducing the SCFA10 coating during cell fabrication, it does not capture potential environmental benefits or burdens arising during operation. A second limitation concerns the scale of the inventory data. The foreground inventory was developed using laboratory-scale experimental information and process data derived from research activities. Although primary data were used whenever available, industrial-scale manufacturing conditions may differ in terms of process efficiency, energy consumption, material utilisation, and production yields. Therefore, the absolute environmental impacts reported in this study should not be interpreted as representative of commercial-scale SOFC production. Furthermore, the environmental differences observed between the reference and coated configurations remain consistently below 1% across all ReCiPe midpoint categories. Although these differences can be quantified through the adopted modelling framework, they should be interpreted with caution considering the uncertainties inherently associated with laboratory-scale inventories, background datasets, and database modelling assumptions. In particular, uncertainties related to precursor production, electricity supply chains, and generic background processes may be comparable to or larger than the observed variations between the two configurations. Despite these limitations, the results provide a robust indication of the relative environmental implications associated with the introduction of the SCFA10 functional coating. The consistency observed among characterisation, normalisation, and hotspot analyses supports the conclusion that the coating introduces only a marginal environmental burden during the manufacturing stage and does not significantly alter the overall environmental profile of the SOFC cell. Future studies should extend the present assessment by incorporating operational performance, degradation behaviour, durability improvements, and end-of-life scenarios. Such an integrated approach would enable the evaluation of whether the potential electrochemical and lifetime benefits associated with the SCFA10 coating can compensate for the small environmental increase observed during manufacturing, thereby providing a more comprehensive assessment of its overall sustainability.

6. LCC and eLCC Methodology and results (SOFC single cell/MEA)

In accordance with LCC methodological guidelines (Wulf et al., 2024), the LCC and eLCC analyses were implemented to quantify the life-cycle economic costs and monetise environmental externalities associated with SOFC cell manufacturing.

6.1. Goal and Scope Definition

The aim of this LCC study is to assess the economic viability of producing a SOFC with innovative material by comparing it with a conventional SOFC. The study is conducted from the perspective of a manufacturer targeting a B2B (business-to-business) market, with a target customer base consisting of research institutions or other companies engaged in R&D. The production process selected for comparison is semi-artisanal, as there are currently no standardised processes for the production of the innovative material and its subsequent application in a purely industrial context. The study incorporates not only an economic evaluation but also an environmental impact analysis, thereby facilitating the determination of the eLCC. The subject of the study encompasses the raw materials and production processes for the manufacture of both the conventional and the alternative cell.

The system boundaries were defined according to a cradle-to-gate approach, using the aggregate of all 18 impact categories assessed through the “Environmental Price (EP)” method as the basis for the environmental cost assessment, which expresses the willingness to pay (WTP) for less pollution (De Bruyn et al., 2018).

The primary distinction between the two cells lies in the materials used in their fabrication. Furthermore, a distinction is made according to specific phases of the production process. It is important to note that the innovative material used (SCFA10) is not yet commercially available. To overcome this circumstance, production has been internalised, with consideration given to the new materials, the equipment required and the associated energy consumption.

6.2. Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) for calculating the eLCC follows the same steps as the LCA. However, to calculate the LCC, expenses were divided into two standard macro-categories, Capital Expenditures (CAPEX) and Operating Expenditures (OPEX), and integrated with relevant financial data. The data used to populate this inventory were obtained mainly through the aggregation of averages derived from accurate market research.

In order to ascertain the total cost and profitability of the investment, the NPV was calculated. The NPV is the sum of all cash flows generated during the life of the investment, discounted at a specific rate.

The formula used to determine it is as follows:

$$NPV = -CAPEX + (1-TR) \sum_{n=1}^N \frac{REV_n - OPEX_n}{(1+r)^n} \quad (1)$$

where CAPEX is the initial investment cost, TR is the tax rate on profits, REV_n represents the annual revenues obtained from the project, $OPEX_n$ are the fixed and variable operating costs at time n, and r is the discount rate.

To determine CAPEX, a market survey was conducted to analyse and quantify the investment costs of the equipment needed for the production cycle of both cells (conventional and alternative).

Table IV presents a comprehensive analysis of the financial expenditures incurred in acquiring the industrial machinery under consideration within the two distinct scenarios examined.

In order to determine the operational expenditure (OPEX), an analysis of the production process was conducted (Fig. 3). From this analysis, production times, electricity consumption and the cost of the necessary workforce (labour cost) were estimated. Furthermore, the category “other possible costs” encompasses ancillary expenses associated with production.

The first step in carrying out the comparative analysis was to define a conventional cell. The second step was to identify its technical characteristics in terms of dimensions – i.e. the total cell surface area, active area, and the cathode and anode area (cm²) – and weight (g) (see Tab V).

