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LIFE CYCLE ASSESSMENT OF FUEL CELLS: COMPARATIVE SCREENING AND CARBON THRESHOLDS

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Abstract
This study investigates the life cycle carbon footprint of stationary fuel-cell systems using a parametric comparison of electrical efficiency, hydrogen supply emissions, and equipment-related impacts. Six fuel-cell technologies are reviewed, while PEMFC, AFC, PAFC, and SOFC are evaluated numerically using a common functional unit of 1 kWh net AC electricity. Three hydrogen carbon intensities (1, 3, and 11 kg CO_2-eq/kg H_2) are considered. The calculated footprints range from 70.0–91.4 g CO_2-eq/kWh in the lowest-emission scenario to 570.0–805.7 g CO_2-eq/kWh in the highest. Analytical thresholds quantify the additional manufacturing and replacement impacts that can be compensated by higher electrical efficiency. A separate criterion determines the future electricity generation required for carbon-beneficial stack replacement. The results show that equipment-related impacts become relatively more important when low-carbon hydrogen is used. The proposed framework supports preliminary technology comparison and maintenance decisions under explicitly defined assumptions, while further validation requires technology-specific life cycle inventory data.

Keywords: fuel cells; life cycle assessment; hydrogen carbon intensity; carbon footprint; stack replacement

INTRODUCTION

The life cycle carbon footprint of fuel-cell systems depends on hydrogen production, electrical efficiency, equipment manufacturing, and service life. A meaningful comparison therefore requires consistent system boundaries and a common functional unit, as established by ISO 14040 and ISO 14044 [1,2] and further addressed in the FC-HyGuide methodology [3].

Previous studies have examined the environmental effects of PEMFC degradation [4] and the manufacturing impacts of SOFC and PAFC systems [5]. However, their different assessment boundaries limit direct comparisons of the trade-off between conversion efficiency and equipment-related emissions. Quantifying this relationship is particularly relevant when fuel cells operate with hydrogen from different production pathways.

This study develops a parametric framework for comparing four hydrogen-based fuel-cell technologies: PEMFC, AFC, PAFC, and SOFC. The proposed model establishes analytical thresholds for determining how much additional non-fuel impact can be offset by higher electrical efficiency and when replacing a degraded stack becomes beneficial in carbon terms. Six fuel-cell technologies are also reviewed qualitatively. The results support preliminary engineering decisions under defined scenarios without claiming a universal environmental ranking.

SCOPE OF THE COMPARISON

Six fuel-cell technologies are considered: proton-exchange-membrane (PEMFC),

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alkaline (AFC), phosphoric-acid (PAFC), solid-oxide (SOFC), molten-carbonate (MCFC), and direct-methanol (DMFC) fuel cells. Their main characteristics and life cycle inventory requirements are summarized in Table 1, based on technical information from the U.S. Department of Energy [6,7]. The listed materials and processes identify relevant inventory inputs without implying a quantitative ranking of environmental impacts.

The numerical comparison focuses on PEMFC, AFC, PAFC, and SOFC systems operating with hydrogen and air. A common hydrogen-based boundary allows differences in conversion efficiency and equipment-related impacts to be examined without introducing variations associated with different primary fuels. Technology-specific requirements remain relevant: AFC systems require appropriate treatment of air and fuel impurities, while SOFC performance depends on thermal management, start-up conditions, and operating cycles [6,7].

MCFC and DMFC are included in the qualitative assessment but excluded from the numerical scenarios. MCFC operation requires accounting for carbon dioxide supplied to the cathode, whereas DMFC systems use methanol and involve a different fuel supply chain and direct carbon emissions [7]. Applying the same delivered-hydrogen model to these systems would therefore introduce inconsistent boundaries. Their exclusion reflects the scope of the mathematical model rather than a judgment about their environmental performance.

METHODOLOGY AND ASSUMPTIONS

A. Function and system boundaries

The functional unit is 1 kWh of net AC electricity delivered by a stationary fuel-cell system (1 kWh = 3.6 MJ). All technologies are evaluated for equivalent electricity quality and service availability. Heat recovery is excluded; extending the comparison to cogeneration would require a common thermal output requirement and an appropriate allocation or system expansion procedure [3].

