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ASSESSING THE ENVIRONMENTAL IMPACT OF HYDROGEN FUEL CELL TECHNOLOGIES (PEMFCs, SOFCs, AFCs): A CRADLE-TO-GATE ATTRIBUTIONAL LIFE CYCLE ANALYSIS

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Abstract. This research addresses the pressing need to comprehensively assess the environmental impact of hydrogen fuel cell technologies, including Proton Exchange Membrane Fuel Cells (PEMFCs), Solid Oxide Fuel Cells (SOFCs), and Alkaline Fuel Cells (AFCs), by conducting an Attributional Life Cycle Assessment (ALCA) within a cradle-to-gate system boundary. The study seeks to answer fundamental research questions related to their environmental performance and identify critical stages contributing to their Global Warming Potential (GWP). Findings indicate that hydrogen production is a pivotal stage, with AFCs exhibiting the lowest GWP, followed by SOFCs and PEMFCs. Recommendations emphasize transitioning to green hydrogen production, optimizing manufacturing processes, and integrating renewable energy sources, offering actionable insights for sustainable technology development and a cleaner energy future.

Keywords: *Alkaline Fuel Cells (AFCs), Attributional Life Cycle Assessment, Environmental Impact, Hydrogen, Proton Exchange Membrane Fuel Cells (PEMFCs), Solid Oxide Fuel Cells (SOFCs).*

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1. Introduction

1.1. Research Motivation

In the pursuit of a sustainable and low-carbon energy (Bouramdane, 2023a; 2023b) to fight against climate change (on temperature and precipitation (Bouramdane, 2022a; 2023c; 2023d), heatwaves and wildfires (Bouramdane, 2022b; 2022c), agriculture (Bouramdane, 2023e), water resources (Bouramdane, 2023f) and associated economic and non-economic damages (Bouramdane, 2023g), hydrogen fuel cell technologies have emerged as a compelling solution (Bouramdane, 2023h; 2023i). These technologies along with other renewable technologies (Bouramdane, Oct. 2021; 2022d), (e.g., offshore floating photovoltaic (Bouramdane, 2023j; 2023k), utility-scale photovoltaic and concentrated solar power (Bouramdane, 2022e; 2018), onshore and offshore wind (Bouramdane, 2023l; 2023m) and agrivoltaic systems (Bouramdane, 2022f) and smart grids (Bouramdane, (2023n), have the potential to revolutionize energy systems by offering clean and efficient means of electricity generation and transportation (Bouramdane, 2022g; 2022h). As hydrogen fuel cell applications expand across various sectors (Staffell *et al.*, 2019), it becomes imperative to comprehensively assess their environmental impact to ensure that they align with the objectives of mitigating climate change and reducing greenhouse gas emissions.

1.1. Existing Research and Knowledge Gap

Previous research has largely focused on the operational advantages (Li *et al*., 2022) and performance characteristics of hydrogen fuel cell technologies (Gillibrand *et al.*, 1967), highlighting their efficiency (Haseli, 2018), reliability (Zhai *et al*., 2022, September) and reduced emissions of local air pollutants (Cyril & Saravanan, 2020). While these merits are indisputable, there is a significant knowledge gap regarding their holistic environmental footprint. Limited attention has been given to assessing the entire life cycle of these technologies, encompassing the stages of raw material extraction, production, utilization, and end-of-life disposal. This knowledge gap poses a critical challenge, as it hinders our ability to make informed decisions and develop strategies that prioritize sustainability in the adoption of hydrogen fuel cell technologies.

1.2. Research Questions and Originality of This Study

This study aims to address this pressing knowledge gap by conducting a comprehensive Attributional Life Cycle Assessment (ALCA) of three prominent hydrogen fuel cell technologies: Proton Exchange Membrane Fuel Cells(PEMFCs), Solid Oxide Fuel Cells (SOFCs) and Alkaline Fuel Cells (AFCs). The central research questions guiding this investigation are as follows:

1. How do these hydrogen fuel cell technologies compare in terms of their environmental impact, specifically in the context of Global Warming Potential (GWP)?
2. What are the critical stages within the life cycle of each technology that contribute significantly to its overall environmental footprint?
3. What recommendations can be derived from these findings to enhance the environmental sustainability of each technology?

The originality of this study lies in its holistic approach to evaluating the environmental performance of hydrogen fuel cell technologies, addressing the entire life cycle and providing tailored recommendations for each technology based on the ALCA results.

1.3. Methodology

The research methodology employed in this study involves conducting an ALCA that considers a "cradle-to-gate" system boundary. The environmental impact, specifically GWP, will be assessed for each technology across key life cycle stages, including hydrogen production and fuel cell assembly and manufacturing. This assessment will rely on hypothetical values for illustrative purposes. Real-world assessments would necessitate the use of precise data and context-specific parameters.

1.4. Outline

This research article is structured as follows: Section 1 provides the research motivation (Section 1.1), identifying existing knowledge gaps (Section 1.2), outlining research questions, and presenting the originality of the study (Section 1.3).

Section 2 details the methodology (Section 1.4) employed in conducting the ALCA, including assumptions and the analytical framework (Section 2.1). Additionally, this section examines the operation, advantages, disadvantages and applications of the three relevant hydrogen fuel cells used in this study: Proton Exchange Membrane Fuel Cells (PEMFCs), Solid Oxide Fuel Cells (SOFCs) and Alkaline Fuel Cells (AFCs) (Section 2.2).

Section 3 presents the findings of the ALCA, including the GWP values for each technology and the critical stages identified (Section 3.1), while offering recommendations for enhancing the environmental sustainability of hydrogen fuel cell technologies (Section 3.2).

In Section 4, the results are meticulously scrutinized to unveil their implications and limitations. Additionally, this section provides valuable recommendations aimed at bolstering the environmental sustainability of hydrogen fuel cell technologies.

Section 5 summarizes the key findings, contributions and potential impacts of this study while highlighting avenues for future research.

Through this comprehensive assessment, this research aims to contribute valuable insights that inform the sustainable adoption and development of hydrogen fuel cell technologies, driving progress towards a cleaner and more sustainable energy landscape.

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2. Methodology

2.1. Life Cycle Assessment (LCA) Framework

Life Cycle Assessment (LCA) serves as a systematic and comprehensive methodology employed to assess the environmental impacts of a product, process or system throughout its entire life cycle. This approach serves as a valuable tool for gaining insights into the environmental consequences of various activities or processes while identifying opportunities for enhancing sustainability and resource efficiency (Silva, 2021).

In the context of hydrogen fuel cell technologies such as Proton Exchange Membrane Fuel Cells (PEMFCs), Solid Oxide Fuel Cells (SOFCs) and Alkaline Fuel Cells (AFCs), LCA proves essential for understanding their environmental footprint. It investigates all stages in the life cycle, encompassing (Bergerson *et al*., 2020):

- **Raw Material Acquisition**: This stage involves the extraction and processing of raw materials needed for the fuel cell technology.
- **Manufacturing**: Here, the production and assembly of the fuel cell technology take place.
- **Use Phase**: This pertains to the usage of the technology, including energy consumption and maintenance requirements.
- **End-of-Life**: This stage deals with the disposal, recycling, or other forms of treatment of the fuel cell technology at the end of its life cycle.