The new cell investigated in this study differs from the conventional configuration by the application of an additional thin SCFA10 layer on the anode. This modification is expected to provide its main advantages during the operational (“use”) phase, which will be the focus of future investigations.

To estimate the cost of the materials used, an in-depth market analysis was conducted, using the average values as a representative figure.

To analyse production times, laboratory data were scaled up to account for increased production quantities. Finally, a full production process lasting approximately 40 hours, corresponding to one working week, was defined.

The estimated weekly production is a batch of around 40 cells, designed primarily for scientific purposes and intended specifically for research institutes.

It was estimated that three operators are needed to manufacture the cells. Considering the average salary in Europe, the expected cost is a gross annual salary of 30,000 € per person (90,000 € in total per year).

The energy consumption of the equipment used in the production process was estimated at 414 kWh/week for the conventional cell and 476 kWh/week for the alternative cell and in-house production of new material SCFA10. This value was calculated by summing the energy consumption of the system components, which was determined by multiplying the nominal power (kW) of the individual units (derived from a combination of experimental data, industry standards, and theoretical calculations) by the operating times defined in the production process described above. The price of electricity was set at 0.328 €/kWh, derived from ARERA (2024) for Italy and based on Eurostat data processing. This value represents the average cost of electricity (total gross price in 2023) for industrial customers with an annual consumption between 20 and 500 MWh (second consumption class). Therefore, as shown in Table VI, assuming 48 working weeks per year, the annual cost of electricity consumption is about 7,490 € for the alternative cell and 6,518 € for the conventional cell.

Finally, an additional budget of 2,000 € per year has been allocated for the purchase of consumables.

The values of the items included in the calculation of operating cost (OPEX) are summarised in Table VI.

The unit cost of each cell was estimated as the sum of the depreciation and operating costs per unit. These values are based on a depreciation period of eight years and a total annual production of 1,920 cells.

Therefore, a profit margin of 16% was assumed, based on a markup pricing (or cost-plus pricing) approach applied to OPEX and CAPEX per year.

To assess the project's economic feasibility, we calculated the discount rate, taking into account the return on equity and the inflation rate. The return on equity was benchmarked against the yield on 15-year Italian Government Bonds (BTPs), which is 4.15% (MEF, 2024). Given the medium-to-high risk nature of the investment, it was deemed appropriate to set this value at 8%, approximately double the benchmark yield. Inflation in Italy has fluctuated sharply in recent years, rising from 1.9% in 2021 (ISTAT, 2023) to 8.1% in 2022 (ISTAT, 2023), before falling to 5.7% in 2023 (ISTAT, 2024) and 1.0% in 2024 (ISTAT, 2025). As the peak in 2022 was related to exceptional circumstances (the start of the Russo-Ukrainian conflict and the ongoing effects of the COVID-19 pandemic), a more stable and realistic inflation rate of 3% was chosen.

Taking these factors into account, the final discount rate was set at 4.85%.

For tax purposes, it was assumed that equipment would depreciate at a rate of 15% annually. The taxable base was defined as the annual profit, net of operating costs and depreciation. Two taxes were applied to this: IRES (corporate income tax) at 24%, and IRAP (regional tax on productive activities) at 3.9%. Therefore, the total tax rate (TR) was 27.9%.

The monetary value of externalities was estimated through the following steps:

- Identification of the input materials used to produce each cell.
- A search for the above materials (or comparable equivalents) in the Ecoinvent database (Ecoinvent Association, n.d.) for both conventional and alternative cells.
- After defining the production processes, the environmental impact was calculated using the SimaPro software, which includes eighteen impact categories (see Fig. 5 and Tab. VII), using the Environmental Price (EP) method.

For the purposes of eLCC, the objective of our study was to consider the environmental value, in monetary terms, of the climate change category. By adjusting the 2015 value for inflation (averaged 1.8% annually), the total impact category of the EP method passes from 1.85 €₂₀₁₅ to 2.21 €₂₀₂₅.

6.3. Life Cycle Impact Assessment (LCIA)

To determine the total cost and overall profitability of the investment, the main financial indicator calculated was the Net Present Value (NPV). To analyse the environmental costs over the life cycle of the SOFC, the Environmental Life Cycle Cost (eLCC) approach (Hunkeler et al., 2008; Rodrigues and da Silva 2024; Maggio et al., 2025) was used. A key component of this analysis is the sensitivity assessment, aimed at evaluating the robustness of both economic and environmental outcomes with respect to variations in the most influential parameters.

As demonstrated in the previous section, the differences between the conventional SOFC configuration and the proposed innovative design are negligible, both in terms of manufacturing costs and monetised environmental impacts.

