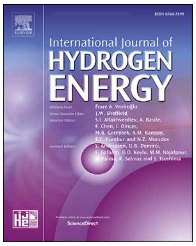
INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 47 (2022) 575–594

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he



Comparative fuel cell sustainability assessment with a novel approach

Canan Acar [a,b,*], *Ahmet Beskese* [a], *Gul Tekin Temur* [a]

[a] *Faculty of Engineering and Natural Sciences, Bahcesehir University, Beşiktaş, Istanbul, Turkey*
[b] *Faculty of Engineering Technology (ET), University of Twente, 7500 AE, Enschede, the Netherlands*

HIGHLIGHTS

- A comprehensive sustainability investigation of fuel cells is conducted.
- The economic, environmental, social, and technical performance are taken into account.
- The selected fuel cells are PEMFC, AFC, PAFC, MCFC, and SOFC.
- The comparative sustainability performance is based on four primary and 15 sub-criteria.
- It is the first one in the literature with an in-detail and very inclusive sustainability evaluation of fuel cells.

ARTICLE INFO

Article history:
Received 20 March 2021
Received in revised form
6 September 2021
Accepted 5 October 2021
Available online 1 November 2021

Keywords:
Clean energy
Fuel cells
Spherical fuzzy AHP
Hydrogen
Multi-criteria decision making
Sustainability

ABSTRACT

Fuel cells have been attracting many researchers and industry partners' attention due to their clean, quiet, modular, and flexible operation characteristics. As Power-to-Gas technologies evolve and get more sustainable, well-developed fuel cells will be needed to convert the chemical energy stored in the gas form to useful products such as power and heat. For that reason, a comprehensive sustainability investigation of fuel cells is conducted by taking their economic, environmental, social, and technical performance into account. The selected fuel cells are polymer electrolyte membrane, alkaline, phosphoric acid, molten carbonate, and solid oxide. These fuel cells' performance is comparatively investigated based on four primary and 15 sub-criteria. The selected performance criteria are economic (initial and running costs), environmental (GHG emissions, land use, solid waste generation, and water discharge quality), social (employment and training opportunities, impact on public health, and public acceptance), and technical (energy and exergy efficiencies, process control, start-up time, and scalability). This study is the first in the literature to conduct an in-detail and very inclusive sustainability evaluation of fuel cells. It is expected to guide many professionals from academia and industry towards developing cleaner, safer, more affordable, and efficient fuel cells.

Introduction

In fuel cells, an electrochemical reaction takes place between hydrogen and oxygen. As a result, the chemical energy stored in hydrogen and oxygen is converted to electrical energy. When they operate with hydrogen and oxygen, fuel cells' only emission is water. Fuel cells are sometimes compared to batteries. However, fuel cells are energy conversion devices,

---

* *Corresponding author*. Faculty of Engineering and Natural Sciences, Bahcesehir University, Beşiktaş, Istanbul, Turkey.
E-mail addresses: Canan.Acar@eng.bau.edu.tr, C.A.Acar@utwente.nl (C. Acar).

https://doi.org/10.1016/j.ijhydene.2021.10.034

while batteries are energy storage devices. In other words, fuel cells can provide uninterrupted electricity as long as there is a continuous fuel supply (i.e., hydrogen and oxygen). However, batteries run out when all stored electricity is used up [1].

Compared to internal combustion engines, fuel cells are quieter and up to two to three times more efficient. Because in fuel cells, an electrochemical reaction takes place instead of combustion, making fuel cells operate in a cleaner manner in terms of pollution. As a matter of fact, a fuel cell can be considered a way to produce zero-emission electricity if it uses hydrogen from carbon and emission-free sources such as solar and wind. Another advantage is that fuel cells do not need conventional fuels such as oil or gas and can reduce economic dependence on foreign fuels, which provides greater energy security for the user side [2].

Fuel cells can meet different end-user demands in many applications such as transportation, building and industry demand, and power generation. Fuel cells are classified based on their types of electrolytes, such as molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), phosphoric acid fuel cells (PAFC), polymer electrolyte membrane fuel cells (PEMFC), and alkaline fuel cells (AFC) [3]. Each fuel cell operates at different temperatures in different sizes, for different applications, and with different efficiencies. Each fuel cell type has certain advantages and disadvantages discussed in detail in the next section.

Fuel cell applications can be categorized into three main groups as portable, stationary, and transportation. In portable applications, fuel cells can be used in a similar sense to batteries in portable devices such as cameras and cell phones. In stationary applications, fuel cells operate in a specific location as a primary energy supplier or to provide backup power, or in combined heating and power (CHP) systems to provide heating and electricity. Fuel cells can be used in a wide range of transportation applications, including aviation, buses, commercial vehicles, heavy-duty vehicles, material handling vehicles, off-road vehicles, passenger cars, and ships. These applications are summarized in Table 1 with their typical power range and technology.

Because of their broad applicability and clean power generation advantages, fuel cells have been attracting many researchers. In the literature, there are many examples of fuel cell studies. For instance, Dekel [4] has reviewed the cell performance and performance stability achieved in PEMFC. Yoshida and Kojima [5] have presented a high-level overview of the various technological advances that had been performed to enable the commercialization of the Toyota MIRAI fuel cell vehicle. Kim et al. [6] have reviewed several alternatives for fuel cell applications to fabricate and evaluate polymer electrolyte and composite membranes. Pandey et al. [7] have critically discussed the suitability of these PEMFCs for fuel cell applications in terms of the dependency of the intrinsic properties of nanohybrid PEMFCs. Rosli et al. [8] have reviewed the performances and critical aspects of high-temperature PEMFCs.

Marino and Kreuer [9] have investigated alkaline fuel cells' stability and durability at different operating temperatures and electrolyte concentrations. Mahato et al. [10] have presented material selection, fundamentals of operation and underlying mechanisms, processing, microstructural and phase characterization, and the functionality and performance of SOFC components in detail. Bi et al. [11] have developed a proton-conducting SOFC with Y-doped $BaZrO_3$ (BZY) electrolyte with a promising way to prepare BZY electrolyte films. Lototskyy et al. [12] have reviewed hydrogen energy systems that integrate fuel cells (PEMFC, AFC, PAFC, MCFC, and SOFC) with metal hydride-based hydrogen storage.

Wang et al. [13,14] have reviewed the progress of the research and the application status of unitized regenerative polymer electrolyte membrane fuel cells, alkaline fuel cells, and solid oxide fuel cells. Alaswad et al. [15] have reviewed the fuel cell cost, durability, and performance challenges associated with fuel cell technologies for transportation applications in detail. Wang et al. [16] have provided some essential

Table 1 – Summary of different fuel cell application types.

Application type	Portable	Stationary	Transport
Definition	Units that are built into, or charge up, products that are designed to be moved, including small auxiliary power units (APU)	Units that provide electricity (and sometimes heat) but are not designed to be moved	Units that provide propulsive power or range extension to a vehicle
Typical power range	Up to 20 kW	Up to 2 MW	Up to 300 kW
Typical technology	PEMFC SOFC	PEMFC MCFC AFC SOFC PAFC	PEMFC
Example	• Small 'movable' APUs (campervans, boats, lighting) • Military applications (portable soldier-borne power, skid-mounted generators) • Portable products (torches, battery chargers), small personal electronics (mp3 player, cameras)	• Large stationary prime power and combined heat and power (CHP) • Small stationary micro-CHP • Uninterruptible power supplies (UPS) • Larger 'permanent' APUs (e.g., trucks and ships)	• Materials handling vehicles • Fuel cell electric vehicles (FCEV) • Trucks and buses • Rail vehicles • Autonomous vehicles (air, land, or water)

perspectives on developing more efficient fuel-cell electrocatalysts featuring high stability, low cost, and enhanced performance, which are the key factors in accelerating the commercialization of fuel-cell technologies.

