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Cleaner Power Generation: An In-depth Review of Life Cycle Assessment for Solid Oxide Fuel Cells

(Penjanaan Kuasa yang Bersih: Kajian Mendalam Penilaian Kitaran Hayat bagi Sel Bahan Api Oksida Pepejal)

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ABSTRACT

Nowadays, there is a growing emphasis on creating alternative power generation methods to replace outdated technologies like coal-fired power and hydroelectric plants. One promising solution is the Solid Oxide Fuel Cell (SOFC), which offers high energy efficiency, low carbon emissions, and cost-effectiveness. This study presents a focused examination of the Life Cycle Assessment (LCA) of SOFCs, with the objective of reducing dependence on non-renewable energy sources. The review encompasses a review of published articles between years 2016 to 2023 and an analysis of research gaps in SOFCs' environmental performance. A systematic literature review underpins this investigation, where several publication selection criteria were considered including plants that can produce hydrocarbon such as biogas and biomass, utilization of LCA software as a method of assessment and incorporation of the life cycle impact assessment in the articles. The results suggest that using SOFC powered by biogas as a stationary power generator is a viable option. This is supported by recent LCA studies demonstrating that SOFCs using biogas have a reduced impact on climate change compared to other fuels. Implementing SOFCs holds great potential for a cleaner energy future, aligning with society's goals for sustainable power production. For a more precise comparison of results, future LCA studies should adopt a multi-criteria environmental impact analysis using a consistent functional unit across different SOFC operations.

Keywords: Solid Oxide fuel cell (SOFC); Life Cycle Assessment; environmental impact

ABSTRAK

Kini terdapat usaha yang semakin meningkat untuk mewujudkan kaedah penjanaan kuasa alternatif bagi menggantikan teknologi lapuk seperti loji janakuasa arang batu dan hidroelektrik. Satu penyelesaian yang mempunyai harapan ialah Sel Fuel Oksida Pepejal (SOFC), yang menawarkan kecekapan tenaga yang tinggi, pelepasan karbon yang rendah dan menjimatkan kos. Kajian ini memberikan pemerhatian yang tertumpu kepada Penilaian Kitaran Hayat (LCA) SOFC, dengan tujuan untuk mengurangkan pergantungan kepada sumber tenaga tidak boleh diperbaharui. Ulasan kajian ini merangkumi semakan artikel yang diterbitkan antara tahun 2016 hingga 2023 dan analisis jurang penyelidikan dalam prestasi alam sekitar SOFCs. Kajian literatur sistematik menyokong penyiasatan ini, di mana beberapa kriteria pemilihan penerbitan dipertimbangkan termasuk plantar yang boleh menghasilkan hidrokarbon seperti biogas dan biojisim, penggunaan perisian LCA sebagai kaedah penilaian dan penggabungan penilaian kesan kitaran hayat dalam artikel. Keputusan menunjukkan penggunaan SOFC yang dikuasakan oleh biogas sebagai penjana kuasa pegun adalah pilihan yang boleh dipertimbangkan. Ini disokong oleh *kajian terbaru LCA yang menunjukkan bahawa SOFC yang menggunakan biogas mempunyai pengurangan kesan terhadap perubahan iklim berbanding bahan api yang lain. Pelaksanaan SOFC mempunyai potensi besar untuk masa depan tenaga yang lebih bersih, sejajar dengan matlamat masyarakat untuk pengeluaran tenaga yang mampan. Untuk perbandingan hasil yang lebih tepat, kajian LCA masa hadapan harus menggunakan analisis kesan alam sekitar dengan pelbagai kriteria menggunakan unit berfungsi yang konsisten merentas operasi SOFC yang berbeza.*

Kata kunci: Sel Fuel Oksida Pepejal; Penilaian Kitaran Hayat; kesan alam sekitar

INTRODUCTION

The global hydrocarbon energy supply is predicted to peak in the 2020–2030 century, after which it will start to decline (Sorrell et al. 2010). This, combined with the increasing demand for energy and the negative effects of burning fossil fuels on the environment (Latake et al. 2015), has led to a global shift towards finding alternative and renewable sources of energy. The Paris Agreement was formed in response to the growing concerns about climate change and the need to reduce greenhouse gas emissions (Jayaraman 2015). As a result, many nations are actively exploring and investing in green energy technologies.