LCA finds extensive application across various industries, enabling assessments of product sustainability in domains ranging from agrifood (Notarnicola *et al*., 2017) and clothing (Zamani *et al*., 2018) to transportation (Jakub *et al*., 2022) and battery energy systems (Porzio & Scown, 2021). By facilitating informed decision-making, LCA supports environmental protection and contributes to a more sustainable future (Saidani *et al*., 2022).

There are several types or variants of LCA, each tailored to address specific objectives and boundaries (Finkbeiner, 2016). Some of the most common types of LCA include:

1. **Attributional LCA (ALCA):** (Finnveden *et al*., 2022; Bamber *et al*., 2020)
    - **Purpose**: ALCA is the most common type of LCA and is often used for assessing the environmental impacts of products or systems at a specific point in time.
    - **Focus**: It quantifies the environmental inputs and outputs associated with a product or process and attributes environmental impacts to specific life cycle stages.
    - **Data**: ALCA relies on historical or current data and does not consider changes over time.
2. **Consequential LCA (CLCA):** (Bamber *et al*., 2020; Elouariaghli *et al*., 2022)
    - **Purpose**: CLCA focuses on the potential consequences of a decision or change in a system, taking into account the wider effects on the economy, environment and society.
    - **Focus**: It considers indirect and possibly unexpected effects that may result from a particular decision or change in a system.
    - **Data:** CLCA uses modeling and scenario analysis to predict potential future outcomes, making it suitable for evaluating the impacts of policy changes or technological shifts.
3. **Prospective LCA (PLCA):** (Rüdisüli *et al*., 2022; Thonemann *et al*., 2020)
    - **Purpose**: PLCA is used for assessing the environmental consequences of products or systems that are in the planning or design phase, before they are actually implemented.
    - **Focus:** It helps designers and decision-makers identify and mitigate potential environmental hotspots in new products or processes.

- **Data:** PLCA relies on estimates, simulations and design specifications, making it a forward-looking approach.

4. **Retrospective LCA (RLCA):** (Morales *et al*., 2023)
    - **Purpose:** RLCA is conducted after a product or system has been in use for some time to evaluate its actual environmental performance.
    - **Focus:** It assesses how well the product or system has met its environmental goals and identifies areas for improvement.
    - **Data:** RLCA uses real-world data and observations, making it valuable for assessing the effectiveness of sustainability initiatives.
5. **Hybrid LCA:** (Zheng *et al*., 2022; Yu *et al*., 2021)
    - **Purpose**: Hybrid LCA combines elements of both attributional and consequential approaches to provide a more comprehensive view of environmental impacts.
    - **Focus:** It considers both the direct effects (ALCA) and the broader system-level consequences (CLCA) of a product or process.
    - **Data:** Hybrid LCA integrates data from various sources, including historical data, modeling, and scenario analysis.
6. **Input-Output LCA (IO-LCA):** (Wei *et al*., 2022; Wu & Han, 2020)
    - **Purpose:** IO-LCA focuses on analyzing the environmental impacts associated with the entire economy by examining the flow of goods and services between sectors.
    - **Focus:** It provides a macroeconomic perspective on environmental impacts and is often used for policy analysis.
    - **Data:** IO-LCA relies on national economic and environmental data and requires complex modeling.
7. **Sectoral LCA:** (Stewart *et al*., 2018)
    - **Purpose**: Sectoral LCA narrows the focus to specific industrial sectors or supply chains within an economy.
    - **Focus:** It assesses the environmental performance of a particular sector or industry, making it useful for sector-specific sustainability assessments.
    - **Data:** Sectoral LCA uses data specific to the selected industry or supply chain.

The choice of LCA type depends on the specific goals, stage of the product or process life cycle, and the level of detail required for the assessment. Each type of LCA has its strengths and limitations and selecting the most appropriate approach is essential for obtaining meaning results (Finkbeiner, 2016).

In this study, we employ Attributional Life Cycle Assessment (ALCA) to quantitatively evaluate the environmental impacts of hydrogen fuel cell from various technologies, including PEMFCs, SOFCs and AFCs.

Key components and concepts integral to ALCA include (Figure 1).

1. **Goal and Scope Definition**: Clearly defining the purpose and scope of the ALCA study is crucial. In this context, it involves assessing the environmental impacts of hydrogen fuel cell technologies (Silva, 2021).
2. **Functional Unit for Comparison and System Boundaries**: Identifying the functional unit for comparison andsetting the system boundaries, which dictate the life cycle stages considered are fundamental (Arzoumanidis *et al*., 2020). In this study,we assume the functional unit is producing 1 megawatt-hours (MWh) of electricity using each fuel cell technology. This choice allows for a direct and meaningful comparison of the environmental impacts associated with hydrogen production from these

technologies, making it a standard and widely used unit of measurementin hydrogen-related assessments. System boundaries can be **"cradle-to-gate"**, which covers stages from raw materials extraction to product leaving the production facility or **"cradle-to-grave"**, encompassing the entirelife cycle, including manufacturing, distribution, use and end-of-life scenarios. The selection depends on the study's goals and data availability (Li *et al*., 2014). In the case of this study, a "cradle-to-gate" boundary was employed, focusing on the critical stages directly affecting the environmental performance of hydrogen fuel cell technologies.

3. **Life Cycle Inventory (LCI)**: During the inventory analysis phase, data on inputs and outputs associated with each life cycle stage are collected and quantified (Surovtseva *et al*., 2022; Munasinghe *et al*., 2021). This includes materials, energy, water consumption, emissions, and waste generation.
4. **Life Cycle Impact Assessment (LCIA)**: LCIA translates inventory data into potential environmental impacts (Ji & Wang, 2021), considering various categories, like Global Warming Potential (GWP) i.e., to calculate the carbon dioxide (CO_2) equivalent emissions and their impact on climate change (Neubauer, 2021), Acidification Potential i.e., to assess the potential for acid rain formation (Provolo *et al*., 2018). Eutrophication Potential i.e., to evaluate nutrient pollution of water bodies (Preisner *et al*., 2020) and Human Toxicity and Ecotoxicity Models i.e., to estimate potential harm to human health andecosystems (Rosenbaum *et al*., 2008). This study particularly emphasizes GWP as the impact assessment method. Characterization Factors (CFs) are used to convert the quantities of emissions, resource use, and other LCI data into impact scores for specific environmental categories. These factors relate the environmental emissions or resource use to theirpotential impacts (Rosenbaum *et al*., 2008). For example (1):

$$\textit{Impact Score} = \text{LCI Data} \times \text{CF} \quad (1)$$

- **Global Warming Potential (GWP)**: CFs are used to convert greenhouse gas emissions (e.g., CO_2, CH_4, N_2O) into CO_2 - equivalents based on their respective global warming potentials over a specified time horizone (Neubauer, 2021).

$$CO_2 = \sum_i (Emissions_i * GWP_i)$$

Where: CO_2 is the carbon dioxide equivalent emission. $Emissions_i$ are the emissions of different greenhouse gases (e.g., CO_2, CH_4, N_2O). GWP_i are the Global Warming Potential factors for each greenhouse gas.