Accordingly, the analysis was carried out considering the most conservative scenario, namely the innovative SCFA10 cell including environmental costs. Figure 6 reports the NPV trend calculated for this configuration. The results indicate that the commercialisation of the new cell achieves a positive economic return after approximately six years, under the assumption of full annual production (1,920 units), with an estimated unit production cost of about € 66 and a selling price of approximately € 77.

The results reported in Fig. 6 refer to a base-case scenario. To further assess the robustness of the economic outcomes, a sensitivity analysis was performed by varying the profit margin (PM) from 7% to 22% (compared to 16% in the base case). As illustrated in Fig. 7, the profit margin has a significant impact on the calculated NPV.

In particular, a PM below 7% does not ensure the economic viability of the SOFC cell + SCFA10. As the profit margin increases, the break-even point (BEP) is reached more rapidly. For instance, at a PM of 22%, the BEP is achieved approximately two years earlier than in the base case, with a total profit of about € 349,700 (compared to € 220,600 under base-case conditions).

6.4. Interpretation of results

The results of the LCC and eLCC analyses, together with the sensitivity assessment, clarify the economic implications of the proposed innovation. As shown in Fig. 6, the SOFC cell + SCFA10 configuration achieves a positive NPV after approximately seven years under base-case conditions, demonstrating its economic feasibility. At the same time, the comparison with the conventional configuration highlights that the introduction of the additional anode layer does not lead to significant variations in either production costs or monetised environmental impacts.

The sensitivity analysis reported in Fig. 7 further confirms the robustness of these findings. Although the NPV is strongly influenced by the profit margin, the overall economic behaviour of the system remains consistent: higher profit margins lead to faster break-even points and increased profitability, while values below 7% compromise economic viability. This indicates that the investment performance is primarily driven by market-related parameters rather than by technological cost differences between the two configurations.

Taken together, these results suggest that the proposed innovation is economically neutral at the cell production level, as it does not introduce additional costs nor economic disadvantages compared to the conventional design. This aspect is particularly relevant, as it demonstrates that the proposed new configuration can be implemented without requiring significant modifications to existing manufacturing processes or cost structures.

However, the main potential of the proposed solution is expected to emerge beyond the scope of the present LCC and eLCC analyses, particularly at the system and operational levels. In fact, the modified anode design may enable the direct utilisation of fuel, eliminating the need for an external chemical processor (reformer). This could substantially reduce both capital and operational costs associated with fuel processing, while simplifying the overall system architecture and enabling the direct use of oxygen.

In addition, the proposed configuration may allow the use of alternative storage systems, potentially providing advantages in terms of reduced space requirements and lower storage costs. These benefits are not explicitly accounted for in the current economic model and therefore represent an additional margin of improvement that could further enhance the competitiveness of the proposed solution.

Overall, while the present results demonstrate that the innovation does not significantly impact economic and environmental performance at the component (cell) level, they highlight its strong potential at the system level. Future work will therefore focus on validating these assumptions through integrated system-level analyses and experimental investigations, with particular attention to operational performance, cost reduction, and system simplification.

Another consideration is the absence of an established market for the commercialisation of the innovative material (SCFA10). Currently, this material is only available on order in small quantities or through laboratory-scale production.

7. Conclusions

This study developed an integrated life cycle framework combining LCA, LCC, and eLCC to assess the introduction of an ultra-thin SCFA10 functional coating in an anode-supported SOFC cell. The modular and process-level modelling approach, supported by experimental data, enabled a transparent and reproducible assessment of the manufacturing stage.

The results show that the addition of the SCFA10 coating does not significantly affect either environmental impacts or production costs at the cell level. The observed variations remain negligible across all indicators, confirming that manufacturing burdens are primarily driven by conventional materials and high-temperature processes rather than by the introduction of ultra-thin functional layers.

From a methodological perspective, the study highlights the importance of integrating primary data into life cycle models to improve robustness and interpretability. This represents a relevant contribution to current SOFC LCA practice, where data availability and process resolution remain critical challenges.

Although no significant differences are observed at the manufacturing stage, the potential advantages of the proposed innovation are expected to emerge during operation. Preliminary considerations suggest that the modified configuration could enable system-level changes, such as simplified fuel processing, modified input management, and improved system integration. However, these aspects remain to be quantitatively validated.

The present work should therefore be regarded as a necessary step towards a more comprehensive life cycle assessment. Future research will extend the analysis to the use phase and system-level integration in order to verify whether the expected functional improvements can translate into measurable environmental and economic benefits.