In general, nations are looking to diversify their energy mix to include renewable sources like solar, hydropower, and biomass (Azni et al. 2023) while also utilizing traditional sources like coal, oil, and natural gas. However, there are challenges in ensuring the security and reliability of the energy supply and in reducing emissions (Sharvini et al. 2018). Fuel cells, including Solid Oxide Fuel Cells (SOFCs), are being seen as a promising solution to these challenges (Choudhury et al. 2013). Fuel cells work similarly to a battery, converting chemical energy stored in fuels into electrical energy. SOFCs are considered one of the cleanest options for the hydrogen economy, with zero combustion and high efficiency (Lee et al. 2015). However, there are challenges in widespread adoption, including the perception that sustainable technologies require significant upfront investments (Salim et al. 2022).

The purpose of this paper is to address the lack of acceptance among manufacturers for solid oxide fuel cells (SOFCs), despite their extensive coverage in journals and publications. It aims to bridge the gap in understanding by providing an overview of the life cycle assessment (LCA) of SOFCs and reviewing recent LCA studies on their environmental impact. The paper will examine the SOFC technology, explain the approach used in conducting the LCA, and present the findings of recent studies.

SOLID OXIDE FUEL CELL

SOFC stands for Solid Oxide Fuel Cell, which is a device for energy conversion that operates at high temperatures, between 500 and 1000°C, due to advancements in technology (Shao & Haile 2010). SOFC has several strong points such as remarkable efficiency, environmentally friendly, fuel adaptability, and operating quietly without vibrations (McPhail et al. 2013). The system has an efficiency rate of between 40% and 60% in power generation, but this rate can be increased to 90% if the heat generated is captured. Unlike other fuel cells, SOFC does not need expensive catalysts and can be formed into any geometry (Steinberger-Wilkens 2012). It can convert various gaseous fuels such as hydrogen, hydrocarbon, methane, carbon monoxide, and biogas into electrical energy with minimal environmental impact (Afroze et al. 2020).

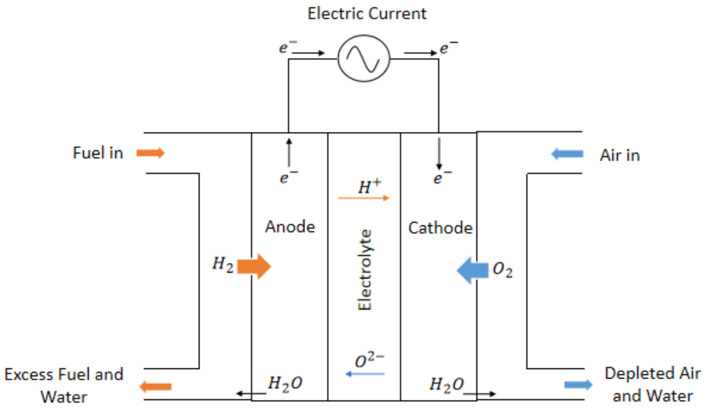

FIGURE 1. Schematic Diagram of SOFC (Afroze et al. 2020)

An anode, a cathode, an electrolyte, and electrical connectors known as bipolar plates are essential components of a SOFC. The cathode is crafted from a mixture of conducting oxides like perovskite, while the anode is composed of ceramics and metals. The electrolyte is usually made of Yttria-stabilized Zirconia (YSZ), which is a solid oxide material. Based on Figure 1, the anode receives fuel, and the cathode receives air. Oxygen ions permeate to the anode while fuel absorbs oxygen and emits heat, water, and electrons. The electrons enter the cathode and then go to an external circuit to provide electricity. SOFC can operate continuously if fuel and temperature are maintained.

While SOFC has many benefits, it also has some challenges in its adoption into real-world applications, including economic, environmental, and social considerations (Ramadhani et al. 2017). Integrating fuel cells with alternative fuels faces challenges like high costs, fuel storage, infrastructure, lifespan, and response time (van Veldhuizen et al. 2023). Choosing appropriate materials is also essential for preserving the excellent electrochemical performance of SOFCs, ensuring efficient conversion of chemical energy into electrical energy (Zainon et al. 2023). A systematic approach with reliable data is needed to demonstrate the sustainability of SOFC and provide decision-makers and consumers with the best evaluation and solutions based on life cycle impacts. SOFC can convert a range of fuels, but contaminants such as halogens, siloxanes, and sulfur compounds must be removed to increase system stability (Mehmeti et al. 2016).