- **Eutrophication Potential:** CFs relate nutrient emission (e.g., nitrogen and phosphorous compounds) to the potential for eutrophication in water bodies (Preisner *et al*., 2020).

$$EP = \sum_i (Emissions_i * EPF_i)$$

Where: EP is the eutrophication potential. $Emissions_i$ are the emissions of nutrients (e.g., nitrogen, phosphorus). EPF_i are the Eutrophication Potential Factors for each nutrient.

- **Human Toxicity Potential (HTP):**

$$HTP = \sum_{i} (Emissions_i * \ HTPF_i)$$

Where: HTP is the human toxicity potential. $Emissions_i$ are the emissions of toxic substances (e.g., heavy metals, organic pollutants). $HTPF_i$ are the Human Toxicity Potential Factors for each toxic substance.

- **Eco-Toxicity Potential (ETP):**

$$ETP = \sum_{i} (Emissions_i * \ ETPF_i)$$

Where: ETP is the eco-toxicity potential. $Emissions_i$ are the emissions of eco-toxic substances. $ETPF_i$ are the Eco-Toxicity Potential Factors for each eco-toxic substance.

5. Interpretation: This phase involves analyzing and evaluating the results to identify environmentally significant stages and impacts for each technology. It also facilitates comparisons of the environmental performance of different hydrogen production technologies.

6. Sensitivity Analysis (Optional): Conducting sensitivity analysis allows for an assessment of how uncertainties and variations in data influence ALCA results (Lo Piano & Benini, 2022).

7. Monte Carlo Simulation (Optional): In more advanced LCA analysis, Monte Carlo simulations may be used to account for uncertainties and variability in the data. Monte Carlo simulations involve running the LCA model with randomly sampled input data to estimate the range of possible outcomes (Sun & Ertz, 2020).

8. Recommendations: ALCA results can inform decisions in product design, process optimization and policy development. Identifying areas with the most significant environmental impacts empowers stakeholders to focus on improving the environmental performance of hydrogen fuel cell technologies.

2.2. Relevant Hydrogen Fuel Cell Technologies

Hydrogen fuel cell technologies have been advancing steadily, with various approaches and applications. The main types of hydrogen fuel cells include:

2.2.1. Proton Exchange Membrane Fuel Cells (PEMFCs)

Proton Exchange Membrane Fuel Cells (PEMFCs) generate electricity through an electrochemical process that involves the conversion of hydrogen and oxygen into water (Figure 2). They use a solid polymer electrolyte membrane. Hydrogen gas is supplied to the anode (negative electrode), where it is catalytically split into protons (H^+) and electrons (e^-). The protons move through the electrolyte membrane to the cathode (positive electrode), while the electrons travel through an external circuit, creating an electric current. At the cathode, oxygen from the air is supplied and it combines with the protons and electrons to form water as the only byproduct (Vishnyakov, 2006; Tellez-Cruz *et al*., 2021).

PEMFCs operate at relatively low temperatures, typically in the range of 60–80°C, reducing the need for extensive thermal management systems, which simplifies design and maintenance in certain applications. This low temperature operation allows for rapid start-up times (i.e., PEMFCs can start and reach their full operating capacity within seconds) [69] and makes PEMFCs suitable for applications that require rapid response times, such as vehicles and portable electronics (Liu, 2018; Hamrock & Herring, 2012).

PEMFCs are known for their high energy conversion efficiency, typically exceeding 50% in real-world applications.

This efficiency means they can effectively convert hydrogen fuel into electricity (Tianyi & Lianfeng, 2022, November; Xue *et al*., 2021).

They offer a high power density, which means they can deliver a significant amount of electrical power relative to their size and weight, making them ideal for applications where space and weight constraints are important (Guan *et al*., 2023; Xue *et al*., 2021).

PEMFCs produce only water as a byproduct when hydrogen is used as a fuel source. This makes them environmentally friendly and a potential solution for reducing greenhouse gas emissions in various applications (Fernandes *et al*., 2023, April).

PEMFCs operate quietly, making them ideal for applications where noise reduction is important (Villalba-Herreros *et al*., 2020).

One of the primary disadvantages of PEMFCs is their high cost. They require expensive catalyst materials, such as platinum, and complex manufacturing processes, which can make them economically challenging to implement on a large scale (Xiao *et al*., 2022; Xue *et al*., 2021).

PEMFCs can suffer from durability issues over time (Xiao *et al*., 2022). Factors like catalyst degradation, membrane degradation, and fuel impurities can affect their long-term reliability. Extensive research is ongoing to improve durability.

Hydrogen is the ideal fuel for PEMFCs, but its storage and distribution present significant challenges. Handling and storing hydrogen can be hazardous, and building an infrastructure for hydrogen distribution is expensive (Dolciamore *et al*., 2013, March).

PEMFCs primarily rely on hydrogen as a fuel source. While hydrogen is abundant, the limited availability of hydrogen refueling stations can restrict the widespread adoption of PEMFC vehicles (Karthikeyan *et al*., 2023).

While the low operating temperature is an advantage in some cases (Liu, 2018; Hamrock & Herring, 2012), it can be a disadvantage in colder climates where additional heating is required to maintain optimal performance (Lim *et al*., 2022, October).

Although PEMFCs produce zero tailpipe emissions, the production of hydrogen may involve emissions if it is derived from fossil fuels. Green hydrogen production methods are being developed to address this concern (Bouramdane, 2023p).

PEMFCs require precise water management to prevent flooding or drying out of the electrolyte membrane, which can be challenging, especially in dynamic operating conditions (Xiao *et al*., 2023).

PEMFCs are commonly used in fuel cell vehicles (FCVs) (Khadhraoui *et al*., 2022), where they provide a clean and efficient alternative to internal combustion engines. They are also used in portable power generators (Jannelli *et al*., 2007), backup power systems (Cheng *et al*., 2022, February) and small-scale stationary applications (Delgado *et al*., 2020). PEMFCs have found applications in various industries (Watve *et al*., 2021), including telecommunications (Dogterom & Kammerer, 2005, September), aerospace (Walker & Civinskas, 2004) and material handling equipment (Liu, 2018).