Abbreviations

1.4 DCB	1.4 Dichlorobenzene
a crop eq	Annual crop equivalents
ARERA	Autorità di Regolazione per Energia, Reti e Ambiente (Italian Regulatory Authority for Energy, Networks and Environment)
B2B	Business-to-Business
BEP	Break-Even Point
BoP	Balance of Plant
BTP	Italian Government Bond
CAPEX	Capital Expenditures
CFC-11	Chlorofluorocarbon-11 (or Freon-11)
CGO	Cerium-Gadolinium Oxide
CHP	Combined Heat and Power
Co-60	Cobalt-60
CRM	Critical Raw Material
DC	Direct Current
EF	Environmental Footprint
eLCC	Environmental Life Cycle Cost
EP	Environmental Price
FCH	Fuel Cells and Hydrogen
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FU	Functional Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
IRAP	Imposta Regionale sulle Attività Produttive (Regional Tax on Productive Activities)
IRES	Imposta sul Reddito delle Società (Corporate Income Tax)
ISO	International Organization for Standardization
ISTAT	Istituto Nazionale di Statistica (Italian National Institute of Statistics)
kBq	Kilobecquerel
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
LSCF	Lanthanum Strontium Cobalt Ferrite
MEA	Membrane–Electrode Assembly
MEF	Ministero dell’Economia e delle Finanze (Italian Ministry of Economy and Finance)
NPV	Net Present Value
OPEX	Operational Expenditure
P2G	Power-to-Gas

PM	Profit Margin
PM _{2.5}	Fine Particulate Matter ($\leq 2.5 \mu\text{m}$ aerodynamic diameter)
R&D	Research and Development
REV	Revenues
SCFA10	$\text{Sr}_{0.9}\text{Ce}_{0.1}\text{Fe}_{0.9}\text{Al}_{0.1}\text{O}_3$
SCS	Solution Combustion Synthesis
SOEC	Solid Oxide Electrolyzer Cell
SOFC	Solid Oxide Fuel Cell
TR	Tax Rate
WTP	Willingness to Pay
YSZ	Yttria-Stabilised Zirconia

Declarations

Competing interests

• The authors have no relevant financial or non-financial interests to disclose.

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Author Contribution

S.S., M.G., and G.M. wrote the main manuscript text. F.D., C.A., L.V., and L.F.L. performed the material synthesis and wrote the corresponding section. M.L. provided the description of the SOFC technology. S.S., M.G., and G.S. conducted the LCA. M.G., A.N., and G.M. performed the LCC. M.G. and A.N. conducted the eLCC. All authors reviewed the manuscript.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Tables

Table I: ReCiPe 2016 Midpoint (H) characterization results: comparison of the two SOFC configurations.

Impact category	Unit	SOFC cell	SOFC cell + SCFA10
Global warming	kg CO ₂ eq	10.97180429	10.99197788
Stratospheric ozone depletion	kg CFC-11 eq	5.13961E-06	5.16404E-06
Ionizing radiation	kBq Co-60 eq	1.250190958	1.252228101
Ozone formation, Human health	kg NO _x eq	0.018103501	0.01813752
Fine particulate matter formation	kg PM _{2.5} eq	0.010568232	0.010589485
Ozone formation, Terrestrial ecosystems	kg NO _x eq	0.020275367	0.020311811
Terrestrial acidification	kg SO ₂ eq	0.029669019	0.029728434
Freshwater eutrophication	kg P eq	0.002247522	0.00225248
Marine eutrophication	kg N eq	0.000215796	0.000216923
Terrestrial ecotoxicity	kg 1.4-DCB	71.34633202	71.50181221
Freshwater ecotoxicity	kg 1.4-DCB	0.751648988	0.753687558
Marine ecotoxicity	kg 1.4-DCB	0.993427024	0.996078435
Human carcinogenic toxicity	kg 1.4-DCB	1.081474063	1.083782646
Human non-carcinogenic toxicity	kg 1.4-DCB	8.846683157	8.870048174
Land use	m ² a crop eq	0.355038086	0.356124633
Mineral resource scarcity	kg Cu eq	0.037890277	0.03797892
Fossil resource scarcity	kg oil eq	3.576668745	3.582959684
Water consumption	m ³	0.206223564	0.206604443

Table II: Normalised ReCiPe 2016 Midpoint (H) results: comparison of the two SOFC configurations.