METHODOLOGICAL APPROACH FOR LIFE CYCLE ASSESSMENT

The concept of a product's life cycle follows ISO standards and is described as comprising 'the consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal" (Guinée et al. 2022).

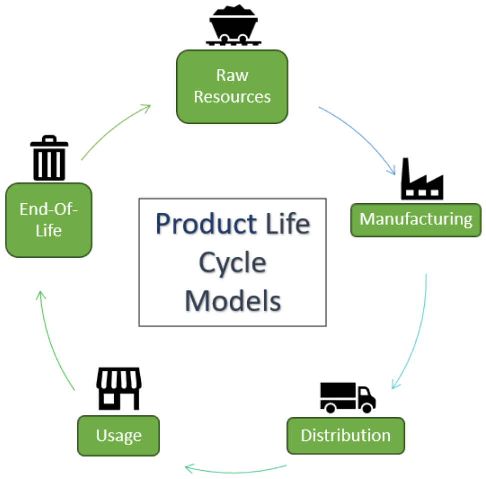

FIGURE 2. Life Cycle Diagram

"Life cycle assessment" (LCA) denotes to a flexible, multi-step process aimed at compiling and evaluating material flow process in and out, and potential environmental effects of a product system over the course of its lifetime, encompassing aspects from manufacturing and usage to maintenance and raw material sourcing (ISO 2020). LCA has been gaining prominence as a means of examining environmental impacts and sustainability (Rashid et al. 2023). LCA findings are instrumental for comparing energy technologies in product or system design, production, and utilization, offering valuable insights for decision-makers in curbing resources consumption and mitigating air, water, and land pollution (Curran 2009; ISO 2020; Manual 2011). LCA may contribute to the choice of one product over another when used in conjunction with other decision-making techniques. According to Figure 3, the four stages of an LCA's systematic process include aim and scope definition, life cycle inventory (LCI) analysis, impact assessment, and interpretation (ISO 2020). Standards for environmental management form the foundation for these phases (ISO14040:2006 and 14044:2006).

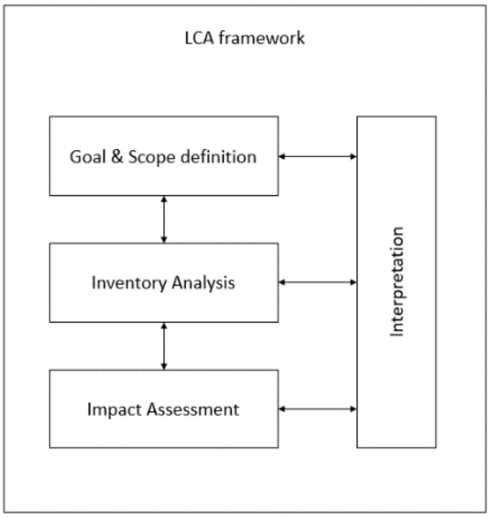

FIGURE 3. LCA methodological steps

The first step in conducting an LCA is to define its purpose and scope, which includes detailing the reasons for conducting the analysis, outlining the full scope of the product or process, and establishing its limit across the various stages of its life cycle. We may comprehend why an LCA is undertaken by stating the study's objective (Curran 2017). The goal of this step is to provide overall guidance so that LCA is carried out consistently and the most significant results are attained. Even though the boundary system is determined by multiple factors, including the study's purpose, assumptions, and intended audience, ISO 14040 recommends that the circumstances used to determine the system boundary be specified and supported in the scope of the study. Determining an LCA's system boundary is therefore essential since it guarantees the precision of model in the comparability of studies (Omolayo et al. 2021).