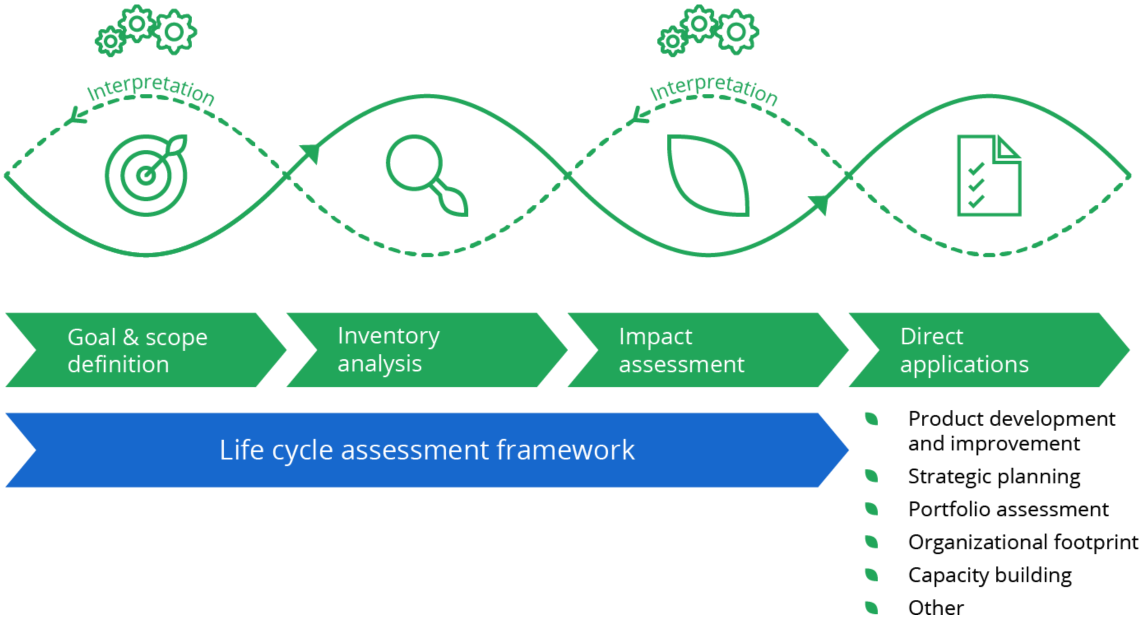

Figure 1: The four main phases of a life cycle assessment (LCA). **(1) Goal and scope definition**: The first step is to define the goal and scope of the LCA. This includes identifying the product or service to be assessed, the system boundaries and the environmental impact categories to be considered (Silva, 2021). **(2) Inventory analysis**: The second step is to collect data on the inputs and outputs of the product or service throughout its life cycle. This includes data on the raw materials used, the energy consumed and the emissions and wastes produced (Surovtseva *et al*., 2022; Munasinghe *et al*., 2021). **(3) Impact assessment**: The third step is to calculate the environmental impacts of the product or service. This is done using impact assessment methods that convert the inventory data into environmental impact indicators, such as greenhouse gas emissions, water use and air pollution (Ji & Wang, 2021). **(4) Interpretation**: The fourth and final step is to interpret the results of the LCA and draw conclusions. This includes identifying the most significant environmental impacts of the product or service and assessing the potential for improvement. LCA is a valuable tool for understanding and reducing the environmental impacts of products and services. It can be used by businesses, governments and non-profit organizations to make informed decisions about product design, production and use (Silva, 2021). LCA is a complex process and there are a number of different methods and tools that can be used. However, the basic steps outlined above are common to all LCAs. Source: (https://pre-sustainability.com/articles/life-cycle-assessment-lca-basics)

Overall, PEMFCs have made significant progress and are well-suited for certain applications, such as fuel cell vehicles and portable electronic devices. However, overcoming challenges related to cost, durability, hydrogen infrastructure and broader fuel options is necessary to make them more widely applicable across various sectors and industries (Tellez-Cruz *et al*., 2021).

2.2.2. Solid Oxide Fuel Cells (SOFCs)

Solid Oxide Fuel Cells (SOFCs) are a type of high-temperature fuel cell known for their efficiency and versatility in a wide range of applications (Wachsman & Lee, 2011; Li et al., 2022, September).

SOFCs generate electricity through an electrochemical process that involves the direct oxidation of fuel (typically hydrogen, natural gas or other hydrocarbons) and oxygen from the air.

They consist of three main components (Figure 3). The anode is typically made of nickel and serves as the site for fuel oxidation. At the anode (negative electrode): Hydrogen gas (H_2) is oxidized to produce electrons (e^-) and hydrogen ions (H^+): H_2^- > $2H^+ + 2e^+$. The cathode is typically made of a perovskite material and facilitates oxygen reduction.

At the cathode, oxygen ions combine with electrons and react with any residual hydrogen to form water(H_2O): $O_2^- + 2e^- + H_2- > H_2O$. Oxygen ions migrate through the solid oxide electrolyte from the cathode to the anode, while electrons flow externally in the opposite direction, creating an electric current. The overall result of these reactions is the generation of electricity, with water as the primary byproduct (Hagen *et al*., 2019). SOFCs are known for their high electrical efficiency, typically exceeding 60%, and can reach up to 85% in combined heat and power (CHP) configurations by capturing and utilizing waste heat (Wachsman & Lee, 2011; Li, *et al*., 2022, September).

Their high operating temperature allows for efficient utilization of waste heat, making them suitable for CHP systems in which electricity and heat are simultaneously generated (Braun, 2010; Abdalla *et al*., 2020).

SOFCs can use a wide range of fuels (Weber, 2021), including hydrogen, natural gas, biogas, syngas (a mixture of hydrogen and carbon monoxide) and even liquid hydrocarbons like diesel and jet fuel. Their internal ability to directly reform hydrocarbons internally is advantageous for certain applications, reducing the need for external reforming processes (Jo *et al*., 2020).

SOFCs are known for their long service life and durability (Horlick *et al*., 2023, August), especially in stationary and industrial applications (Xu *et al*., 2021; Jo *et al*., 2020). They have few moving parts, which reduces wear and tear. Their solid-state nature and robust materials contribute to their reliability.

SOFCs operate as solid-state devices, which means they are less susceptible to corrosion and thermal stress compared to some other fuel cell types (Zheng *et al.*, 2022).

SOFCs produce low emissions, especially when fueled with hydrogen or clean hydrocarbon sources. They generate virtually no nitrogen oxides (NOx) or particulate matter (Wachsman & Lee, 2011).

SOFCs operate quietly, which is advantageous in applications where noise reduction is important (Santarelli *et al*., 2009; Adavbiele, 2014).