Das et al. [17] have given insights about fuel cell operation and the application of various power electronics systems. Wilberforce et al. [18] have provided an overview of the fuel cells' technology level with their advantages and disadvantages. The authors have also compared existing fuel cell technologies with competitive technologies. In another study, Wilberforce et al. [19] have explored and compared the latest advances in the electric car and fuel cell car technologies and their design specifications. Sulaiman et al. [20] have reviewed critical energy management strategies for fuel cell vehicles and compared them with internal combustion engines, battery vehicles, and hybrid electric vehicles.

Dodds et al. [21] have examined the potential benefits of fuel cell technologies across different markets, particularly the current state of development and performance of micro-CHP units. Ellamla et al. [22] have defined and classified the types of fuel cells used in CHP systems with their current technological status. The authors have compared two leading fuel cell technologies used in CHP systems: PEMFC and SOFC. Elmer et al. [23] have provided a state-of-the-art review of fuel cell technology operating in the domestic built environment in CHP and combined cooling, heat, and power (CCHP) system applications.

In this study, a comprehensive sustainability investigation of fuel cells is conducted by taking their economic, environmental, social, and technical performance into account. The selected fuel cells are polymer electrolyte membrane, alkaline, phosphoric acid, molten carbonate, and solid oxide. These fuel cells' performance is comparatively investigated based on 15 criteria, which are initial and running costs as economic performance indicators; GHG emissions, land use, solid waste generation, and water discharge quality as environmental performance indicators; employment and training opportunities, impact on public health, and public acceptance as social performance indicators; energy and exergy efficiencies, process control, scalability, and start-up time as technical performance indicators. In the literature, many studies are focusing on different aspects of fuel cells. However, there is a lack of studies that conduct an in-detail and very inclusive sustainability evaluation of fuel cells.

For this reason, this study is a one-of-a-kind example in the literature that considers social aspects in addition to technical and economic performance criteria. Besides, unlike other studies in the literature, this study covers multiple environmental impact assessment dimensions and not just emissions. Using a Multi-criteria Decision Making (MCDM) method called Analytic Hierarchy Process (AHP) enables the usage of qualitative and quantitative evaluation criteria together in a model. Also, the usage of a novel method called Spherical Fuzzy AHP (SFAHP), which is the use of spherical fuzzy sets (SFS) as an extension in AHP for the calculation of the criteria weights and preference scores of alternatives, let the use of independently defined hesitancy from membership and non-membership degrees in the decision-maker's preferences. As a result, a more realistic mathematical representation of experts' judgments could be used in calculations. Because it is one of a kind in the field, this study's outcomes have the potential to guide many professionals from academia, industry, and governments towards the development of cleaner, safer, more affordable, and efficient fuel cells.

Fuel cells

Fuel cells will be used in a wide range of products, ranging from very small fuel cells in portable devices such as mobile phones and laptops, through mobile applications like cars, delivery vehicles, buses, and ships, to heat and power generators in stationary applications in the domestic and industrial sector.

In this study, five fuel cell types are selected for a comprehensive sustainability investigation. These are polymer electrolyte membrane, alkaline, phosphoric acid, molten carbonate, and solid oxide fuel cells. These fuel cells are introduced in this section with their electrolyte type, size, operating temperature, efficiency, applications, advantages, and challenges.

Polymer electrolyte membrane fuel cell (PEMFC)

In PEMFC, a hydrated polymeric ion exchange membrane (fluorinated sulfonic acid polymer or other similar polymers), which is an efficient proton conductor, is used as the electrolyte. The anode and cathode electrode material of PEMFCs is generally carbon with platinum as an electrocatalyst. The interconnections are either carbon or metal. The charge carrier of proton exchange membrane fuel cells is H^+ ions. In the case of anion exchange membrane fuel cells, the charge carrier is OH^- ions.

When the PEMFC is operating, the membrane must be adequately hydrated. For this reason, it is critical to choose the operating temperature and pressures where water does not evaporate faster than its generation rate. Therefore, the efficient performance of the PEMFC relies on proper water management. As a result, the operating temperature of PEMFC is commonly less than 100 °C. Most of the PEMFCs operate between 40 °C and 80 °C. However, in the recent literature, high-temperature proton exchange membrane fuel cells have become an attractive research topic [24,25].

In order to maintain the water balance for membrane hydration, hydrogen feed must have minimal impurities. Even small traces of CO, sulfur, or halogens can easily poison the anode. Therefore, extensive feed gas processing is required. Compared to other fuel cells, both the anode and cathode of PEMFCs require higher catalyst loading. The most common catalyst used in PEMFCs is Pt [26].

PEMFCs can be used in all types of applications that conventional energy systems are used. There have been significant developments in PEMFC use for stationary applications such as backup power units and distributed generation. However, PEMFCs are still preferred in portable and transportation applications. One of the most common applications is fuel cell vehicles (FCVs). There is increasing interest in hydrogen use in fuel cell vehicles in the literature and industry. PEMFC investments have surpassed the total investment in all other fuel cell types during the last ten years. The typical stack size of PEMFCs can reach up to 100 kW. Moreover, the PEMFC efficiencies can be as high as 60% [27].

The PEMFC has a solid electrolyte, which provides excellent resistance to gas crossover and corrosion. The PEMFC's low operating temperature allows rapid start-up, which is generally less than 1 min. Other advantages of PEMFCs are their small and lightweight design. Furthermore, with the absence of corrosive cell constituents, the use of the exotic materials required in other fuel cell types is not required. Test results have demonstrated that PEMFCs can have high current densities of over 2 kW/L and 2 W/cm^2. The PEMFC lends itself to situations where pure hydrogen can be used as a fuel [28].

The low and narrow operating temperature range makes thermal management problematic, especially at very high current densities, making it difficult to use the rejected heat for cogeneration. Water management is another significant challenge in PEMFC design, as engineers must balance, ensuring the electrolyte's sufficient hydration against flooding the electrolyte. Also, PEMFCs are pretty sensitive to poisoning by trace levels of contaminants, including CO, sulfur species, and ammonia. PEMFCs are also sensitive to salinity and water temperature. Some of these disadvantages can be counteracted by lowering operating current density and increasing 1–10 electrode catalyst loading, but both increase cost of the system. The lack of a fully developed hydrogen infrastructure causes a threat to the commercialization of PEMFC.

Alkaline fuel cell (AFC)

AFCs can operate in two different conditions. In the first one, the operating temperature is high, about 250 °C, and the electrolyte is concentrated (85 wt % KOH). The fuel cell operates at temperatures less than 120 °C with lower electrolyte concentration (35–50 wt % KOH) in the second condition. AFC's operating temperature range varies from 65 to 250 °C. The electrolyte is retained in a matrix (usually asbestos), and a wide range of electrocatalysts can be used (e.g., Ni, Ag, metal oxides, noble metals, etc.). The electrodes are made out of transition metals supported by platinum catalysts. The charge carrier is OH^- ions [29].

AFCs are sensitive to CO and CO_2 since CO poisons the electrode, and CO_2 reacts with KOH to form K_2CO_3, which alters the electrolyte. Therefore, AFCs can only work with zero-carbon fuels such as hydrogen. Even oxygen supply must be treated because tiny traces of CO_2 in the air could potentially damage the electrodes [14].

The AFCs are the first modern fuel cells developed in history; the first ones had been built around at the beginning of the 1960s. The first application of the AFC was providing electricity to the Apollo spacecraft. Even though AFCs have shown significant performance in space applications, their use in industry, buildings, and other transportation modes is limited because of the CO_2 and CO sensitivity. However, AFCs still offer promising results in closed systems such as reversible fuel cells as backup power units [30].

The AFC's desirable attributes include its excellent performance on hydrogen and oxygen compared to other candidate fuel cells due to its active O_2 electrode kinetics and its flexibility to use a wide range of electrocatalysts. This allows AFCs to use lower-cost components. AFCs also have low operating temperatures and quick start-up, which is less than 1 min. AFCs can reach up to 200 kW power outputs with about 60% efficiencies [31].

The sensitivity of the electrolyte to CO_2 requires the use of highly pure H_2 as a fuel. As a consequence, the use of a reformer would require a highly effective CO and CO_2 removal system. Besides, if the ambient air is used as the oxidant, the CO_2 in the air must be removed. While this is technically not challenging, it significantly impacts the system's size and cost. AFCs are also generally heavier and larger compared to PEMFC [32].