Inventory analysis in energy systems modeling is an iterative process that focuses on the established goals and scope. It involves gathering detailed information on all inputs, outputs, energy use, water and material consumption, and environmental releases, such as air emissions, solid waste disposal, and wastewater discharges, throughout the product's life cycle or operation. This information is crucial for a comprehensive analysis (Curran 2009; Finkbeiner et al. 2006)

Consequently, the life cycle inventory is translated into life cycle impact assessment (LCIA). Omolayo et al. (2021) stated that the conversion of these emissions and resource into ratings for environmental effects aids in the comprehension of the assessment. In the LCIA stage, it connects the elementary flows pinpointed during the LCI phase and evaluates a wide range of potential environmental consequences. Due to the fact that the weighting stage for fuel cell production is not advised because it is based on opinions rather than objective data (such as economic, political, or environmental reasons), the LCA's findings and conclusions could be significantly influenced (Mehmeti et al. 2016). Regarding its LCI inputs, LCIA assesses the potential environmental impact of a product or service through either a midpoint (problem-oriented) or endpoint (damage-oriented) method, utilizing a cause-and-effect sequence (environmental mechanism).

Mehmeti et al. (2016) stated that endpoint evaluations estimate the overall impact of the actions, such as human well-being, the ecological environment, and available resources while midpoint evaluations concentrate on actions that cause environmental damages, such as Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP). Endpoint modelling simplifies the assessment of impact magnitude and provides more understandable results concerning societal issues, whereas midpoint modelling allows for more confidence (reduced modelling complexity) and lower uncertainty (minimized assumptions) (Bare et al. 2000). These criteria for the life cycle impact category were chosen because they applied to the systems examined the most (Hauschild & Huijbregts 2015). There are numerous LCIA tools available, such as TRACI, ReCipe, and GaBi, and the selection of environmental categories depends on the LCIA tools being utilized.

Despite other studies (Gantner et al. 2001; Kawajiri & Inoue 2016; Staffell et al. 2012) examined one concept of indicator, such as the acidification potential (AP) or global warming potential (GWP), Mehmeti et al. (2016) stated that using a single indicator may not provide a precise representation of the environmental impact. For instance, a product or process could exert a lesser influence on climate change, featuring reduced CO_2 emissions in contrast to a equivalent competitor, but it could have more severe effects on acidification due to higher emissions of SO_2 and NO_X.

The life cycle interpretation phase, which comes after the other stages of an LCA, is when the data are evaluated and further studied based on the study's assumptions about uncertainties and variabilities. In addition, this phase entails evaluating the results of the inventory analysis and impact assessment while maintaining a clear understanding of uncertainty and underlying assumptions to enhance environmental performance. Therefore, completeness, consistency, and sensitivity checks should be taken into consideration in interpretations (Hauschild et al. 2018). Additionally, recommendations for improving project and policy selections can be made in the life cycle interpretation based on the assessment's findings. To meet the assessment's objectives and scope, it is necessary to choose the types of environmental impacts that will be considered and to specify the level of detail.

METHODOLOGY FOR LIFE CYCLE ANALYSIS OF SOFC REVIEW

SOFC becomes a promising energy conversion technology in recent times (Abdelkareem et al. 2021). The growth of scholarly literature that examines the life cycle of fuel cells over the past several years is evidence of the growing interest in this technology. This is shown in Figure 4.