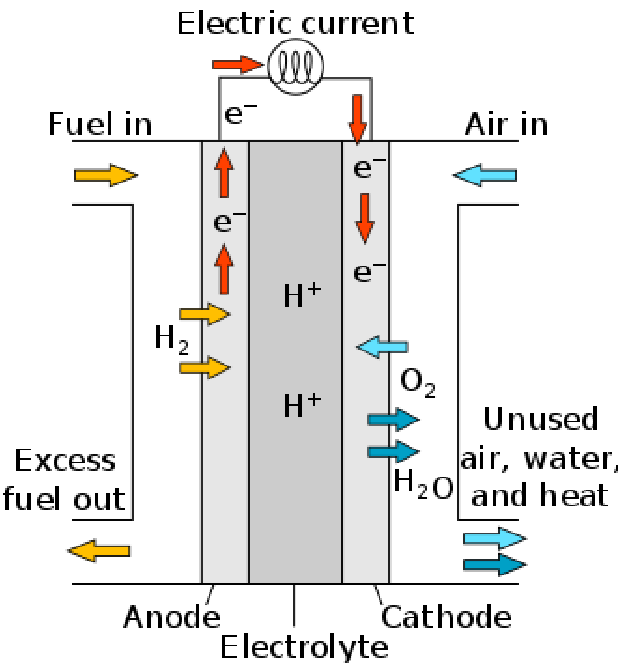

Figure 2: Diagram of the Proton-Exchange Membrane Fuel Cell (PEMFC). A PEM fuel cell consists of three main components: (1) anode (i.e., the negative electrode where hydrogen gas is fed. The hydrogen molecules are split into protons and electrons at the anode catalyst layer. The protons pass through the proton exchange membrane while the electrons flow through an external circuit to the cathode), (2) Cathode (i.e., the cathode is the positive electrode where oxygen gas is fed. The oxygen molecules react with the electrons from the external circuit to form water molecules), (3) Proton Exchange Membrane (PEM) (i.e., the PEM is a thin, solid polymer that allows protons to pass through but blocks electrons. This forces the electrons to flow through the external circuit, generating electricity). The PEM is sandwiched between the anode and cathode, and the entire assembly is compressed by bipolar plates. The bipolar plates provide electrical contact between the electrodes and collect the current generated by the fuel cell. The operation of PEM fuel cells is as follows: (1) hydrogen gas is fed to the anode and oxygen gas is fed to the cathode; (2) the hydrogen molecules are split into protons and electrons at the anode catalyst layer; (3) the protons pass through the PEM while the electrons flow through an external circuit to the cathode; (4) at the cathode, the oxygen molecules react with the electrons from the external circuit to form water molecules; (5) the water molecules are removed from the fuel cell (Vishnyakov, 2006; Tellez-Cruz *et al.*, 2021). The overall reaction in a PEM fuel cell is: $2H_2 + O_2 - > 2H_2O + Electricity$. PEM fuel cells are highly efficient (Tianyi & Lianfeng, 2022, November; Xue *et al.*, 2021) and produce clean electricity (Fernandes *et al.*, 2023, April), with water as the only by-product. They are also relatively quiet (Villalba-Herreros *et al.*, 2020) and have a fast start-up time (Gkanas *et al.*, 2022). These characteristics make them ideal for a variety of applications, including transportation, power generation and portable electronics (Watve *et al.*, 2021). Source: (https://en.wikipedia.org/wiki/Proton-exchange_membrane_ fuel_cell)

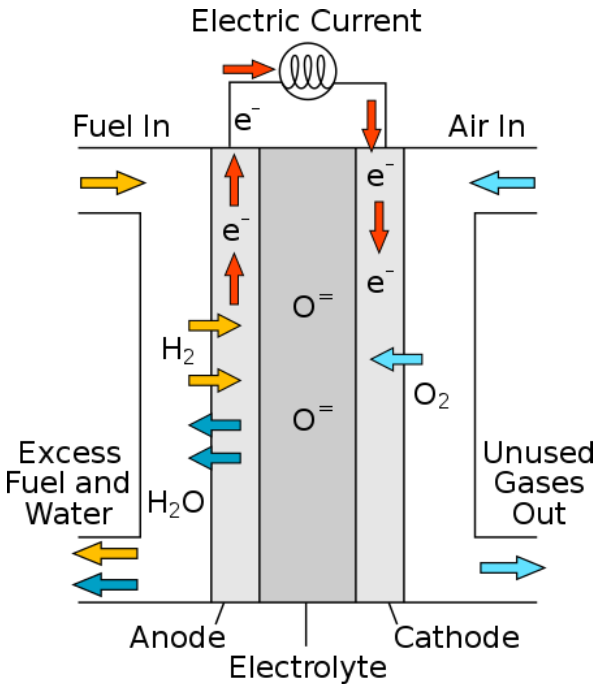

Figure 3: Scheme of a Solid-Oxide Fuel Cell (SOFC). A SOFC is an electrochemical device that converts chemical energy from a fuel into electrical energy. SOFCs operate at high temperatures (600–1000 °C), which allows them to use a wide range of fuels, including natural gas, methane, propane and even biodiesel. SOFCs consist of three main components: (1) the anode (i.e., the negative electrode where the fuel is fed. The fuel molecules are oxidized at the anode catalyst layer, releasing electrons and producing positively charged ions); (2) the cathode (i.e., the positive electrode where oxygen is fed. The oxygen molecules react with the electrons from the external circuit to form negatively charged ions); and the (3) electrolyte (i.e., a solid oxide material that allows oxygen ions to pass through, but blocks electrons. This forces the electrons to flow through the external circuit, generating electricity). The anode and cathode are separated by the electrolyte and the entire assembly is compressed by bipolar plates. The bipolar plates provide electrical contact between the electrodes and collect the current generated by the fuel cell. The operation of SOFCs is as follows: (1) Fuel is fed to the anode and oxygen is fed to the cathode; (2) The fuel molecules are oxidized at the anode catalyst layer, releasing electrons and producing positively charged ions; (3) The positively charged ions pass through the electrolyte to the cathode; (4) At the cathode, the oxygen molecules react with the electrons from the external circuit to form negatively charged ions; (5) The negatively charged ions pass through the electrolyte back to the anode. The overall reaction in an SOFC is $Fuel + O2 - > CO2 + H2O + Electricity$ (Hagen *et al.*, 2019). SOFCs are highly efficient (Li *et al.*, 2022, September) and produce clean electricity with water and carbon dioxide as the only by-products (Wachsman & Lee, 2011). They are also relatively quiet (Santarelli *et al.*, 2009; Adavbiele, 2014) and have a long lifespan (Horlick *et al.*, 2023, August). These characteristics make them ideal for a variety of applications, including stationary power generation, transportation and distributed power generation (Modena *et al.*, 2006). SOFCs are still under development, but they have the potential to play a significant role in the future of energy production (Li *et al.*, 2022, September). Source: (https://en.wikipedia.org/wiki/Solid_oxide_fuel_cell).

SOFCs operate at very high temperatures, typically between 600 and 1000°C. This high-temperature operation can lead to challenges related to material selection, i.e., high operating temperatures can cause material compatibility issues, especially with interconnects and seals. Developing materials that can withstand these conditions is essential), thermal management and slow start-up times, which can increase complexity and energy consumption (Minary-Jolandan, 2022).

The high operating temperature necessitates expensive materials and components, including thermal insulation, which can contribute to the overall cost of SOFC systems (Minary-Jolandan, 2022; Sajid *et al*., 2022)

SOFCs are relatively bulky and heavy compared to some other fuel cell types, limiting their use in portable and lightweight applications (Sajid *et al*., 2022).

SOFCs are relatively brittle due to their ceramic components, making them susceptible to mechanical stress and thermal cycling (Christensen *et al*., 2023; Wachsman & Lee, 2011).

Contaminants in fuels, such as sulfur in natural gas, can poison the catalysts and reduce performance. Fuel purification may be required (Li *et al*., 2014).

Achieving and maintaining high operating temperatures can result in slow start-up times, which may not be suitable for applications requiring rapid response (He *et al*., 2023).

Frequent start-stop cycles can lead to thermal stress and reduce the lifespan of SOFCs, making them less suitable for applications requiring rapid cycling (Baldi *et al*., 2018, June).

Like other fuel cells, SOFCs face infrastructure challenges related to fuel storage, distribution and refueling for hydrogen-based systems (Abdalla *et al*., 2020).

SOFC systems can be complex, requiring control systems and auxiliary components to manage temperature and performance effectively (Wachsman & Lee, 2011).

SOFCs have a wide range of applications (Horlick *et al*., 2023, August), including stationary power generation for homes, businesses and industries (Roth & Tricoli, 2023, May), as well as combined heat and power (CHP) systems (Braun, 2010; Abdalla *et al*., 2020).

They are also used in auxiliary power units (APUs) for vehicles (Salameh, 2008), marine applications (Li *et al*., 2022, September) and as portable generators for military and remote operations (Chu *et al*., 2019).