Impact category	SOFC cell	SOFC cell + SCFA10
Global warming	0.001371476	0.001373997
Stratospheric ozone depletion	8.58315E-05	8.62395E-05
Ionizing radiation	0.002600397	0.002604634
Ozone formation, Human health	0.00087983	0.000881483
Fine particulate matter formation	0.000413218	0.000414049
Ozone formation, Terrestrial ecosystems	0.001141503	0.001143555
Terrestrial acidification	0.000723924	0.000725374
Freshwater eutrophication	0.003461184	0.003468819
Marine eutrophication	4.68278E-05	4.70724E-05
Terrestrial ecotoxicity	0.004694589	0.004704819
Freshwater ecotoxicity	0.029840465	0.029921396
Marine ecotoxicity	0.022848822	0.022909804
Human carcinogenic toxicity	0.105011132	0.105235295
Human non-carcinogenic toxicity	0.000283094	0.000283842
Land use	5.75162E-05	5.76922E-05
Mineral resource scarcity	3.15626E-07	3.16364E-07
Fossil resource scarcity	0.003648202	0.003654619
Water consumption	0.000773338	0.000774767

Table III: Relative contribution of the main SOFC components to selected ReCiPe 2016 Midpoint impact categories for the SCFA10-coated configuration.

Impact category	Anode (%)	Cathode (%)	Electrolyte (%)	Barrier layer (%)	SCFA10 coating (%)
Global warming	47.5	17.5	17.5	17.5	0.18
Human carcinogenic toxicity	41.2	19.5	19.5	19.5	0.21
Freshwater ecotoxicity	16.8	27.6	27.5	27.5	0.27
Marine ecotoxicity	18.9	27.0	26.9	26.9	0.27
Fossil resource scarcity	47.7	17.2	17.2	17.2	0.18

Table IV: List of equipment to build a conventional and alternative SOFC.

Equipment	SOFC cell	SOFC cell + SCFA10
Ball milling machine	12,000 €	12,000 €
Tape casting (doctor blade)	32,500 €	32,500 €
Screen printing	65,000 €	65,000 €
Drying phase	22,500 €	22,500 €
Sintering	95,000 €	95,000 €
Fume hood with activated carbon filters	11,500 €	11,500 €
Heating plate	1,000 €	N/A*
Analytical balance	3,750 €	N/A*
Muffle furnace	5,250 €	N/A*
CAPEX:	248,500 €	238,500 €

* N/A = Not applicable (equipment not included).

Table V: Details of the characteristics of the cells analysed.

Setup	Amount
Cell area	96 cm ²
Active area	82.5 cm ²
Anode	96 cm ²
Cathode	82.5 cm ²
Quantity of material making up the cell	53 g

Table VI: Evaluation of operative costs for the conventional and alternative SOFC.

Cost item	SOFC cell	SOFC cell + SCFA10
Cost of materials	6,073.77 €/year	6,057.56 €/year
Labour cost	90,000.00 €/year	90,000.00 €/year
Electricity consumption and other energy consumption	7,490.00 €/year	6,518.00 €/year
Other possible costs	2,000.00 €/year	2,000.00 €/year
OPEX:	105,564.77 €/year	104,575.56 €/year

Table VII: Evaluation of impact category for the conventional and alternative SOFC.

Impact category	SOFC cell	SOFC cell + SCFA10
Climate change	0.606767581 _{EUR2015}	0.607881711 _{EUR2015}
Ozone depletion	0.000025641 _{EUR2015}	0.000025688 _{EUR2015}
Terrestrial acidification	0.246223405 _{EUR2015}	0.246720322 _{EUR2015}
Freshwater eutrophication	0.003904179 _{EUR2015}	0.003912414 _{EUR2015}
Marine eutrophication	0.003677830 _{EUR2015}	0.003691511 _{EUR2015}
Human toxicity	0.259574858 _{EUR2015}	0.260213953 _{EUR2015}
Photochemical oxidant formation	0.036551867 _{EUR2015}	0.036618103 _{EUR2015}
Particulate matter formation	0.437098154 _{EUR2015}	0.438018676 _{EUR2015}
Terrestrial ecotoxicity	0.071311586 _{EUR2015}	0.071480503 _{EUR2015}
Freshwater ecotoxicity	0.017454294 _{EUR2015}	0.017501714 _{EUR2015}
Marine ecotoxicity	0.003318450 _{EUR2015}	0.003327279 _{EUR2015}
Ionizing radiation	0.059155598 _{EUR2015}	0.059252928 _{EUR2015}
Agricultural land occupation	0.088228949 _{EUR2015}	0.088422130 _{EUR2015}
Urban land occupation	0.013168744 _{EUR2015}	0.013208878 _{EUR2015}
Natural land transformation	0.000000000 _{EUR2015}	0.000000000 _{EUR2015}
Water depletion	0.000000000 _{EUR2015}	0.000000000 _{EUR2015}
Metal depletion	0.000000000 _{EUR2015}	0.000000000 _{EUR2015}
Fossil depletion	0.000000000 _{EUR2015}	0.000000000 _{EUR2015}
Total	1.846461138 _{EUR2015}	1.850275811 _{EUR2015}