Table 1. *Technologies and inventory priorities.*

Type	Electrolyte / fuel	Key flows
PEMFC	Polymer membrane; H_2	Platinum catalysts, membrane, humidification, cooling
AFC	Alkaline electrolyte; H_2	Electrolyte, catalysts, CO_2 removal
PAFC	Phosphoric acid; H_2 or reformate	Platinum catalysts, phosphoric acid, fuel reforming where applicable
SOFC	Solid oxide; H_2 or other fuels	Ceramic materials, nickel, heating, thermal cycling
MCFC	Molten carbonates; fuel-dependent	Fuel processing, cathode CO_2 supply
DMFC	Polymer membrane; methanol	Platinum-containing catalysts, methanol production and oxidation

The system boundary covers hydrogen production, compression, transportation, and storage, together with equipment manufacturing, installation, maintenance, stack replacement, and end-of-life treatment. Equipment-related processes include the fuel-cell stack and balance-of-plant components, such as air supply, cooling, control equipment, and power electronics. Downstream electricity transmission is excluded.

The assessment considers global warming potential over a 100-year horizon (GWP100). All emission factors are assumed to follow a consistent characterization method. Other environmental indicators, including acidification, toxicity, water consumption, and resource depletion, remain outside the quantitative analysis.

B. Normalized model

The model relates electricity generation to hydrogen consumption over the considered operating period. For technology j, let E_j denote the net AC electricity delivered and M_j the total hydrogen mass consumed. Using the hydrogen lower heating value H_L = 33.333 kWh/kg, the equivalent electrical efficiency is defined as:

$$\eta_{\mathrm{j}} = \frac{E_{\mathrm{j}}}{H_{\mathrm{L}} M_{\mathrm{j}}} \tag{1}$$

Unlike instantaneous conversion efficiency, this parameter accounts for the total hydrogen consumed during normal operation, start-up, and standby. Auxiliary and converter losses are included through the net electrical output. Any electricity imported separately for auxiliary operation must be accounted for through an additional emission term.

The equipment-related contribution is obtained from the initial manufacturing impact B_0, stack replacement B_r, maintenance B_m, end-of-life treatment B_e, and applicable recycling credit C_r. The corresponding specific non-fuel impact is:

$$b_{\mathrm{j}} = \frac{B_{0,\mathrm{j}} + B_{\mathrm{r,j}} + B_{\mathrm{m,j}} + B_{\mathrm{e,j}} - C_{\mathrm{r,j}}}{E_{\mathrm{j}}} \tag{2}$$

All equipment-related impact terms are expressed in kg CO_2-eq, while b_j represents the normalized non-fuel impact in kg CO_2-eq/kWh.

For a delivered-hydrogen carbon intensity I_H, expressed in kg CO_2-eq/kg H_2, the specific carbon footprint of generated electricity is calculated as:

$$G_{\mathrm{j}} = b_{\mathrm{j}} + \frac{I_{\mathrm{H}}}{H_{\mathrm{L}} \eta_{\mathrm{j}}} \tag{3}$$

A common I_H is used for the baseline comparison. Where hydrogen purity, compression, or delivery requirements differ between technologies, their associated impacts must be included in technology-specific factors or separate inventory terms to avoid double counting. Recycling credits are excluded from the baseline calculation (C_r = 0).

C. Scenarios and data status

The numerical scenarios examine four fuel-cell technologies using the input parameters summarized in Table 2. The adopted net electrical efficiencies are 0.50 for PEMFC, 0.52 for AFC, 0.42 for PAFC, and 0.60 for SOFC. These values are modeling assumptions selected for comparative analysis rather than measured lifetime performance or representative commercial averages [6].

Three delivered-hydrogen carbon intensities are considered: 1, 3, and 11 kg CO_2-eq/kg H_2. The highest value is comparable in magnitude to the 10–12 kg CO_2-eq/kg H_2 reported by the IEA for hydrogen production from natural gas without carbon capture [8]. The selected scenarios do not represent site-specific hydrogen supply chains.

An identical non-fuel contribution of 20 g CO_2-eq/kWh is initially assigned to all four technologies to isolate the influence of electrical efficiency. Its effect is subsequently examined through independent variation between 10 and 50 g CO_2-eq/kWh, together with efficiency changes of ±0.05.