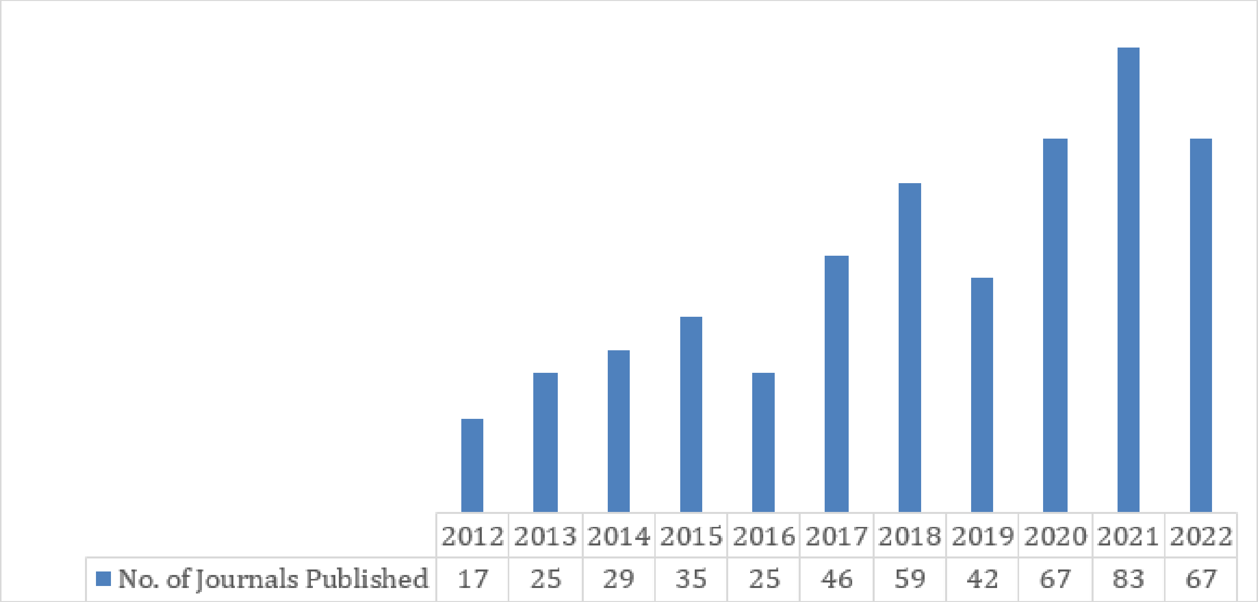

FIGURE 4. Papers published in ScienceDirect for "Life cycle assessment" AND "SOFC" between 2012-2022. Searched on 12/7/2022

This review was conducted based on the systematic approach (Suhariyanto et al. 2017). The central research inquiry can be formulated as follows: What are the impact assessment indicators of SOFCs using various life cycle assessment methods? The keyword search used are ("Life Cycle Assessment" AND "SOFC") through the Science Direct databases to find relevant studies. Through the database search, 603 records were found. Next is, applying practical screening criteria which comprises of publication's language, date of publication and publications' content. Upon closer inspection, 8 of the 603 papers were found to meet our inclusion requirements, which included being original research publications written in English and published online between January 1, 2016, and December 31, 2021. Furthermore, for methodological screening criteria, the review was very focused on case study that involved any plant that can produce hydrocarbon such as biogas and biomass. On the other hand, the review criteria also include LCA software as a method of assessment. Finally, the life cycle impact assessment must be included in the article for analysis and comparison with other articles.

REVIEW RESULTS FOR LIFE CYCLE ANALYSIS OF SOFC

The identified LCA research on SOFCs, most of which were published in scholarly journals, is included in Table 1. The studies reveal a wide geographic distribution.

Research in the field of Life Cycle Assessment (LCA) for SOFCs has predominantly centered on achieving two primary goals for reducing environmental impacts: (1) identifying critical processes and materials that exert the most significant influence on the environment implications of SOFC systems and evaluating the effects of potential improvements; and (2) accessing the environmental advantages and equivalencies of different energy supply sources.

The intended use of the findings was to support decision-making for the public. Setting the target audience is a crucial step in the LCA process because it helps determine the resources required for the study and clarifies who will benefit from the findings (Masoni & Zamagni 2011). Few studies specify their intended audience explicitly, focusing primarily on individuals who lack technical expertise (i.e., legislators and policymakers). This was accomplished by describing the results from a life cycle perspective in a nontechnical manner, despite their technical basis.

GOAL AND SCOPE DEFINITION

SYSTEM BOUNDARIES

Three of the studies (Bargiacchi et al. 2021; Bicer & Khalid 2020; Wen et al. 2018) under consideration selected the boundaries of the system with a "from cradle to grave" strategy, which includes the procurement of raw materials, the construction of the system, the production of fuel, the operation, maintenance, and end-of-life phases. Four of the studies (Gandiglio et al. 2019; Kawajiri & Inoue 2016; Moretti et al. 2020; Rillo et al. 2017) opted for a "from cradle to gate" approach, omitting certain life cycle stages such as the maintenance or the end-of-life due to limited data availability. Figure 5 shows the general system boundaries.