Phosphoric acid fuel cell (PAFC)

In PAFCs, the electrolyte is concentrated phosphoric acid (~100 wt.%), the operating temperature is between 150 °C and 220 °C. PAFCs are not preferred at lower operating temperatures because of phosphoric acid's low ionic conductivity at low temperatures. Also, at lower temperatures, CO severely poisons the Pt catalyst on the anode. The high operating temperature does not become an issue since phosphoric acid's stability is higher than the other common acids at temperatures between 100 °C and 220 °C. A significant advantage of PAFC is the minimized water vapor pressure due to highly concentrated acid use. As a result, water management in the system is not tricky. Silicon carbide matrix is used to keep the acid in the PAFC. Pt is used as the catalyst in both the anode and cathode sides. The charge carrier is H^+ ions [33].

The most common use of PAFCs is stationary applications such as distributed generation or backup power supply. PAFC technology is well-developed, and it is one of the few fuel cell alternatives commercially available in different sizes. PAFCs can provide power outputs between 5 and 400 kW. PAFC research and development have slowed down during the past decade due to the rapid innovation and performance enhancement of PEMFCs, but not stopped [34].

Compared to PEMFCs and AFCs, PAFCs have less sensitivity to impurities like CO. PEMFC and AFC electrodes are poisoned by even small traces of CO, while PAFCs can tolerate CO up to 1% in the fuel mix or air. Although the operating temperature of PAFC is higher than PEMFC and AFC, it is still low enough to use ordinary materials for construction instead of special temperature-resistant and expensive ones. Other advantages of PAFCs relatively low operating temperature are flexible design and ease of thermal management. The demonstrated system efficiency of PAFCs reaches almost 50%. This efficiency could further be augmented by recovering the byproduct heat from PAFC and using it in residential, commercial, and industrial cogeneration applications. With waste heat recovery and utilization, i.e., cogeneration (CHP), PAFC efficiencies reach up to 80% [35].

The cathode-side reaction in PAFCs requires Pt catalyst and is still slower compared to the AFC cathode reaction. PAFCs are considered to be less complicated than PEMFC, but they still involve extensive fuel processing. PAFCs generally require a water gas shift reactor to accomplish decent performance.

PAFC has sulfur sensitivity and a long start-up time. Finally, phosphoric acid's highly corrosive nature requires costly materials in the cell, in particular the graphite separator plates.

Molten carbonate fuel cell (MCFC)

The most typical electrolyte used in MCFCs is a mixture of alkali carbonates maintained in a ceramic matrix of $LiAlO_2$. The operating temperature of MCFCs varies between 600 °C and 700 °C, which is quite high. Alkali carbonates form a highly conductive molten salt at these temperatures, and carbonate ions provide ionic conductivity. Due to the high operating temperatures, MCFCs do not require expensive catalysts, or noble metals like Pt. Nickel and nickel oxide are sufficient to act as catalysts on the anode and cathode sides, respectively. MCFCs are not easily poisoned, so extensive fuel processing and limitations are not required. The charge carrier is CO_3^{-2} ions [36].

The focus of MCFC development has been larger stationary and marine applications, where the relatively large size and weight of MCFC and slow start-up time are not an issue. MCFCs have power outputs up to 3 MW. Because of their high operating temperature, MCFCs best run continuously at larger scale applications or processes where the operation is continuous. MCFCs have the advantage of being used with a wide variety of fuels, including hydrocarbons (e.g., fossil fuels) and zero-carbon alternatives (e.g., hydrogen, ammonia). MCFCs are most commonly used in stationary applications. Similar to PAFCs, MCFC research and development activities have decreased over the last decade due to the improvements in PEMFC technologies. Nevertheless, there is still significant research going on in the field of MCFC technologies [37].

MCFCs reach relatively high system efficiencies compared to other fuel cell technologies. The overall system efficiency of MCFCs varies between 45% and 55% in single generation mode. Furthermore, MCFCs generate high-temperature waste heat, which could be recovered and used in various applications, enhancing the combined system efficiency up to 80% via cogeneration, i.e., CHP [38].

The main challenge for MCFC developers stems from the very corrosive and mobile electrolyte, which requires the use of nickel and high-grade stainless steel as the cell hardware (cheaper than graphite but more expensive than ferritic steels). The higher temperatures promote material problems, impacting mechanical stability and stack life. Because of higher operating temperatures, the start-up times are longer (around 10 min). Besides, the cathode side of MCFCs requires a source of CO_2 to produce the necessary carbonate ions. Generally, this CO_2 requirement is met by recovering the anode exhaust gas, which increases the component requirements.

Nevertheless, MCFCs could potentially work with carbon capture and storage facilities in the long run, which is a promising application. MCFCs have high contact and cathode resistances. As a result, their power densities are limited to below 200 mW/cm^2 at practical operating voltages [36].

Solid oxide fuel cell (SOFC)

SOFCs use solid and nonporous metal oxides as electrolytes. The most typical electrolyte is Y_2O_3-stabilized ZrO_2. The operating temperature of the SOFCs is between 600 °C and 1000 °C. The ionic conduction in the cell takes place via the oxygen ions at these operating temperatures. The most common anode material is Co-ZrO_2 or Ni-ZrO_2 cermet, and the cathode material is generally Sr-doped $LaMnO_3$. The charge carrier is O^{-2} ions [39].

The earlier SOFC models required operating temperatures higher than 1000 °C because of the solid electrolytes' low conductivity. Recently, with the developments in material sciences, such as thin electrolyte cells, the operating temperature of the new SOFCs has been reduced to 650–850 °C. The current research and development activities attempt to reduce the operating temperatures of the SOFCs even lower. Over the last ten years, the research and development activities have made SOFCs compact and highly efficient with more affordable construction materials [40].

Intensive SOFC research and development activities have significantly expanded the understanding and knowledge of thin-electrolyte planar SOFCs. SOFC performance has also significantly improved. As a result, SOFCs can be utilized in many different applications such as buildings, industry, mobile and stationary systems, transportation, distributed generation, and many other special applications. SOFCs output power capacity can reach up to 2 MW with efficiencies of around 60%. Because of their high operating temperatures, the SOFCs best run continuously [41].

Another advantage of SOFCS is that they do not require precious metal catalysts. The materials used in SOFC are modest in cost. Thin-electrolyte planar SOFC unit cells have been demonstrated to have power densities close to those achieved with PEMFC. As with the MCFC, the high operating temperature allows the use of most of the waste heat for cogeneration (CHP) or in bottoming cycles. Efficiencies ranging from around 40% (simple cycle small systems) to over 50% (hybrid systems) have been demonstrated, and the potential for efficiencies higher than 60% exists [41].

The high operating temperature of the SOFCs causes several challenges. Any thermal expansion mismatch between the construction materials makes system insulation quite complicated and expensive. In order to avoid the thermal expansion mismatch issue, SOFCs have a complicated material selection, fabrication, and assembly procedures. Because of higher operating temperatures, the start-up times are longer (around 60 min). Corrosion, low power density, thermal cycling, and cell lifetime are other challenges of SOFCs. However, it should be noted that SOFCs power densities are still higher than PAFC and MCFC. Besides, the lifetime of SOFCs is generally higher than MCFCs and PEMFCs [40].

Research methodology

MCDM constitutes an arsenal of tools designed to help managers make decisions that require dealing with various qualitative and quantitative criteria simultaneously. Also, those criteria may inalienably conflict with one another. For evaluation of the alternatives and criteria weights, the opinions of experts are taken into consideration. AHP, ELimination Et Choix Traduisant la REalité (ELimination and Choice Expressing Reality – ELECTRE), preference ranking organization method for enrichment evaluation (PROMETHEE), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) are some of the commonly known and used MCDM tools. With its capacity to handle the whole decision-making process, from defining the weights of criteria to selecting the most preferable alternative, AHP developed by Saaty [42] has become a widely used MCDM tool [43–46]. To manage inadequate data and ambiguity occurring in countless real-world cases, fuzzy sets that have been presented by Zadeh [47] have turned out to be a very widely used approach accompanying the MCDM methods. As the inadequacy and vagueness rose colossally in the modern-day business life, some extensions such as type-II, intuitionistic, hesitant, Pythagorean, picture, and neutrosophic fuzzy sets have been added to the fuzzy-set family. One of the most recent members of these extensions is spherical fuzzy sets that have been created by Gundogdu and Kahraman [48–50]. These authors have added SFAHP to the fuzzy MCDM arsenal [51,52].