Table 2. *Parameters and assumptions used in the comparative scenarios.*

Parameter	Value	Definition
η: PEMFC / AFC	0.50 / 0.52	Assumed net efficiency
η: PAFC / SOFC	0.42 / 0.60	Assumed net efficiency
I_H (kg CO_2-eq/kg H_2)	1; 3; 11	Hydrogen carbon intensity
b_j (g CO_2-eq/kWh)	20	Baseline non-fuel impact
Efficiency variation	±0.05	Sensitivity analysis
b_j variation (g CO_2-eq/kWh)	10–50	Sensitivity analysis
G_{ref} (g CO_2-eq/kWh)	400	Comparison threshold

A reference footprint of 400 g CO_2-eq/kWh is introduced solely as a comparison

threshold, without representing a particular national electricity mix. The resulting calculations provide controlled parametric relationships rather than measured life cycle inventory results.

RESULTS AND CARBON THRESHOLDS

A. Role of delivered hydrogen

The carbon footprints calculated using Equation (3) are presented in Table 3 for the four fuel-cell technologies. Figure 1 illustrates their dependence on delivered-hydrogen carbon intensity (I_H). Under the fixed efficiency and non-fuel impact assumptions, the relationship is linear, with its slope determined by hydrogen consumption per unit of electricity generated.

Table 3. *Calculated G for b_j = 20 g CO_2-eq/kWh. G is in g CO_2-eq/kWh; IH,max is in kg CO_2-eq/kg H_2.*

Type	$I_H = 1$	$I_H = 3$	$I_H = 11$	$I_{H,max}$
PEMFC	80.0	200.0	680.0	6.33
AFC	77.7	193.1	654.6	6.59
PAFC	91.4	234.3	805.7	5.32
SOFC	70.0	170.0	570.0	7.60

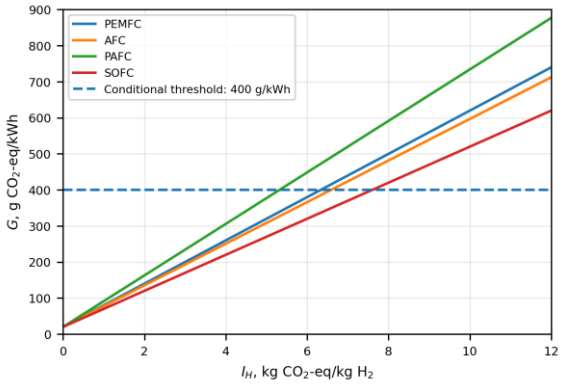


Fig. 1. *Scenario footprint as a function of delivered-H2 intensity. The dashed horizontal threshold is conditional, not a regional grid value.*

At I_H = 1 kg CO_2-eq/kg H_2, the calculated footprints range from 70.0 g CO_2-eq/kWh for SOFC to 91.4 g CO_2-eq/kWh for PAFC. Increasing I_H to 11 kg CO_2-eq/kg H_2 raises these values to 570.0 and 805.7 g CO_2-eq/kWh, respectively. The difference between the two technologies therefore increases from 21.4 to 235.7 g CO_2-eq/kWh.

The relative contribution of non-fuel impacts also changes substantially. At the lowest hydrogen intensity, the assumed 20 g CO_2-eq/kWh accounts for 21.9–28.6% of the total footprint, compared with less than 4% at I_H = 11. Consequently, equipment manufacturing and replacement become relatively more important as hydrogen-related emissions decrease.

For a selected reference footprint G_{ref}, the maximum permissible hydrogen intensity is obtained by rearranging Equation (3):

$$I_{H,max,j} = (G_{ref} - b_j)H_L\eta_j \quad (4)$$

Using G_{ref} = 400 g CO_2-eq/kWh, the calculated limits range from 5.32 kg CO_2-eq/kg H_2 for PAFC to 7.60 kg CO_2-eq/kg H_2 for SOFC (Table 3). These thresholds provide a direct means of determining whether a specified hydrogen supply scenario satisfies the reference footprint under the adopted operating assumptions.