TABLE 1. Status of life cycle studies on SOFC

Literature	Application	System Boundaries	Inventory Data	Fuel type	LCA software	Functional Unit	Region
Kawajiri & Inoue (2016)	Greehouse Gas impacts SOFCs nano films using scale effect	Cradle to gate (stack)	Primary Data Secondary Data (Electric Consumption)	n. a.	n. a.	1 kW cell	Japan
Rillo et al (2017)	Sewage biogas	Cradle to gate approach	Primary Data (Modelling Foreground Processes) Secondary Data	Natural Gas Biogas	GaBi Software	1 kW of electricity generated	Italy
Bicer et al (2018)	Heat and power production	Cradle to grave approach	Secondary Data (previous studies)	Natural gas, hydrogen, ammonia, methanol	GaBi Software	1 kW electricity	Qatar
Wen et al (2018)	Auxiliary power unit (APU)	Cradle to grave	Secondary Data (Scientific Literature, CLCD and ELCD)	Biomass-based fuel ethanol	eBalance	1 kWh of electricity	China
Gandiglio et al (2019)	Wastewater treatment plant	Cradle to gate (stack)	Primary Data Secondary Data (Manufacturing)	Biogas	GaBi Software	14 Mm^3/yr; wastewater treated by the plant in one year	Italy
Moretti et al (2020)	Biomass-fueled CHPs	Cradle to gate approach	Secondary Data	Biogas	n. a.	1 kWh of electricity or 1 MJ of heat	German

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Bargiacchi et al (2020)	Power generation	Cradle to grave approach	Secondary Data	Biogas	SimaPro Software	1 kg of SNG or and 1 MJ of output energy (SNG and electricity)	Italy
Al-Khori et al (2021)	Natural gas plant operation	Cradle to grave approach	Secondary data	Natural gas	Gabi Software	1 MW of electricity output	Qatar

The final stage, known as disposal, is not mandatory and can be excluded from the study's scope; however, it should still be described with statistics. The analysis reveals that recent literature has started to explore the SOFC system's recycling and disposal phase, which was often overlooked in earlier studies due to undefined end-of-life plans and a lack of associated data. (Al-Khori et al. 2021). According to Lee et al. (2015), the environmental impact of a SOFC system is minimally influenced by the manufacturing and end-of-life stages. A thorough assessment of how processes and the entire system interact with the environment can be achieved by establishing a well-defined system boundary through modeling (Mehmeti et al. 2016).

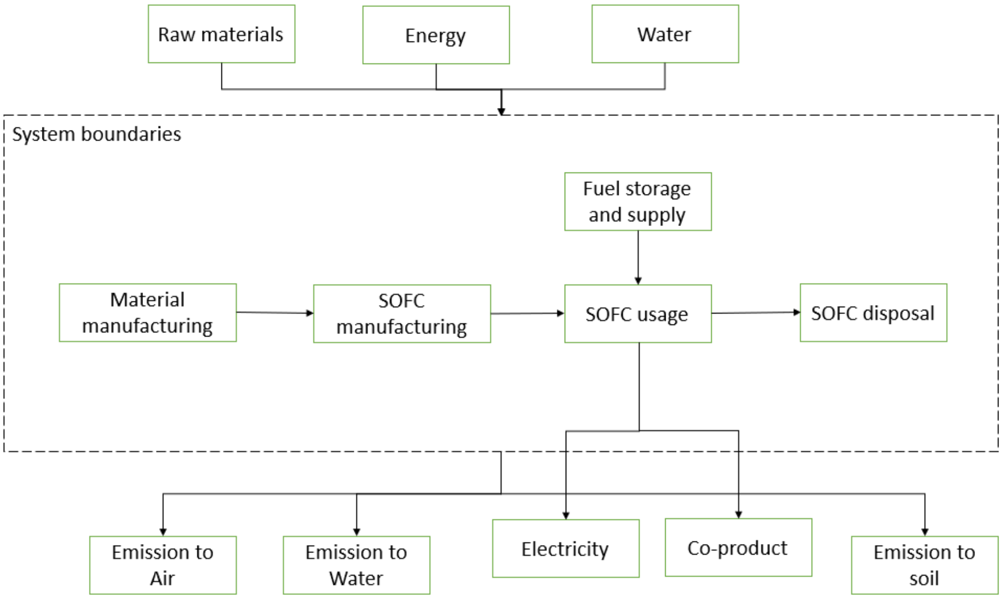

FIGURE 5. General input/output and life cycle processes involved in SOFC

FUNCTIONAL UNITS

The functional unit (FU) is described as the "quantified performance of a product system for use as a reference unit" by ISO 14040 (2006). It's crucial for the comparison of several research that focus on the same product, for example in conducting literature reviews.