Figures

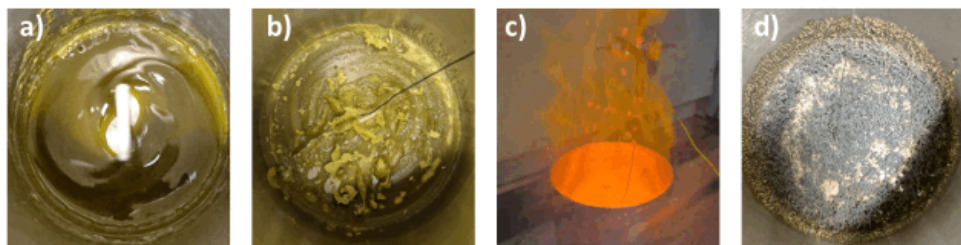


Figure 1

Sol formation (a), gel formation (b), self-combustion reaction (c), as-burned powder (d).

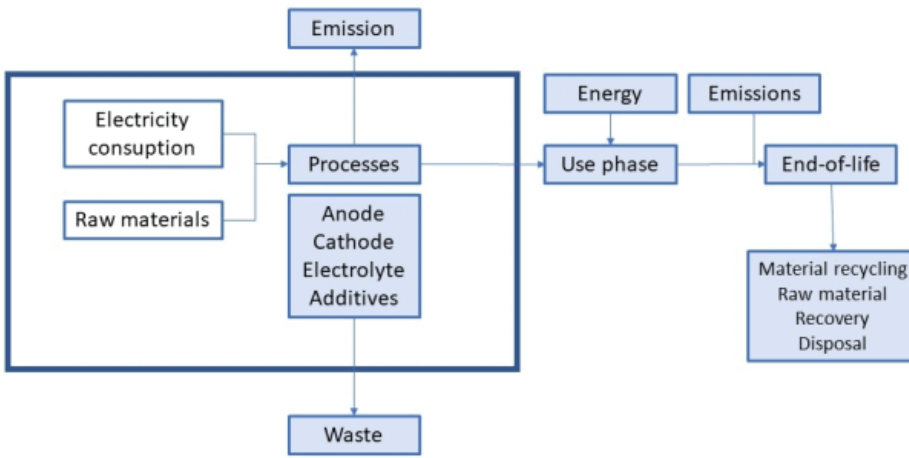


Figure 2

Schematic of the system boundaries.

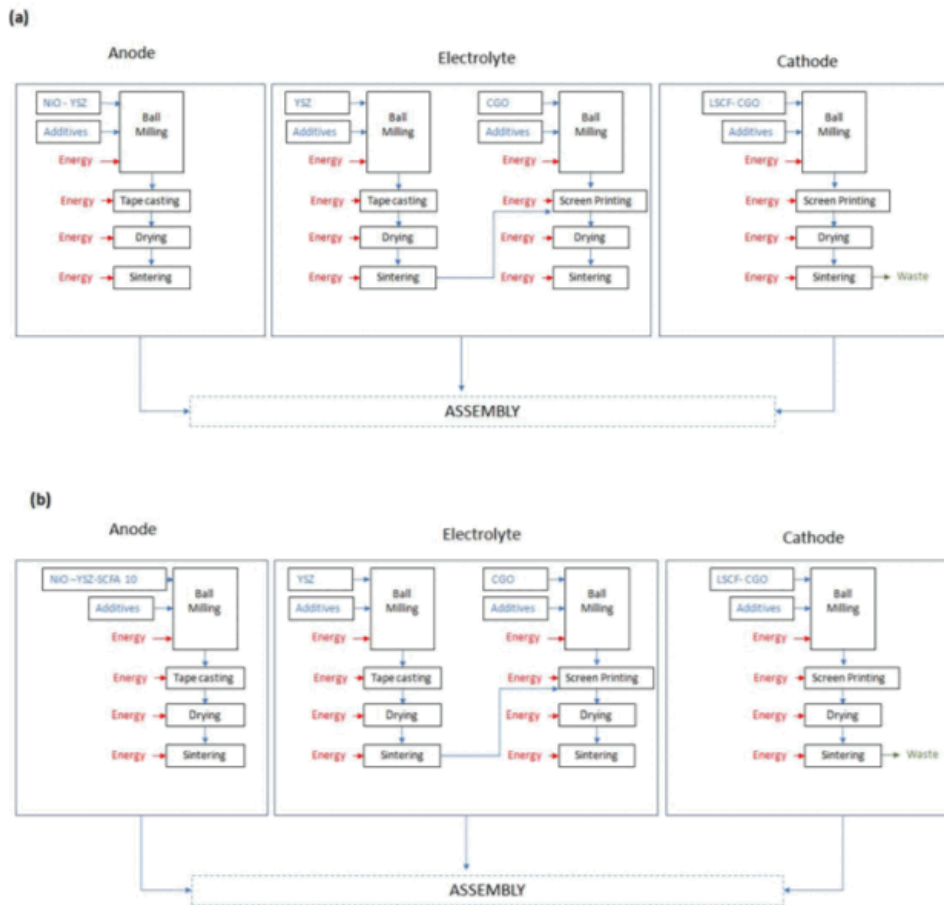


Figure 3

Flow diagram of the conventional SOFC (a) and of the SOFC + SCFA10 (b) cell production process.