Overall, SOFCs offer high efficiency, low emissions and fuel flexibility, making them well-suited for stationary and industrial applications. However, their high operating temperature, cost and material challenges are areas of ongoing research and development to improve their competitiveness and expand their use across various sectors.

2.2.3. Alkaline Fuel Cells (AFCs)

Alkaline Fuel Cells (AFCs) are a type of fuel cell that uses a liquid alkaline electrolyte, usually a concentrated solution of potassium hydroxide (KOH), which is typically stored in a reservoir and continuously supplied to the cell. The electrochemical reaction in an AFC occurs at the anode and cathode, with hydrogen (H_2) typically used as the fuel and oxygen (O_2) as the oxidant (Figure 4). The overall reaction is as follows: at the anode $(2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-)$ and at the cathode: $O_2 + 4H_2O + 4e^- \rightarrow 4OH^-$ (Xiao *et al*., 2021).

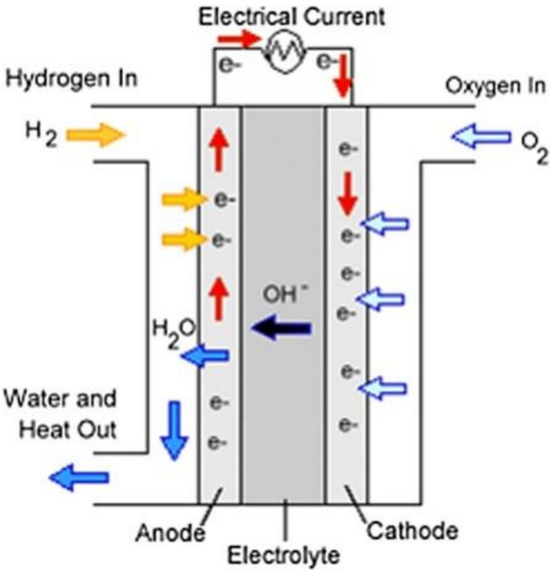

Figure 4: Scheme of an Alkaline Fuel Cell (AFC). An AFC consists of the following components: (1) the anode (i.e., the negative electrode where hydrogen gas is fed. The hydrogen molecules are split into protons and electrons at the anode catalyst layer. The protons pass through the electrolyte, while the electrons flow through an external circuit to the cathode); (2) the cathode (i.e., the positive electrode where oxygen gas is fed. The oxygen molecules react with the electrons from the external circuit to form water molecules); (3) the electrolyte (i.e., an aqueous solution of potassium hydroxide (KOH). The KOH solution allows protons to pass through, but blocks electrons. This forces the electrons to flow through the external circuit, generating electricity) and (4) the separator (i.e., a porous material that prevents the anode and cathode from coming into direct contact. This is important to prevent the hydrogen and oxygen from reacting directly, which would not produce electricity). The anode and cathode are separated by the electrolyte and separator and the entire assembly is compressed by bipolar plates. The bipolar plates provide electrical contact between the electrodes and collect the current generated by the fuel cell. The operation of AFCs is as follows: (1) hydrogen gas is fed to the anode and oxygen gas is fed to the cathode; (2) the hydrogen molecules are split into protons and electrons at the anode catalyst layer; (3) the protons pass through the electrolyte to the cathode; (4) at the cathode, the oxygen molecules react with the electrons from the external circuit to form water molecules; (5) the water molecules are removed from the fuel cell. The overall reaction in an AFC is: $2H_2 + O_2 \rightarrow 2H_2O$ + Electricity (Xiao *et al*., 2021). AFCs are highly efficient (Cai & Rozario, 2022; Haritha *et al*., 2022) and produce clean electricity, with water as the only by-product (Sapucaia *et al*., 2023). They are also relatively quiet and have a fast start-up time (Zhao *et al*., 2021). However, AFCs are more expensive than other types of fuel cells, and they are not as durable. For these reasons, AFCs are not as widely used as other types of fuel cells (Slade *et al*., 2018). AFCs are still under development, and researchers are working to improve their durability and reduce their cost. If these challenges can be overcome, AFCs have the potential to play a significant role in the future of energy production. Source: (Vaghari *et al*., 2013).

AFCs are known for their high efficiency in converting chemical energy into electricity, typically in the range of 50–70%, depending on operating conditions and materials used, making them suitable for various applications where efficiency is crucial (Cai & Rozario, 2022; Haritha *et al*., 2022).

AFCs produce low emissions, especially when using pure hydrogen as a fuel source, as they generate only water and heat as byproducts (Sapucaia *et al*., 2023).

AFCs have demonstrated good durability and long service life in certain applications, such as space missions. They can operate reliably for thousands of hours without significant degradation (Xiao *et al*., 2021).

AFCs can start up quickly and respond rapidly to changes in power demand, making them suitable for applications requiring dynamic operation (Zhao *et al*., 2021).

AFCs typically operate at moderate temperatures, ranging from 60°C to 250°C, making them less thermally demanding compared to Solid Oxide Fuel Cells (SOFCs). The moderate operating temperature of AFCs simplifies thermal management and extends the lifespan of materials compared to high-temperature fuel cells (Sapucaia *et al*., 2023; Maimani *et al*., 2022, October).

AFCs require high-purity hydrogen as a fuel source. Impurities such as carbon monoxide (CO) and sulfur compounds can poison the catalyst and degrade performance (Slade *et al*., 2018).

The liquid electrolyte used in AFCs can lead to issues related to electrolyte leakage and handling, making them less suitable for portable applications (Jiang & Li, 2021).

AFCs use precious metal catalysts like platinum, which can be costly and sensitive to impurities, potentially driving up system costs (Jiang & Li, 2021; Xiao *et al*., 2021)

The alkaline environment in AFCs can challenge the compatibility of materials used in cell components, such as seals and bipolar plates. Special materials may be required to withstand these conditions (Tang *et al*., 2022).

AFCs operate within a relatively narrow temperature range compared to other fuel cell types. This limitation can impact their versatility, especially in extreme environmental conditions (Sapucaia *et al*., 2023; Maimani *et al*., 2022, October).

As with other fuel cell technologies, developing a hydrogen infrastructure for production, storage and distribution is essential for widespread AFC deployment (Maimani *et al*., 2022, October).

AFCs can be bulky and heavy compared to some other fuel cell types, which can limit their use in portable and lightweight applications (Jiang & Li, 2021).

Traditional AFCs have relied on precious metal catalysts, which are expensive and subject to supply and cost fluctuations (Bouramdane, 2023q).

AFCs have found applications in various sectors, thanks to their high efficiency and relatively low emissions (Schneider-Coppolino *et al*., 2022, July).

Some notable applications include:

- **Space Exploration**: AFCs were initially developed for space missions by NASA and have been used in various spacecraft. Their reliability, long life and ability to operate in a microgravity environment make them suitable for powering spacecraft and space stations (Nash *et al*., 2014).
- **Aircraft and Drones**: AFCs have been explored for use in aircraft and drones, where they offer the potential for longer endurance and reduced emissions compared to traditional internal combustion engines. They are particularly suitable for high-altitude and long-endurance missions (Bradley, 2022, June).