According to the following descriptions, various FUs have been chosen in the LCA experiments covered in this review:

1. 1 kWh of electricity generated (Bicer & Khalid 2020; Kawajiri & Inoue 2016; Moretti et al. 2020; Rillo et al. 2017; Wen et al. 2018). In this instance, the effects are quantified as a unit of energy production, and their magnitude is correlated with systems' performances running during the operation step: the smaller the impacts, the better the system's performance during the usage phase. In some cases, Al-Khori et al. (2021) defined FU as 1 MW of net energy produced by the SOFC system during the course of its 10-year service life (and afterwards that used by the gas plant).
2. 1 kg of SNG or 1 MJ of total energy produced by Bargiacchi et al. (2021). This is due to the system's polygenerative nature, as SNG and energy are both co-produced.
3. 14 Mm3/year; wastewater treated by the plant in one year by Gandiglio et al. (2019). This is because the purification process uses a lot of electricity to ensure that the water and sludge are circulated throughout the plant. For the anaerobic digestion process, thermal energy is required, and it functions most efficiently within a specific temperature range.

LIFE CYCLE INVENTORY

There are two types of data that are gathered for LCA research: primary and secondary.

Secondary data refer to secondary sources such as environmental databases and literature studies, which includes energy sources data that were utilized to produce material or its component, while primary data such as input, and output data of material flows are directly gathered or measured in situ.

Primary data on manufacturing processes was lacking, according to LCA studies of SOFCs. Only two recent studies (Gandiglio et al. 2019; Kawajiri & Inoue 2016) utilize primary data to describe the SOFC manufacturing process, and while Rillo et al. (2017) uses primary data to simulate foreground processes. Six other studies (Al-Khori et al. 2021; Bargiacchi et al. 2021; Bicer & Khalid 2020; Moretti et al. 2020; Wen et al. 2018), in contrast, make use of secondary data, including records from previous studies, databases, and electricity usage. Simulated data on the operating step is gathered by questionnaires, lab tests, or manufacturer catalogues. Utilizing secondary data, the end-of-life and raw material supply are investigated.

LIFE CYCLE IMPACT ASSESSMENT

The impact evaluation techniques employ a vast array of pollutant chemicals and characterization factors to determine the effect category. Multiple environmental indicators can be used to represent the same category of environmental impact (for example, ozone depletion expressed in g R11 eq or kg CFC-11 eq). The literature analysis on SOFCs revealed variations in the LCIA phase, impact evaluation methodology, and some impact categories (Longo et al. 2017).

TABLE 2. Life Cycle Impact Assessment of SOFC studies

	Life Cycle Impact Assessment Categories										
Literatures	CC/ GWP	TA/AP/ AC	MFRD/ ADP	TE/EP	ODP	PED/ CED	PMF/PM/ HHPM	FD	POF/POCP	HT/ HTP	WD/WU/ WRD
Kawajiri & Inoue (2016)	√										
Rillo et al (2017)	√	√					√	√	√		
Bicer et al (2018)	√						√	√	√	√	√
Wen et al (2018)	√	√	√	√	√	√	√				√
Gandiglio et al (2019)	√	√	√	√	√	√			√		
Moretti et al (2020)	√	√	√	√			√		√		√
Bargiacchi et al (2020)	√	√				√					
Al-Khori et al (2021)	√	√		√	√		√			√	

Legend:

CC/GWP: Climate Change/ Global Warming Potential

TA/AP/AC: Terrestrial Acidification/ Acidification Potential/ Acidification

MFRD/ADP: Mineral, Fossil & Renewable Resource Depletion/ Abiotic Depletion Potential of elements

TE/EP: Terrestrial Eutrophication/ Eutrophication Potential

ODP: Ozone Depletion Potential

PED/CED: Primary Energy Demand/ Cumulative Energy Demand

PMF/PM/HHPM: Particulate Matter Formation/ Particulate Matter/ Human Health Particulate Matter Potential