B. Allowable additional impact

Higher electrical efficiency reduces hydrogen consumption, but the resulting carbon benefit must be compared with possible differences in manufacturing, maintenance, and replacement impacts. For two technologies j and k, where $\eta_j > \eta_k$, the maximum additional non-fuel impact that can be compensated by the efficiency advantage is:

$$b_j - b_k < \frac{I_H}{H_L}\left(\frac{1}{\eta_k} - \frac{1}{\eta_j}\right) \quad (5)$$

Figure 2 presents this relationship for SOFC relative to PEMFC, AFC, and PAFC.

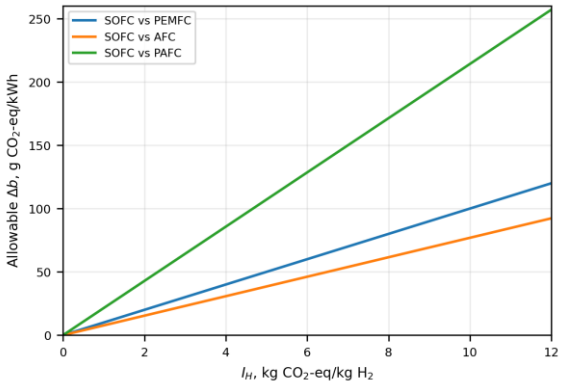


Fig. 2. *Maximum additional non-fuel component of SOFC compensated by the assumed higher efficiency. The lines are equal-footprint boundaries.*

For SOFC compared with PEMFC, the allowable additional non-fuel impact is 10, 30, and 110 g CO_2-eq/kWh at I_H = 1, 3, and 11 kg CO_2-eq/kg H_2, respectively. The corresponding values relative to AFC are 7.7, 23.1, and 84.6 g CO_2-eq/kWh.

These results quantify the trade-off between conversion efficiency and equipment-related emissions. At low hydrogen carbon intensity, even a moderate additional manufacturing burden can eliminate the benefit of higher efficiency. As I_H increases, reduced hydrogen consumption can compensate for larger differences in non-fuel impacts.

When the higher-efficiency technology also has a greater non-fuel footprint, the carbon intensity at which the two alternatives become equivalent is calculated as:

$$I_{\mathrm{H,crit}} = \frac{H_{\mathrm{L}}(b_{\mathrm{j}} - b_{\mathrm{k}})}{\frac{1}{\eta_{\mathrm{k}}} - \frac{1}{\eta_{\mathrm{j}}}} \qquad (6)$$

For example, assuming an additional non-fuel impact of 10 g CO_2-eq/kWh for SOFC relative to PEMFC, both technologies produce the same calculated footprint at I_H = 1 kg CO_2-eq/kg H_2. Below this value, PEMFC has the lower footprint; above it, SOFC becomes preferable in carbon terms.

The crossover condition is relevant only when the efficiency advantage and additional non-fuel burden act in opposite directions. Otherwise, the relative carbon performance is determined directly by the adopted efficiency and equipment-impact parameters.

SERVICE LIFE, REPLACEMENT, AND UNCERTAINTY

A. When does replacement pay back in carbon terms?

Replacing a degraded fuel-cell stack may improve electrical efficiency and reduce hydrogen consumption, but it introduces additional manufacturing and end-of-life impacts. The carbon benefit therefore depends on the electricity generated after replacement.

Two alternatives are considered over the same future electricity output ΔE: continued operation of the existing stack at efficiency η_d and replacement with a new stack operating at $\eta_n > \eta_d$. Let B_r represent the additional net impact of replacement, including relevant transport and end-of-life processes. For constant delivered-hydrogen carbon intensity I_H, replacement becomes beneficial when:

$$\Delta E > \frac{H_{\mathrm{L}} B_{\mathrm{r}}}{I_{\mathrm{H}}(\frac{1}{\eta_{\mathrm{d}}} - \frac{1}{\eta_{\mathrm{n}}})} \qquad (7)$$

For the assumed values B_r = 300 kg CO_2-eq/kW, η_d = 0.45, and η_n = 0.50, the minimum future electricity generation is 45,000/I_H kWh/kW of installed capacity. This corresponds to 45,000, 15,000, and approximately 4,091 equivalent full-load hours at I_H = 1, 3, and 11 kg CO_2-eq/kg H_2, respectively.