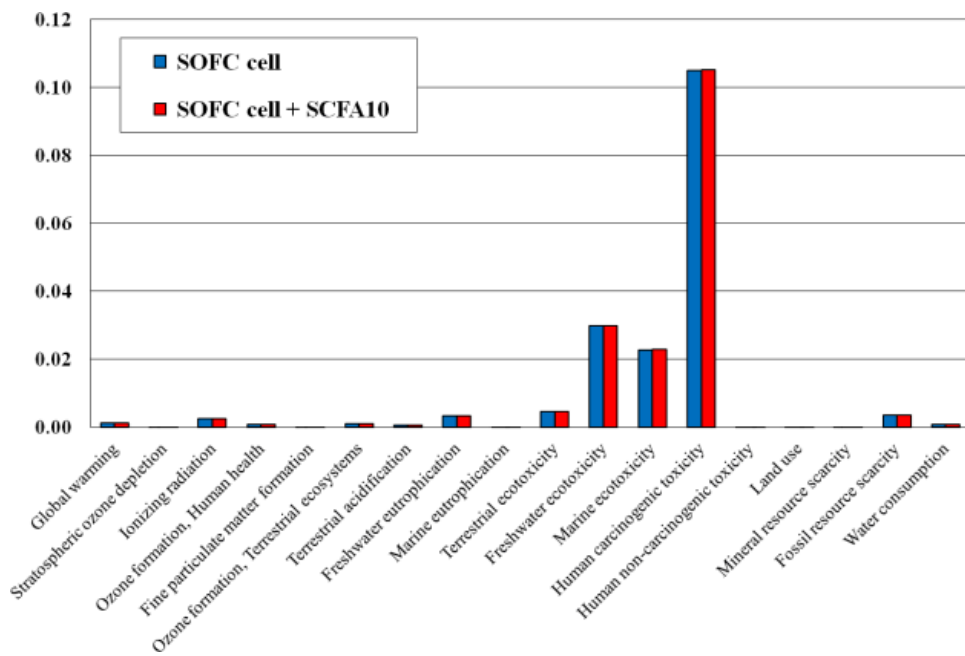


Figure 4

Normalised ReCiPe 2016 Midpoint (H) results of the comparison between the two SOFC cells.

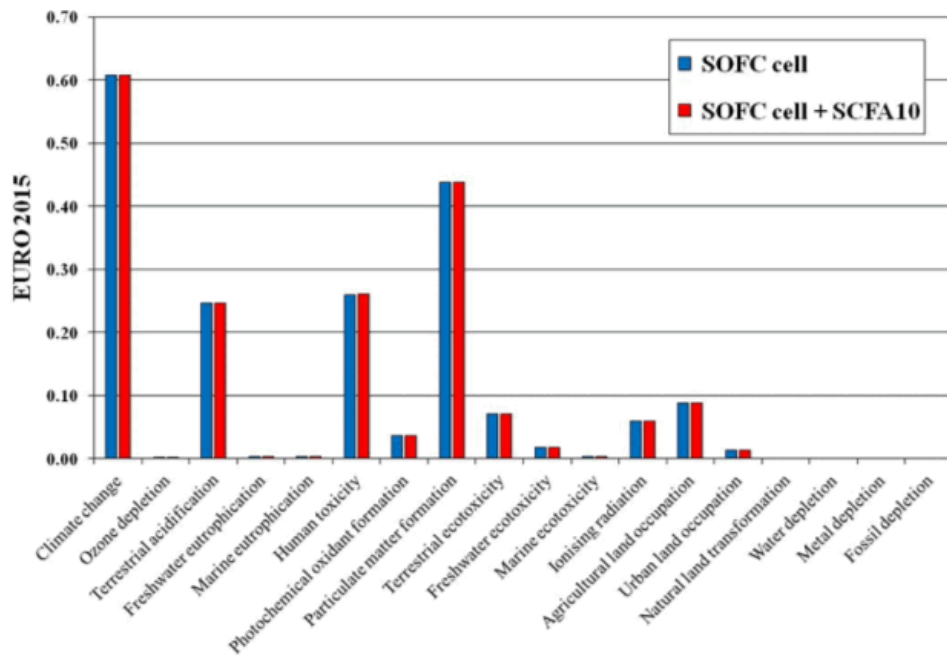


Figure 5

Normalised Environmental Prices (2015) results for the two SOFC cells.