FD: Fossil Depletion

POF/POCP: Photochemical Ozone Formation/Photochemical Ozone Creation Potential

HT/HTP: Human Toxicity/ Human Toxicity Potential

WD/WU/WRD: Water Depletion/ Resources depletion – Water/ Water Resources Depletion

The environmental impact of alternative energy production methods is frequently evaluated through impact assessments that focus on two main categories: climate change and global warming potential. These categories are considered important due to their direct connection to CO2 emissions. To effectively communicate the findings of these assessments to policymakers and legislators, comparisons between different methods are often required. Popular impact assessment methods include Gabi Software, SimaPro, and eBalance. Despite differences between these approaches, Gabi Software has gained increased popularity over time.

LCA INTERPRETATION

Studies on the life cycle assessment (LCA) of SOFCs have shown that they are a greener alternative to traditional power generation methods. Several studies have been conducted to evaluate the environmental performance of SOFCs, including their impact on climate change, human health, and depletion of fossil fuels.

Kawajiri & Inoue (2016) reported that reducing energy consumption at each stage of thin-film SOFCs is the most effective way to lower greenhouse gas (GHG) emissions. The use of solar-grade silicon wafer and reducing the working temperature of SOFCs to 500°C can enhance system efficiency and cut greenhouse emissions. Rillo et al. (2017) compared the use of carbon capture technology, natural gas, and biogas as fuel for SOFCs. Biogas was found to have a lower impact on climate change compared to natural gas, but natural gas performed better in terms of particulate matter, acidification potential, and photochemical oxidant formation.

Bicer & Khalid (2020) observed that using natural gas in SOFCs has a lower environmental impact than other conventionally produced fuels. Producing hydrogen and ammonia from renewable energy sources can offset their negative environmental effects. Wen et al. (2018) assessed the environmental impact of SOFCs powered by biomass ethanol. Fuel production was found to be the largest contributor to environmental impact, not system manufacturing. Biofuels, including corn-based ethanol, were found to have a lower impact compared to other fuels.

Gandiglio et al. (2019) compared the environmental impact of different scenarios for a wastewater treatment plant (WWTP) using SOFCs. The study found that the power required for the operation of WWTP was a major factor affecting the environmental impact. Moretti et al. (2020) studied the combination of biomass gasification with SOFCs and found that gasoline production and transportation had the largest environmental impact, followed by the manufacturing of the fuel cell stack.

Bargiacchi et al. (2021) evaluated the use of biomass and electrolytic hydrogen as a substitute for natural gas and found that it resulted in reduced environmental impact, although the production of alkaline electrolyzers related to metal mining significantly increased acidification. Al-Khori et al. (2021) assessed how integrating SOFCs into a natural gas processing plant affected the facility and found that the operational phase had the greatest impact on acidification, global warming, and particulate matter. The production process had a greater impact on eutrophication, ozone depletion, and human toxicity.

In summary, the studies show that LCA is a reliable method for evaluating the environmental performance of SOFCs. The fuel supply is one of the biggest factors affecting environmental performance, and it is important to include the fuel life cycle, production and operation stages, and balance of plant (BoP) in the LCA. BoP includes all components other than the fuel cell stack that are required to handle the power conditioning system, supply, and regulate water and air, or process the fuel. The production of BoP components has a significant environmental impact, particularly in terms of metal depletion. This is primarily attributed to the extensive use of steel in separator manufacturing (Jolaoso et al. 2023). None of the studies discussed the implementation of a circular economy approach. Morsy et al. (2020) delved into the circular economy concept, highlighting its potential for reusing energy and adopting a business model aimed at curbing the overall energy consumption.

CONCLUSION

This study provides an overview of the life cycle assessment of SOFCs and reviews recent LCA studies on their environmental performance. The results show that SOFCs have environmental benefits, but their implementation can be impacted by several factors such as different functional units, system limits, and geographical variability. In pursuit of a more sustainable energy future, it is imperative for both the industry and government to take proactive steps in advocating environmentally sustainable life cycle business plans and establishing incentive structures that encourage the widespread adoption of SOFCs. Future studies should include a more comprehensive review with a focus on cost, social aspect, and a consistent, trustworthy LCA methodology.

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