Decisions related to fuel cells inherently include ambiguity and high complexity since it requires to handle conflicting criteria with quantitative and qualitative data simultaneously. Hence, SFAHP presents a very good fit for the nature of the problem.

Although there is a limited number of studies using MCDM tools for other fuel cell-related topics, as summarized below, to our knowledge, there is no MCDM study for evaluating the sustainability of different fuel cells.

Shanian and Savadogo [53] have utilized ELECTRE IV for choosing the best material for the bipolar plate of a polymer electrolyte fuel cell (PEFC). Since there had been a high conflict claimed in evaluating related criteria, multi-criteria decision-making to be chosen for being more efficient than optimization. They had discussed the obtained results comparing the ranking of alternative materials with the findings of existing reports. The authors have reported that ELECTRE IV is a useful tool for material selection in this field. In another study, Shanian and Savadogo [54] have used the ranking Preferences by Similarity to the Ideal Solution (TOPSIS) to select the best material among 12 alternatives. The authors have developed a user-defined code to make the model easily applicable. They have also calculated entropy values to discover the relative importance of the criteria.

Lee et al. [55] have proposed a fuzzy AHP based methodology to rank six alternative hydrogen energy technologies. Using fuzzy sets has been making the procedure able to handle the vagueness originated from subjective assessments efficiently. Four main criteria, economic impact, commercial potential, inner capacity, and technological spin-off, have been considered, and polymer electrolyte membrane fuel cell has been selected as the best alternative.

In the study of Nikouei et al. [56], 12 different membrane samples for proton exchange membrane fuel have been assessed using PROMETHEE and Shannon entropy technique. In the proposed method, the criteria such as proton conductivity, ion exchange capacity, inherent viscosity, thermal stability, water absorption, glass transition temperature, and tensile strength have been considered. As a result, it has been shown that poly (ether ketone) membranes are more satisfactory than poly (ether sulfone) membranes.

Acar et al. [44] have proposed an innovative hesitant fuzzy analytic hierarchy process (HFAHP) and hesitant fuzzy TOPSIS (HFTOPSIS) based method for defining the best energy storage system. The method has been chosen to strengthen the evaluation process's robustness against the vagueness in decision-makers' assessments. The model has consisted of economic, environmental, social, and technical criteria. The findings have indicated that hydrogen is a better option than pumped hydro, conventional battery, high-temperature battery, and flow battery.

In another study by Acar et al. [43], HFAHP based method has been proposed to support decision-makers in selecting the best hydrogen production method. The main criteria influencing the decision have been economic, environmental, social, technical, and availability/reliability indicators. According to their selection criteria and analysis, grid electrolysis is the most satisfactory option.

Besides the studies summarized above, there are also some other MCDM studies in several topics, such as selecting the best electric power plant [57], selecting the best electric thermal power plant [58], prioritizing alternative energy exploitation projects [59], and more [60]. Although some studies have been carried out in the related literature, a significant need for a systematic decision-making method is vital in tackling vagueness to support decision-makers responsible for selecting the most sustainable fuel cell option. This is possible through using an evolved fuzzy set-based MCDM method. This study contributes to the related literature by developing an evolved fuzzy set (named Spherical Fuzzy Sets) based AHP method to select the most sustainable fuel cell.

Spherical fuzzy sets

As a novel extension to classical fuzzy set theory, the spherical fuzzy set (SFS) theory differentiates itself from its predecessors with an independently defined hesitancy from membership and non-membership degrees in the decision-maker's preferences. Essentially, it has roots in Pythagorean and Neutrosophic Fuzzy Sets. Nevertheless, as an additional value, the SFS allows the decision-makers to use membership behavior on a spherical surface (as the name suggests) and autonomously characterize

Table 2 – Linguistic measures of importance used for pair-wise comparisons (adapted from Ref. [52]).

	(μ, υ, π)			Score Index (SI)
Absolutely Higher Importance (AHI)	0.9	0.1	0	9.00
	0.85	0.15	0.04	8.00
Very High Importance (VHI)	0.8	0.2	0.1	7.00
	0.75	0.25	0.14	6.00
High Importance (HI)	0.7	0.3	0.2	5.00
	0.65	0.35	0.23	4.00
Slightly Higher Importance (SHI)	0.6	0.4	0.3	3.00
	0.55	0.45	0.3	2.00
Equally Important (EI)	0.5	0.4	0.4	1.00
	0.45	0.55	0.3	0.50
Slightly Lower Importance (SLI)	0.4	0.6	0.3	0.33
	0.35	0.65	0.23	0.25
Low Importance (LI)	0.3	0.7	0.2	0.20
	0.25	0.75	0.14	0.17
Very Low Importance (VLI)	0.2	0.8	0.1	0.14
	0.15	0.85	0.04	0.13
Absolutely Lower Importance (ALI)	0.1	0.9	0	0.11

all of the parameters involving hesitancy in a broader space. Subsequently, the entirety of the membership, non-membership, and hesitancy parameters can be picked freely as long as they are somewhere in the range of 0 and 1 independently. The squared sum of all these parameters is no more than 1. A summary of the mathematical basis of Spherical Fuzzy Sets is given below as adapted from Ref. [52].

Let $\mu_{\tilde{A}_S}(x)$, $\upsilon_{\tilde{A}_S}(x)$, and $\pi_{\tilde{A}_S}(x)$ represent membership, non-membership, and hesitancy degrees, respectively, of each x to $\tilde{A}_S$. Also, $\mu_{\tilde{B}_S}(y)$, $\upsilon_{\tilde{B}_S}(y)$, and $\pi_{\tilde{B}_S}(y)$ represent membership, non-membership, and hesitancy degrees, respectively, of each y to $\tilde{B}_S$. $\tilde{A}_S$, and $\tilde{B}_S$ are spherical fuzzy numbers, and x and y are designated in two different universes of discourse, U_1 and U_2, respectively, as shown in Eqs. (1)–(6).

$$\tilde{A}_s = \{x, (\mu_{\tilde{A}_s}(x), \upsilon_{\tilde{A}_s}(x),\ \pi_{\tilde{A}_s}(x)) | x \in U_1\} \tag{1}$$

And

$$\tilde{B}_s = \{y, (\mu_{\tilde{A}_s}(y), \upsilon_{\tilde{A}_s}(y),\ \pi_{\tilde{A}_s}(y)) | y \in U_2\} \tag{2}$$

where

$$\mu_{\tilde{A}_S}(x):\ U_1 \rightarrow [0,\ 1],\ \upsilon_{\tilde{A}_S}(x):\ U_1 \rightarrow [0,\ 1],\ \pi_{\tilde{A}_S}(x):\ U_1 \rightarrow [0,\ 1] \tag{3}$$

$$0 \le \mu^2_{\tilde{A}_S}(x) + \upsilon^2_{\tilde{A}_S}(x) + \pi^2_{\tilde{A}_S}(x) \le 1,\ \forall x \in U_1 \tag{4}$$

$$\mu_{\tilde{B}_S}(y):\ U_2 \rightarrow [0,\ 1],\ \upsilon_{\tilde{B}_S}(y):\ U_2 \rightarrow [0,\ 1],\ \pi_{\tilde{B}_S}(y):\ U_2 \rightarrow [0,\ 1] \tag{5}$$

$$0 \le \mu^2_{\tilde{B}_S}(y) + \upsilon^2_{\tilde{B}_S}(y) + \pi^2_{\tilde{B}_S}(y) \le 1,\ \forall y \in U_2 \tag{6}$$

To increase intelligibility, some basic operator definitions are given in the following equations:

Addition:

$$\tilde{A}_s \oplus \tilde{B}_s = \left\{ \left({\mu_{\tilde{A}_s}}^2 + {\mu_{\tilde{B}_s}}^2 - {\mu_{\tilde{A}_s}}^2 {\mu_{\tilde{B}_s}}^2 \right)^{\frac{1}{2}}, \upsilon_{\tilde{A}_s}\upsilon_{\tilde{B}_s},\ \left(\left(1 - {\mu_{\tilde{B}_s}}^2\right) {\pi_{\tilde{A}_s}}^2 + \left(1 - {\mu_{\tilde{A}_s}}^2\right) {\pi_{\tilde{B}_s}}^2 - {\pi_{\tilde{A}_s}}^2 {\pi_{\tilde{B}_s}}^2 \right)^{\frac{1}{2}} \right\} \tag{7}$$

Multiplication:

$$\tilde{A}_s \otimes \tilde{B}_s = \left\{ \mu_{\tilde{A}_s}\mu_{\tilde{B}_s},\ \left({\upsilon_{\tilde{A}_s}}^2 + {\upsilon_{\tilde{B}_s}}^2 - {\upsilon_{\tilde{A}_s}}^2 {\upsilon_{\tilde{B}_s}}^2 \right)^{\frac{1}{2}}, \left(\left(1 - {\upsilon_{\tilde{B}_s}}^2\right) {\pi_{\tilde{A}_s}}^2 + \left(1 - {\upsilon_{\tilde{A}_s}}^2\right) {\pi_{\tilde{B}_s}}^2 - {\pi_{\tilde{A}_s}}^2 {\pi_{\tilde{B}_s}}^2 \right)^{\frac{1}{2}} \right\} \tag{8}$$

Multiplication by a scalar λ (for λ > 0):

$$\lambda.\tilde{A}_s = \left\{ \left(1 - \left(1 - {\mu_{\tilde{A}_s}}^2\right)^{\lambda}\right)^{\frac{1}{2}}, \upsilon^{\lambda}_{\tilde{A}_s}, \left(\left(1 - {\mu_{\tilde{A}_s}}^2\right)^{\lambda} - \left(1 - {\mu_{\tilde{A}_s}}^2 - {\pi_{\tilde{A}_s}}^2\right)^{\lambda} \right)^{\frac{1}{2}} \right\} \tag{9}$$

$\tilde{A}_s$ to the power of λ (for λ > 0):

$$\tilde{A}_s^{\lambda} = \left\{ \mu^{\lambda}_{\tilde{A}_s},\ \left(1 - \left(1 - \upsilon^2_{\tilde{A}_s}\right)^{\lambda}\right)^{\frac{1}{2}}, \left(\left(1 - \upsilon^2_{\tilde{A}_s}\right)^{\lambda} - \left(1 - {\mu_{\tilde{A}_s}}^2 - {\pi_{\tilde{A}_s}}^2\right)^{\lambda} \right)^{\frac{1}{2}} \right\} \tag{10}$$

Furthermore, in Eqs. (11) and (12), spherical weighted arithmetic mean (SWAM) and spherical weighted geometric mean (SWGM) are given, respectively, corresponding to weights which are annotated by $w = (w_1,\ w_2,\ \ldots,\ w_n)$ where $w_1 \varepsilon [0,\ 1]$, and $\sum_{i=1}^{n} w_1 = 1$ are defined.

$$\begin{aligned} \mathrm{SWAM}_W(\tilde{A}_{S1},\ \ldots,\ \tilde{A}_{Sn}) &= w_1\tilde{A}_{S1} + w_2\tilde{A}_{S2} + \ldots + w_n\tilde{A}_{Sn} \\ &= \left\{ \left[1 - \prod_{i=1}^{n} \left(1 - \mu^2_{\tilde{A}_{si}}\right)^{w_i} \right]^{\frac{1}{2}}, \prod_{i=1}^{n} \upsilon^{w_i}_{\tilde{A}_{Si}}, \left[\prod_{i=1}^{n} \left(1 - \mu^2_{\tilde{A}_{si}}\right)^{w_i} - \prod_{i=1}^{n} \left(1 - \mu^2_{\tilde{A}_{si}} - \pi^2_{\tilde{A}_{si}}\right)^{w_i} \right]^{\frac{1}{2}} \right\} \end{aligned} \tag{11}$$

$$\begin{aligned} \mathrm{SWGM}_W\left(\tilde{A}_{S1},\ \ldots,\ \tilde{A}_{Sn}\right) &= w_1\tilde{A}_{S1} + w_2\tilde{A}_{S2} + \ldots + w_n\tilde{A}_{Sn}\tilde{A}_{S1},\ \ldots,\ \tilde{A}_{Sn}\Big) = {\tilde{A}_{S1}}^{w_1} + {\tilde{A}_{S2}}^{w_2} + \ldots + {\tilde{A}_{Sn}}^{w_n} \\ &= \left\{ \prod_{i=1}^{n} \mu^{w_i}_{\tilde{A}_{Si}},\ \left[1 - \prod_{i=1}^{n} \left(1 - \upsilon^2_{\tilde{A}_{si}}\right)^{w_i} \right]^{\frac{1}{2}}, \left[\prod_{i=1}^{n} \left(1 - \upsilon^2_{\tilde{A}_{si}}\right)^{w_i} - \prod_{i=1}^{n} \left(1 - \upsilon^2_{\tilde{A}_{si}} - \pi^2_{\tilde{A}_{si}}\right)^{w_i} \right]^{\frac{1}{2}} \right\} \end{aligned} \tag{12}$$

Spherical fuzzy AHP

This study constitutes a comprehensive sustainability investigation of fuel cells, evaluating them against economic, environmental, social, and technical performance dimensions. To define the criteria and sub-criteria's priority weights within the model, and select the most sustainable fuel cell option, a spherical fuzzy AHP methodology for aggregated expert preferences adapted from Ref. [52] is utilized. The methodology can be summarized in seven steps, as presented below:

Step 1. Through a thorough literature review and unstructured interviews with the experts in the field, the authors built a draft hierarchical model, including primary and sub-criteria and alternatives. The model is finalized with a few minor modifications in wording based on the suggestions of the experts.

Step 2. Three experts are selected considering their academic and practical expertise on the topic and availability. These experts evaluated the main and sub-criteria and alternatives in a pair-wise manner using linguistic variables in Table 2. When they felt undecided between two linguistic variables, their evaluation is accepted as the mid-values within the table created explicitly by authors for such situations. For the linguistic values between EI and AHI, the score indices of these mid values can be determined, and for linguistic values between EI and ALI, Eq. (13) can be used (please note that the score index for EI can be calculated in both ways). For example, when the experts have hesitated to choose from two different linguistic variables given as Absolutely Higher Importance (AHI), which had a spherical number of (0.9, 0.1, 0) and Very High Importance (VHI), which had a spherical number of (0.8, 0.2, 0.1), the authors offered a mid-value which is annotated as (0.85, 0.15, 0.04). In Table 1, all these mid-values can be seen. The exact process has been repeated for all levels of the hierarchy (i.e., main-criteria, sub-criteria, and alternatives).

$$SI=\sqrt{\left|100\times\left[\left(\mu_{\tilde{A}_S}-\pi_{\tilde{A}_S}\right)^2-\left(v_{\tilde{A}_S}-\pi_{\tilde{A}_S}\right)^2\right]\right|} \tag{13}$$

$$\frac{1}{SI}=\frac{1}{\sqrt{\left|100\times\left[\left(\mu_{\tilde{A}_S}-\pi_{\tilde{A}_S}\right)^2-\left(v_{\tilde{A}_S}-\pi_{\tilde{A}_S}\right)^2\right]\right|}} \tag{14}$$

Step 3. For checking the consistency, the usage of defuzzified matrices is a standard method [43,60,61]. In Table 2, by using the related score indices (SI), the spherical fuzzy numbers are directly defuzzified, and by using Eqs. (15) and (16), consistency ratio (CR) is calculated for each decision table.

$$CI=\frac{\lambda_{max}-n}{n-1} \tag{15}$$

$$CR=\frac{CI}{RI} \tag{16}$$

In those equations, *CI* represents the consistency index, $\lambda_{\max}$ is the largest eigenvector of the matrix, n is given as the number of decision criteria while evaluating the selected alternatives' sustainability performance, and *RI* can be defined as the random index. When calculated, the evaluations would be considered consistent, given that the CR value is lower than 0.1; thus, the process could then proceed to Step 4.