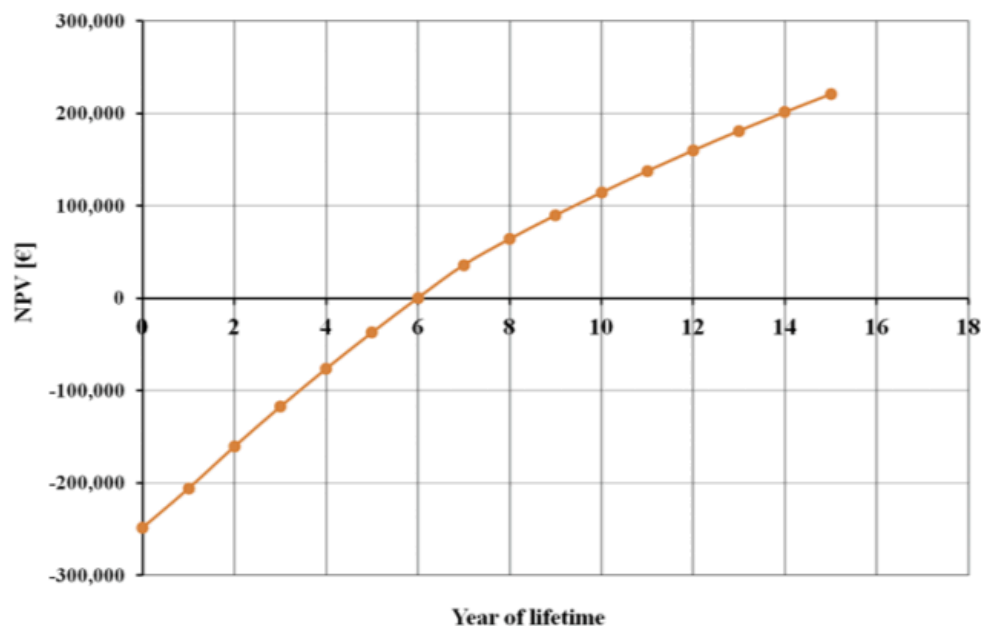


Figure 6

NPV for SOFC CELL + SCFA10 over 15 years.

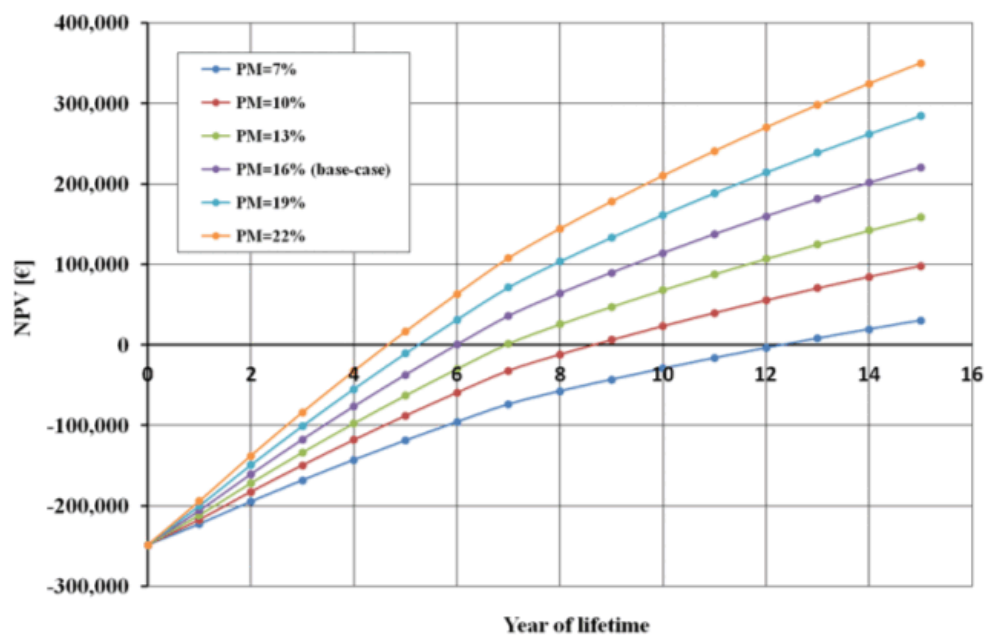


Figure 7

Sensitivity analysis for the alternative cell.