The results indicate that stack replacement becomes more difficult to justify on carbon grounds as hydrogen production becomes less emission-intensive. For low-carbon hydrogen, the additional manufacturing impact may exceed the emissions avoided through improved efficiency during the remaining service period.

This criterion applies only when continued operation is technically feasible and both alternatives provide equivalent service. Safety requirements, reliability constraints, and future degradation must be

considered separately. If efficiency varies during operation, the comparison should use cumulative hydrogen consumption rather than constant equivalent efficiencies.

B. Deterministic sensitivity

The sensitivity analysis examines independent changes in electrical efficiency of ±0.05 and non-fuel impacts between 10 and 50 g CO_2-eq/kWh. The minimum and maximum footprints are calculated using the corresponding extreme parameter combinations.

At I_H = 1 kg CO_2-eq/kg H_2, the calculated ranges are 64.5–116.7 g CO_2-eq/kWh for PEMFC, 62.6–113.8 for AFC, 73.8–131.1 for PAFC, and 56.2–104.5 for SOFC. The overlap between all four intervals indicates that the baseline technology ranking is sensitive to the assumed efficiencies and equipment-related impacts.

At I_H = 11 kg CO_2-eq/kg H_2, SOFC varies between 517.7 and 650.0 g CO_2-eq/kWh, compared with 712.1–941.9 g CO_2-eq/kWh for PAFC. These intervals remain separated within the investigated parameter ranges. However, the SOFC and PEMFC intervals overlap, preventing an unambiguous ranking of these two technologies under the same sensitivity assumptions.

The analysis identifies the influence of parameter uncertainty on comparative results but does not provide statistical confidence intervals. Possible correlations between efficiency, material requirements, service life, and manufacturing impacts are not included.

C. Limitations and end of life

End-of-life treatment depends on fuel-cell composition, recovery efficiency, and recycling processes. Platinum catalyst recovery in PEMFC systems [9] and material recovery from solid-oxide cells [10] require separate inventories covering processing energy, recovered materials, and applicable recycling credits. A high material recovery rate alone does not establish a lower life cycle carbon footprint.

The present model evaluates global warming potential and does not quantify acidification, eutrophication, toxicity, or resource depletion. Manufacturing-related assessments of PAFC and SOFC systems [5] demonstrate the importance of material-specific inventory data. Future technology configurations should also be assessed using prospective assumptions where appropriate [11].

A complete inventory-based comparison would require measured material quantities, manufacturing energy, operating and degradation profiles, replacement frequency, auxiliary electricity consumption, and end-of-life pathways. Consistent emission factors and treatment of methane and hydrogen losses are also necessary before making comparative environmental claims under ISO 14044.

The accompanying Python 3.10 script, input and output CSV files, and vector figures support reproducibility. Model checks cover dimensional consistency, hydrogen-consumption normalization, linearity, crossover conditions, and replacement thresholds. These checks verify the mathematical implementation but do not constitute experimental validation of the assumed parameters.

CONCLUSION

This study developed a parametric framework for evaluating the influence of hydrogen carbon intensity, electrical efficiency, and equipment-related impacts on the life cycle carbon footprint of fuel-cell systems. For the investigated scenarios, emissions ranged from 70.0 to 91.4 g CO_2-eq/kWh at a hydrogen carbon intensity of 1 kg CO_2-eq/kg H_2, increasing to 570.0–805.7 g CO_2-eq/kWh at 11 kg CO_2-eq/kg H_2. The results indicate that equipment-related emissions become more influential in relative terms as the carbon intensity of hydrogen decreases.

The main contribution is the derivation of analytical thresholds linking efficiency advantages to allowable additional non-fuel impacts. For SOFC compared with PEMFC, the assumed efficiency difference compensates for an additional 10–110 g

CO_2-eq/kWh across the investigated hydrogen scenarios. The stack-replacement criterion further establishes the minimum future electricity generation required to offset replacement-related emissions. These relationships provide quantitative support for preliminary technology selection and maintenance planning.

The analysis is based on controlled assumptions rather than measured life cycle inventories. Its application to specific installations therefore requires technology-dependent manufacturing data, operating profiles, hydrogen supply characteristics, and end-of-life inventories. Future work will focus on incorporating these inputs and extending the assessment to additional environmental impact categories.

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