Step 4. Both Spherical Weighted Geometric Mean (SWGM) and Spherical Weighted Arithmetic Mean (SWAM) can be used for aggregating the experts' preferences. In this study, SWAM is preferred as used in Refs. [46,52].

While being dependent on the weights, $w=(w_1, w_2, \ldots, w_n)$, where $w_1\varepsilon[0,\ 1]$, and $\sum_{i=1}^{n} w_1=1$, Spherical Weighted Arithmetic Mean (SWAM) can be calculated as in Eq. (17)

$$SWAM_W(\tilde{A}_{S1},\ \ldots,\ \tilde{A}_{Sn})=w_1\tilde{A}_{S1}+w_2\tilde{A}_{S2}+\ldots+w_n\tilde{A}_{Sn}=\left\{\left[1-\prod_{i=1}^{n}\left(1-\mu^2_{\tilde{A}_{si}}\right)^{w_i}\right]^{\frac{1}{2}},\ \prod_{i=1}^{n}v^{w_i}_{\tilde{A}_{si}},\ \left[\prod_{i=1}^{n}\left(1-\mu^2_{\tilde{A}_{si}}\right)^{w_i}-\prod_{i=1}^{n}\left(1-\mu^2_{\tilde{A}_{si}}-\pi^2_{\tilde{A}_{si}}\right)^{w_i}\right]^{\frac{1}{2}}\right\} \tag{17}$$

Step 5. Similarly, Spherical Weighted Arithmetic Mean (SWAM) is used on the fuzzy local weights of main and sub-criteria and the alternatives to calculate their respective values.

Step 6. In order to defuzzify the spherical fuzzy criteria weights, the score function (S) is used (please see Eq. (18)), and the calculated values are normalized with Eq. (19) to give the final crisp local weights.

$$S\left(\tilde{w}_j^s\right)=\sqrt{\left|100\times\left[\left(3\mu_{\tilde{A}_S}-\frac{\pi_{\tilde{A}_S}}{2}\right)^2-\left(\frac{v_{\tilde{A}_S}}{2}-\pi_{\tilde{A}_S}\right)^2\right]\right|} \tag{18}$$

$$w_j=\overline{w}_j^s=\frac{S\left(\tilde{w}_j^s\right)}{\sum_{j=1}^{n}S\left(\tilde{w}_j^s\right)} \tag{19}$$

Step 7. To calculate the global weights of the sub-criteria and the alternatives, the local weights are multiplied with the weights of corresponding parent criteria.

Proposed model

This section presents the proposed model in detail, explaining each criterion and showing how the criteria weights are calculated along with numerical illustrations. Upon calculating the criteria weights, the selection process of the alternatives is defined, and the results are discussed. The section is concluded with a sensitivity analysis.

Sustainability criteria

The model for selecting the most sustainable fuel cell consists of four primary and fifteen sub-criteria (Fig. 1), which are initial and running costs (economic performance), GHG emissions, land use, water discharge quality, and solid waste generation (environmental performance), impact on public health, employment and training opportunities and public acceptance (social performance), energy and exergy efficiencies, process control, start-up time, and scalability (technical performance). The structure of the model is illustrated in Fig. 2.

The economic performance evaluation is based on two costs, which are initial and running. Initial cost includes purchasing all items needed to design, develop, and build the fuel cell with its auxiliary components. The initial cost can also be referred to as investment cost or capital expense. Running cost occurs during the fuel cell operation, including operating and maintenance costs, fuel costs (such as hydrogen and oxygen), catalyst costs, and so on. Reducing cost and improving durability are the two most significant challenges to fuel cell commercialization. Fuel cell systems must be cost-competitive and perform as well or better than traditional power technologies over the system's life. Ongoing research is focused on identifying and developing new materials that will reduce the cost and extend the life of fuel cell stack components, including membranes, catalysts, bipolar plates, and membrane-electrode assemblies. For instance, a critical barrier to fuel cell adoption is the cost of platinum, making the development of alternative catalyst materials a key driver for their mass implementation. Low-cost, high-volume manufacturing processes will also help to make fuel cell systems cost-competitive with traditional technologies.

Four sub-criteria are used in the environmental performance category: GHG emissions, land use, water discharge quality, and solid waste generation. Unlike the standard approach focusing on the GHG emissions only in the environmental impact category, this study takes a broader and more inclusive approach to environmental impact assessment. By including the impact on air, water, and land, some sustainable development goals of the United Nations are addressed. These goals are clean water and sanitation, affordable and clean energy, sustainable cities and communities, responsible consumption and production, climate action, life below water, and life on land.

When pure hydrogen is fed as the fuel, all fuel cells have zero tailpipe emissions. However, in this study, a lifecycle approach has been taken. Hence, the construction process of the selected fuel cells is considered when assessing their GHG emissions. Land use is the area occupied by the fuel cell and the area required for the fuel cell to operate appropriately, including fuel tanks and exhaust systems. Large area requirements might be a severe issue for portable applications.

Nevertheless, even stationary applications might be a problem. We have limited land sources and have competing expectations such as protection of the natural ecosystem and our agriculture, industry, housing, etc., needs. Therefore, future energy systems are required to occupy smaller spaces. Water discharge quality not only includes the contaminants in the water but also the temperature and pressure of the fuel cell's water output. Excessive catalyst use and high-temperature operation could severely reduce the water

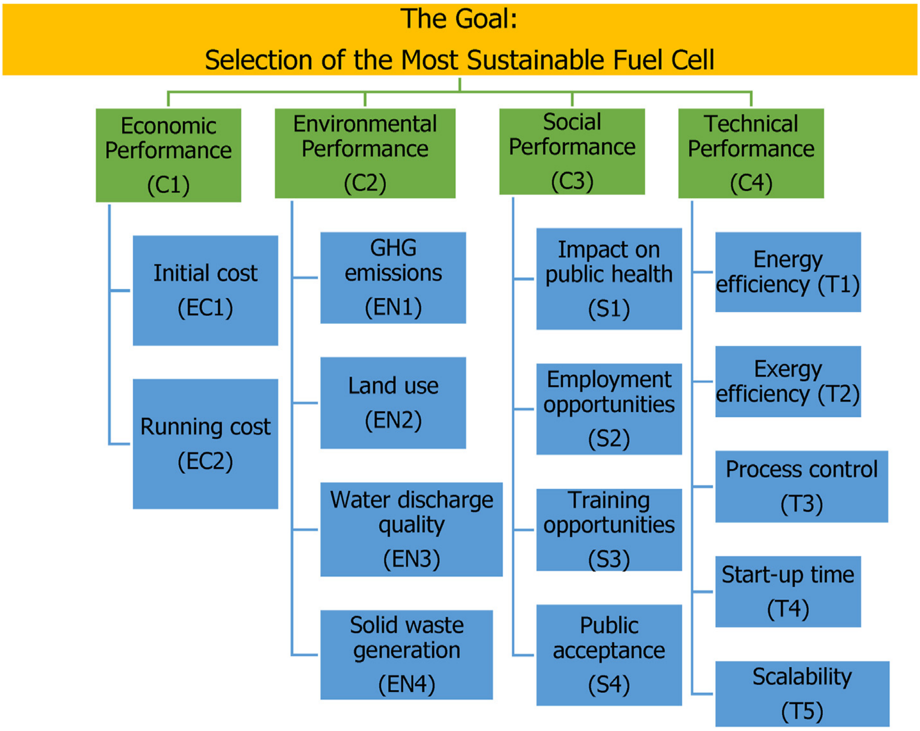


Fig. 1 – Main and sub-criteria used to evaluate the sustainability of fuel cells.