- **Marine Applications**: AFCs have been considered for maritime propulsion systems, including submarines, ferries and research vessels. Their high energy density and efficiency make them attractive for applications where space and weight constraints are less critical (Sürer & Arat, 2022).
- **Military and Defense**: AFCs can be used in military applications, such as portable power generation for soldiers in the field, where their quiet operation, long runtime and low emissions are advantageous (Sapru *et al*., 1997, July).
- **Stationary Power Generation**: AFCs can be employed for stationary power generation in residential, commercial and industrial settings (Visvanathan *et al*., 2023). They can operate as combined heat and power (CHP) systems, providing both electricity and useful heat. These systems offer high efficiency and can reduce energy costs (Wang *et al*., 2021).
- **Remote and Off-Grid Power**: AFCs are suitable for providing power in remote or off-grid areas where establishing traditional power infrastructure is challenging. They can be used in telecommunications, remote monitoring stations and remote communities (Zhao *et al*., 2023).
- **Backup Power Systems**: AFCs can serve as backup power systems for critical infrastructure, data centers, hospitals and other facilities that require uninterrupted power in case of grid failures (Fernández *et al*., 2017).
- **Water and Wastewater Treatment**: AFCs can be used to generate electricity from the hydrogen produced during the electrolysis of water in water and wastewater treatment facilities. This energy can help offset the energy requirements of the treatment process (Shu-bao, 2008).
- **Hydrogen Refueling Stations:** AFCs can be used in hydrogen refueling stations to generate hydrogen on-site through water electrolysis. This can help provide a local source of hydrogen for fuel cell vehicles (Kim *et al*., 2022).
- **Grid Support**: AFCs can be part of distributed energy systems that provide grid support, including peak shaving and load leveling. They can help stabilize the grid by responding quickly to changes in demand (Zhao *et al*., 2023).

Overall, AFCs offer advantages in terms of efficiency and rapid response, but they also have specific limitations related to fuel purity and material compatibility. Their use has historically been more prevalent in niche applications, such as space exploration, but ongoing research aims to address some of these challenges and broaden their potential applications.

3. Results

In this study, we applied the Attributional Life Cycle Assessment (ALCA) methodology to assess the environmental impact or carbon footprint of three different hydrogen fuel cell technologies: Proton Exchange Membrane Fuel Cells (PEMFCs), Solid Oxide Fuel Cells (SOFCs) and Alkaline Fuel Cells (AFCs). The functional unit considered for this assessment was the production of 1 megawatt-hour (MWh) of electricity using each of these fuel cell technologies, with the system boundaries defined as "cradle-to-gate” (Section 2). Global Warming Potential (GWP) was chosen as the impact category for evaluating the environmental performance of these technologies.

3.1. Critical Stages and Their Environmental Impact

1. Hydrogen Production (Crude Oil Reforming):

- PEMFC: The production of hydrogen for PEMFCs predominantly involves steam methane reforming (SMR) of natural gas. This process is energy-intensive and releases a significant amount of greenhouse gases, particularly carbon dioxide (CO_2) (Bouramdane, 2023p). The GWP associated with hydrogen production for PEMFCs is assumed to be 1000 kg of CO_2 equivalent per MWh.
- SOFC: Hydrogen production for SOFCs also relies on SMR but can utilize a wider range of feedstocks, including biomass and renewable sources (Section 2.2.2). Therefore, the GWP associated with hydrogen production for SOFCs was assumed to be 800 kg CO_2 equivalent per MWh, which is lower than that of PEMFCs.
- AFC: Alkaline Fuel Cells primarily use alkaline electrolysis to produce hydrogen, which can be powered by renewable energy sources, reducing the GWP to 500 kg CO_2 equivalent per MWh, making it the most environmentally friendly option for hydrogen production (Bouramdane, 2023p).

2. Fuel Cell Assembly and Manufacturing: All three fuel cell technologies require the manufacturing of components such as membranes, electrodes and catalysts. However, the energy and material requirements for manufacturing vary between technologies, impacting their GWP (Ahmed *et al*., 2023). The GWP associated with the manufacturing phase was assumed to be highest for PEMFCs, followed by SOFCs and AFCs, with values of 200 kg CO_2 equivalent per MWh, 150 kg CO_2 equivalent per MWh and 100 kg CO_2 equivalent per MWh, respectively.

3. Electricity Generation: During electricity generation, all three fuel cell technologies produce electricity efficiently with minimal greenhouse gas emissions, resulting in negligible GWP contributions (Ahmed *et al*., 2023).

In the simplified hypothetical scenario provided earlier, the critical stage for each technology, based on their respective GWP values, would be as follows “Hydrogen Production (Crude Oil Reforming)”:

- **For PEMFCs**: The critical stage with the highest GWP impact is hydrogen production, specifically through processes like steam methane reforming (SMR), which can have a high carbon footprint. In this scenario, reducing the GWP of hydrogen production is essential for mitigating the overall environmental impact of PEMFCs.
- **For SOFCs**: Similarly, the critical stage with the highest GWP impact is hydrogen production, but SOFCs utilize a more efficient and cleaner method compared to PEMFCs. Nevertheless, improvements in hydrogen production can further reduce the environmental impact of SOFCs.
- **For AFCs**: In this hypothetical scenario, AFCs have the lowest GWP impact in hydrogen production. Therefore, AFCs already exhibit an environmentally friendly approach to hydrogen production, making this stage less critical in terms of GWP.

It is important to note that in a real-world assessment, the critical stage may vary depending on numerous factors, including the specific technology variants, energy sources and operational practices. Conducting a comprehensive life cycle assessment would provide a more accurate identification of critical stages and their associated impacts (Ahmed *et al*., 2023). Based on the critical stages analyzed, the total GWP for producing 1 MWh of electricity using each fuel cell technology is as follows: PEMFC (1200 kg CO_2 equivalent per MWh), SOFC (950 kg CO_2 equivalent per MWh), and AFC (600 kg CO_2 equivalent per MWh).

3.2. Recommendations

The following recommendations are intended to highlight potential strategies for reducing the environmental impact of hydrogen fuel cell technologies based on a simplified assessment:

1. **Transition to Green Hydrogen for PEMFCs**: Given their higher GWP for hydrogen production, transitioning to the production of "green hydrogen" is crucial. This can be achieved by using renewable energy sources, such as wind or solar power (Bouramdane, 2021, October), to power the electrolysis process, significantly reducing carbon emissions associated with hydrogen production (Bouramdane, 2023p; 2023i).
2. **Improve Manufacturing Efficiency for All Technologies**: Manufacturers should focus on enhancing material efficiency and adopting cleaner production processes to reduce the GWP associated with fuel cell manufacturing. For example, exploring lightweight materials and more energy-efficient manufacturing techniques can help lower GWP values for manufacturing stages.
3. **Material Recycling and Sustainability for All Technologies:** Promote material recycling and sustainability practices throughout the life cycle. Design fuel cell components for easy disassembly and recycling, reducing the need for raw materials and minimizing the GWP associated with material extraction and production.
4. **Carbon Capture and Utilization (CCU) for All Technologies**: Investigate the feasibility of carbon capture and utilization technologies to capture and repurpose carbon emissions generated during hydrogen production or manufacturing processes. CCU can help offset GWP by converting carbon emissions into valuable products (Bouramdane, 2023h).
5. **Life Cycle Perspective for Stakeholders**: Encourage stakeholders to consider the entire life cycle of fuel cell technologies when making decisions. Recognize that focusing solely on operational phase emissions may not provide a complete picture of environmental impact, and upstream processes like hydrogen production and manufacturing significantly contribute to GWP (Bouramdane, 2023p).
6. **Research and Innovation for the Industry**: Invest in research and development to create more energy-efficient processes, advanced materials and improved catalysts (Bouramdane, 2023p). Innovation can lead to breakthroughs in reducing the environmental impact of fuel cell technologies across their life cycle.