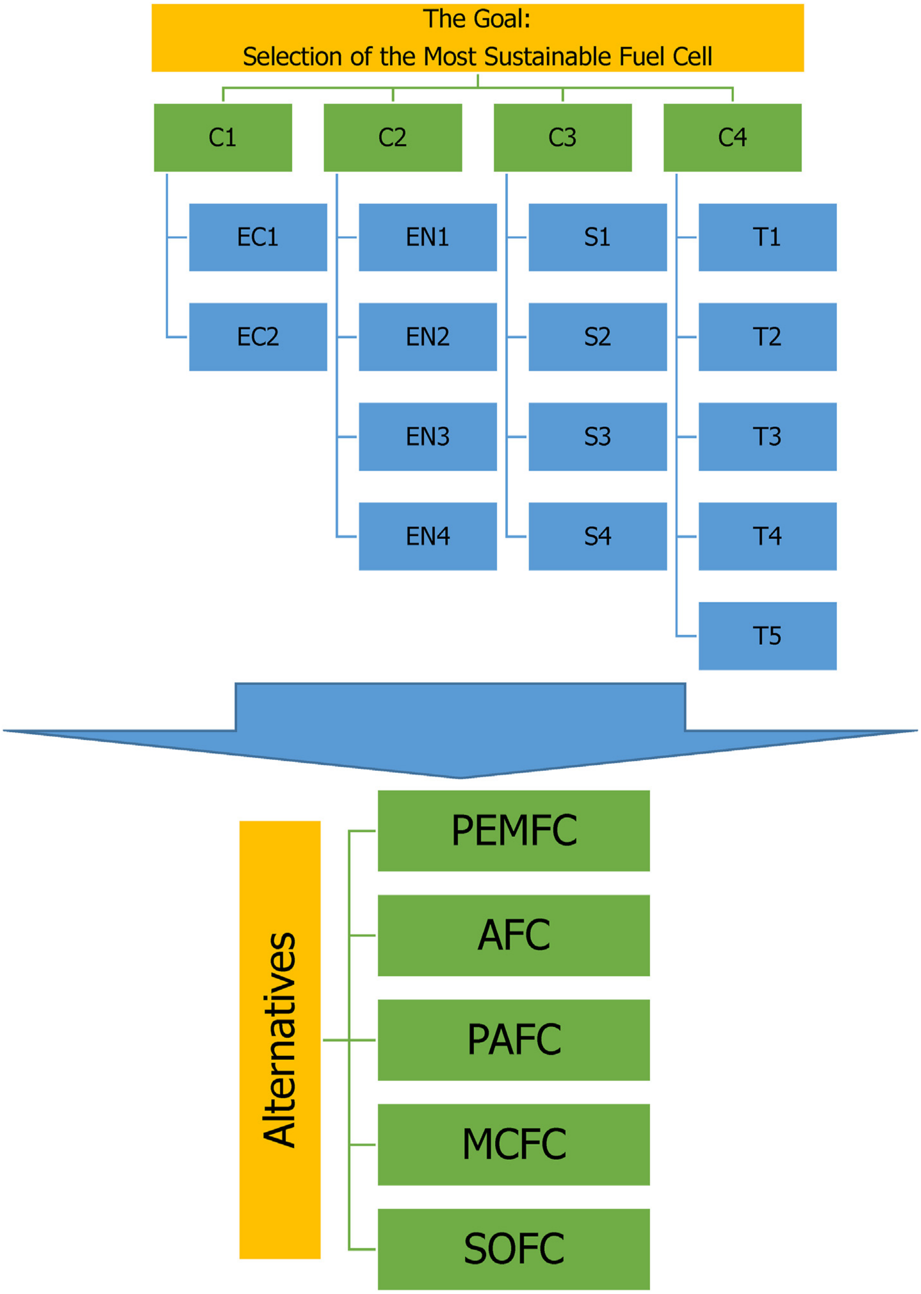


Fig. 2 – The proposed model for sustainable fuel cell selection decision.

discharge quality, which is seen as unsustainable if the water discharge is not treated correctly. Similarly, in parallel with the "zero waste" requirement from future energy systems, fuel cells are expected to generate the smallest possible, solid waste for a sustainable future.

The impact on public health, employment and training opportunities, and public acceptance are the social performance sub-criteria. These selected issues address the "good health and well-being," "decent work and economic growth," and "sustainable cities and communities" among the UN sustainable development goals. Any noise, smell, temperature change, and safety risks such as an explosion, leaks, or melting are considered to negatively impact human health. Employment and training opportunities are taken as two separate criteria. Employment opportunities indicate possibilities of new job openings. In training opportunities, the possibility of gaining new skills and adaptation to more dynamic markets are meant. In both cases, sustainable energy systems are expected to have both suitable employment and training opportunities. Last, public acceptance is considered because any system that is not accepted by the society is expected to have difficulty entering the market and, even if entered, surviving in it.

Energy and exergy efficiencies, process control, start-up time, and scalability are considered in the technical performance category. Energy efficiency is the first step for a sustainable global energy system. It can mitigate climate change, improve energy security, and grow economies while delivering environmental and social benefits. It is calculated based on the first law of thermodynamics: energy content of the useful product divided by the input sources' energy content. More efficient fuel cells use less energy to perform the same task by eliminating energy waste. Exergy efficiency is calculated based on the second law of thermodynamics, and it measures how the quality of energy (exergy) is conserved in a process. Exergy is the quality of energy that shows the highest useful work that can be obtained from a process or system. Process control is the ease of controlling all of the operating parameters during fuel cell operation, including temperature, pressure, flow rates, and so on. This affects the safety aspects, and also, the easier (or more automated control) is more suitable for portable and household applications. More complex process control requirements also increase system costs. Start-up time is crucial for portable and small-scale applications, but in general, shorter response times are required by the end-users. Scalability indicates operational flexibility. Higher scores in scalability mean the fuel cell can be easily used in smaller and larger scales and in stationary and portable applications, which is more desirable.

Fuel cells have numerous advantages in terms of sustainable development. This study aims to thoroughly investigate their sustainability and provide some research directions for their performance enhancement in terms of social, technical, economic, and environmental perspectives. So far, the selected fuel cell types are described with their advantages and disadvantages, and the performance criteria are introduced. In the following chapters, the procedure for calculating the weights of each sustainability criterion is provided in detail.

Criteria weight calculation

In order to define the importance levels (weights) of the criteria, three international experts filled in the questionnaires, including pair-wise criteria comparisons. The experts are selected based on the following standards:

- number of years of experience in hydrogen energy systems and fuel cells
- impact of their research or product
- technologies they have developed

All of the experts selected in this study have more than 15 years of experience in fuel cells. One expert is a professor who serves as Board Member in the Turkish Hydrogen Technology Association. One expert is a member of the Hydrogen Europe Research. Moreover, one expert is a director at a multinational advanced technology company focusing on producing commercial fuel cells.

As an initial step of this phase, information about this study's goal, explanations about the criteria set, and characteristics of the alternatives are shared with the experts. Secondly, a user-friendly questionnaire enables experts to easily compare the criteria, and the alternatives pairwisely are shared. The authors assisted the experts throughout the evaluation by providing them with a correct understanding of the evaluation process. As an example, pair-wise comparisons

Table 3 – Sample questionnaire for pair-wise comparisons of main criteria.

Main Criteria	Absolutely Higher Importance	Very High Importance	High Importance	Slightly Higher Importance	Equally Important	Slightly Lower Importance	Low Importance	Very Low Importance	Absolutely Lower Importance	Main Criteria
Economic Performance						X				Environmental Performance
Economic Performance				X						Social Performance
Economic Performance								X		Technical Performance
Environmental Performance				X						Social Performance
Environmental Performance					X					Technical Performance
Social Performance								X		Technical Performance

of main criteria made by one of the experts are given in Table 3.

After receiving the evaluations, decision matrices are created for each expert individually. The consistency ratio is calculated for each of these matrices to check the reliability of the comparisons. Consistency ratios are calculated as described in Step 3 of the spherical fuzzy AHP method presented above. If the evaluation is observed inconsistent, in other words, if the consistency ratio is equal to or greater than 0.10, pair-wise comparisons in this matrix are re-evaluated by the corresponding expert with further guidance by the authors. After two iterations, it is confirmed that all consistency ratios are under 0.10, and the scores are ready to use for the weight calculations. This step's successor is an aggregation (as defined in Step 4 of the methodology defined in spherical fuzzy AHP) where individual preferences are aggregated in a single decision matrix representing the group preference. An aggregated decision matrix can be seen in Table 4.