It is important to note that these recommendations are based on the simplified hypothetical values provided earlier and should be adapted and refined based on real-world data and detailed life cycle assessments. Implementing these recommendations can help reduce the environmental impact of hydrogen fuel cell technologies and contribute to a more sustainable energy future.

4. Discussion

The results of this hypothetical Attributional Life Cycle Assessment (ALCA) provide insights into the environmental performance of three distinct hydrogen fuel cell technologies: Proton Exchange Membrane Fuel Cells (PEMFCs), Solid Oxide Fuel Cells (SOFCs) and Alkaline Fuel Cells (AFCs). The assessment focused on two critical stages:

hydrogen production and fuel cell assembly/manufacturing, with an emphasis on Global Warming Potential (GWP) as the impact category. It is essential to recognize that these results are based on simplified hypothetical values and are intended for illustrative purposes.

1. **Hydrogen Production Stage:**
   - **PEMFCs:** The assessment identified hydrogen production as the most environmentally impactful stage for PEMFCs. This emphasizes the urgency of transitioning to green hydrogen production methods, such as renewable-powered electrolysis, to significantly reduce carbon emissions (Bouramdane, 2023p; 2023i). Additionally, exploring carbon capture and utilization (CCU) technologies could offer further mitigation potential (Bouramdane, 2023h).
   - **SOFCs:** SOFCs demonstrated a lower GWP for hydrogen production compared to PEMFCs, highlighting their environmental advantage in this aspect. Nevertheless, optimization opportunities remain, such as exploring renewable-powered hydrogen sourcing and improving process efficiency to further reduce emissions.
   - **AFCs**: AFCs exhibited the lowest GWP for hydrogen production among the three technologies. This suggests that AFCs already employ environmentally friendly hydrogen production methods. Integrating renewable energy sources into the hydrogen production process can enhance their sustainability further.
2. **Fuel Cell Assembly/Manufacturing Stage:**
   - **PEMFCs:** The manufacturing stage for PEMFCs was identified as having the highest GWP. Recommendations include a focus on material efficiency, supply chain sustainability and the adoption of eco-friendly production methods to reduce environmental impact.
   - **SOFCs:** SOFC manufacturing exhibited a moderate GWP. Enhancing manufacturing techniques, exploring advanced materials and embracing circular economy practices can contribute to reduced emissions and resource efficiency.
   - **AFCs:** AFC manufacturing displayed the lowest GWP among the three technologies. To maintain this advantage, recommendations include improving efficiency, durability and quality control, along with localized production strategies.

The practical implications derived from this study carry substantial significance for multiple stakeholders, encompassing policymakers, industry leaders and the research community. A key takeaway is the imperative of transitioning towards sustainable practices within hydrogen fuel cell technologies. This includes prioritizing the adoption of green hydrogen production techniques, streamlining and improving manufacturing procedures and facilitating the seamless integration of renewable energy sources into these innovative technologies. By embracing and implementing these recommendations, a substantial advancement can be made in augmenting the overall environmental sustainability and efficiency of hydrogen fuel cell technologies.

In this simplified hypothetical analysis, it is essential to acknowledge the limitations and uncertainties associated with the values provided. Real-world assessments would require extensive data gathering, location-specific considerations and technology-specific variations. Furthermore, the recommendations offered here should be regarded as starting points and adapted to the unique circumstances and goals of each hydrogen fuel cell technology application. In conclusion, the results and recommendations emphasize the significance of sustainable hydrogen sourcing and efficient manufacturing practices to reduce the environmental impact of hydrogen fuel cell technologies. These findings underscore the need for continued research, innovation and collaboration among stakeholders to advance the environmental sustainability of these technologies in practical applications.

5. Conclusion

5.1. Research Motivation and Methodology

Hydrogen fuel cell technologies hold immense promise as clean energy solutions, with the potential to reduce greenhouse gas emissions and mitigate climate change. As these technologies become increasingly integral to the global energy landscape, it is essential to comprehensively assess their environmental impact. This study aimed to address this imperative by applying Attributional Life Cycle Assessment (ALCA) to evaluate the environmental performance of three prominent hydrogen fuel cell technologies: Proton Exchange Membrane Fuel Cells (PEMFCs), Solid Oxide Fuel Cells (SOFCs) and Alkaline Fuel Cells (AFCs).

5.2. Existing Research and Knowledge Gap

Prior research has explored various aspects of hydrogen fuel cell technologies, often focusing on their operational efficiency and advantages in reducing local air pollutants. However, there remains a significant knowledge gap regarding their holistic environmental impact, particularly when considering the entire life cycle from raw material extraction to end-of-life disposal. This study sought to bridge this gap by conducting a comprehensive ALCA that addressed this multifaceted aspect.

5.3. Research Questions and Originality

The central research questions guiding this study were: How do different hydrogen fuel cell technologies compare in terms of their environmental impact, especially considering critical stages like hydrogen production and fuel cell assembly? What specific recommendations can be derived from these findings to enhance the environmental sustainability of each technology? The originality of this study lies in its holistic approach, utilizing ALCA to evaluate the GWP impact, considering both critical stages and providing tailored recommendations for each technology.

5.4. Research Findings

The findings of this study have highlighted the environmental nuances associated with each hydrogen fuel cell technology. Hydrogen production was identified as a critical stage with significant GWP contributions, emphasizing the need for green hydrogen production methods. Among the technologies, AFCs exhibited the lowest GWP for both hydrogen production and manufacturing. SOFCs demonstrated advantages in hydrogen production, whereas PEMFCs showed potential for improvement in both hydrogen production and manufacturing stages. Detailed recommendations were provided to address these specific findings.

5.5. Practical Implications

The practical implications of this research are profound, offering insights for policymakers, industry stakeholders and researchers. The study underscores the importance of transitioning to green hydrogen production methods, optimizing manufacturing processes and integrating renewable energy sources into these technologies. Implementing these recommendations can significantly enhance the environmental sustainability of hydrogen fuel cell technologies.

5.6. Limitations

Several limitations must be acknowledged. Firstly, the values used in this study were hypothetical and simplified for illustrative purposes. Real-world assessments would require precise data and location-specific considerations. Additionally, ALCA, while comprehensive, is inherently dependent on available data and methodology, which may evolve over time.

5.7. Future Directions

Future research in this domain should focus on refining ALCA methodologies, gathering extensive real-world data and conducting more nuanced assessments of hydrogen fuel cell technologies. Moreover, exploring emerging technologies and their potential environmental benefits, such as green hydrogen production methods and advanced materials, presents an exciting avenue for future research.

In conclusion, this study has contributed valuable insights into the environmental impact of hydrogen fuel cell technologies, emphasizing the significance of sustainable practices across their life cycle. The findings offer a foundation for informed decision-making, ultimately advancing the adoption of clean and sustainable energy solutions on a global scale.

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