To calculate the local weights (the importance weight of each criterion within the related hierarchy level) and global weights (the importance weight of each sub-criterion within the whole model), Steps 5–7 of the methodology are applied on the aggregated matrices. SWAM operator in Eq. (17) is selected for the calculation of the weights. For instance, μ, v, and π values in $\tilde{w}^s_{C1} = (\mu_{C1}, \upsilon_{C1}, \pi_{C1})$ are computed for the main criterion “Economic Performance (C1)” as follows:

$$\mu_{C1} = \sqrt{\left(1 - (1 - 0.5^2)^{\frac{1}{4}} \times (1 - 0.65^2)^{\frac{1}{4}} \times (1 - 0.71^2)^{\frac{1}{4}} \times (1 - 0.38^2)^{\frac{1}{4}}\right)} = 0.5887 \tag{20}$$

$$\upsilon_{C1} = 0.4^{\frac{1}{4}} \times 0.36^{\frac{1}{4}} \times 0.29^{\frac{1}{4}} \times 0.59^{\frac{1}{4}} = 0.3970 \tag{21}$$

$$\pi_{C1} = \sqrt{\begin{array}{l}(1 - 0.5^2)^{\frac{1}{4}} \times (1 - 0.65^2)^{\frac{1}{4}} \times (1 - 0.71^2)^{\frac{1}{4}} \times (1 - 0.38^2)^{\frac{1}{4}} - \\ (1 - 0.5^2 - 0.4^2)^{\frac{1}{4}} \times (1 - 0.65^2 - 0.23^2)^{\frac{1}{4}} \times (1 - 0.71^2 - 0.2^2)^{\frac{1}{4}} \times (1 - 0.38^2 - 0.29^2)^{\frac{1}{4}}\end{array}} = 0.2845 \tag{22}$$

After calculating μ, v, and π, the score function $(S(\tilde{w}^s_{C_1}))$ is calculated for all main criteria by using Eq. (18). The following numerical example illustrates the calculation for the score function of C1, Economic Performance.

$$S\left(\tilde{w}^s_{C_1}\right) = \sqrt{\left|100 \times \left[\left((3 \times 0.5887) - \left(\frac{0.2845}{2}\right)\right)^2 - \left(\left(\frac{0.397}{2}\right) - 0.2845\right)^2\right]\right|} = 16.22 \tag{23}$$

In the next step, each one of these values is divided by the sum of their score functions $(\sum_{j=1}^{4} S(\tilde{w}^s_{C_j}))$ as in Eq. (19) to normalize the values and find the weights of the main criteria. As a result, spherical fuzzy $(\tilde{w}^s)$ weights, score functions, and crisp weights $(\overline{w}^s)$ for the main criteria are calculated as given in Table 5. After checking the individual comparison matrices' consistencies for the sub-criteria, individual preferences are aggregated using a similar procedure. In the end, all the local and global weights are obtained, as seen in Table 6. The results are visualized in Figs. 3 and 4. The global weight of initial cost, for instance, can be determined as the product of the local weight of this criterion (i.e., 0.484) and the weight of its parent criterion (i.e., 0.281), as

$$0.484 \times 0.281 = 0.136. \tag{24}$$

As shown in Fig. 3, technical performance has the highest importance when evaluating the sustainability performance of the selected fuel cells, and the least important performance criterion is social. The detailed sub-criteria weights in Fig. 4 show that the running cost has the highest importance when selecting a fuel cell, immediately followed by the initial cost. One reason is that financial competitiveness is key to switching from traditional energy systems (i.e., fossil fuel combustion) to fuel cells. The rest of the sub-criteria have similar global weights, but among them, exergy efficiency seems to have the highest importance. Exergy efficiency shows the ratio of input energy being converted to useful work, and higher efficiency means fewer resources are wasted, which is quite essential. GHG emissions is another critical factor since fuel cells are proposed as alternatives to fossil fuel devices; they should reduce emissions significantly. Scalability is needed for the broad application of a fuel cell; impact on health would significantly affect the fuel cell

Table 4 – Aggregated decision matrix for the main criteria.

	C1			C2			C3			C4		
C1	0.50	0.40	0.40	0.65	0.36	0.23	0.71	0.29	0.20	0.38	0.59	0.29
C2	0.44	0.58	0.27	0.50	0.40	0.40	0.57	0.40	0.33	0.43	0.50	0.35
C3	0.31	0.70	0.22	0.44	0.52	0.34	0.50	0.40	0.40	0.29	0.73	0.20
C4	0.68	0.30	0.25	0.64	0.32	0.30	0.75	0.25	0.17	0.50	0.40	0.40

Table 5 – Spherical fuzzy ($\tilde{w}^s$) weights, score functions, and crisp weights ($\overline{w}^s$) for the main criteria.

		$\tilde{w}^s$		$S(\tilde{w}^s_{C_j})$	$\overline{w}^s$
C1	0.59	0.40	0.28	16.22	0.28
C2	0.49	0.46	0.34	12.99	0.22
C3	0.40	0.57	0.31	10.36	0.18
C4	0.66	0.31	0.28	18.29	0.32

utilization in residential applications. Among the given sub-criteria, employment and training opportunities seem to have the lowest weight. According to the experts, the reason is that energetic, economic, and environmental aspects have higher importance than the social aspects.

Selection of the most sustainable fuel cell alternative

In this study, fuel cells' sustainability performance is investigated for two application types: residential and transportation. Currently, the biggest challenge for the transition to wide fuel cell use in these applications is the cost issue. The experts evaluated the selected fuel cells based on how they tackle the economic, environmental, social, and technical challenges in residential and transport applications.

For finding the most sustainable fuel cell option among five alternatives (Polymer Electrolyte Membrane (A1), Alkaline (A2), Phosphoric Acid (A3), Molten Carbonate (A4), Solid Oxide (A5)), the steps given in Section Spherical Fuzzy AHP are followed. Firstly, the fuel cell alternatives are compared with each other in a pair-wise manner by each expert against each sub-criterion. The individual preference matrices are checked for consistency, and the inconsistencies found are fixed, as explained above. The SWAM operator is utilized to aggregate the results. A sample aggregated decision matrix for the initial cost is given in Table 7.

To calculate each fuel cell option's local weights and global weights, Steps 5–7 of the methodology are applied on the aggregated matrices. SWAM operator in Eq. (17) was selected for the calculation of the weights. For instance, μ, v, and π values in $\tilde{w}^s_{A1} = (\mu_{A1}, \upsilon_{A1}, \pi_{A1})$ are computed for the main criterion initial cost as follows:

$$\mu_{A1} = \sqrt{\left(1-(1-0.5^2)^{\frac{1}{5}} \times (1-0.67^2)^{\frac{1}{5}} \times (1-0.67^2)^{\frac{1}{5}} \times (1-0.60^2)^{\frac{1}{5}} \times (1-0.54^2)^{\frac{1}{5}}\right)} = 0.604 \tag{25}$$

$$\upsilon_{A1} = 0.4^{\frac{1}{5}} \times 0.34^{\frac{1}{5}} \times 0.34^{\frac{1}{5}} \times 0.40^{\frac{1}{5}} \times 0.40^{\frac{1}{5}} = 0.374 \tag{26}$$

Table 6 – The weights of main and sub-criteria.

Main Criteria	Local Weights of Main Criteria	Sub Criteria	Local Weights of Sub Criteria	Global Weights of Sub Criteria
Economic Performance (C1)	0.28	Initial Cost	0.48	0.136
		Running Cost	0.52	0.145
Environmental Performance (C2)	0.22	GHG Emissions	0.31	0.069
		Land Use	0.22	0.048
		Water Discharge Quality	0.25	0.056
		Solid Waste Generation	0.23	0.051
Social Performance (C3)	0.18	Impact on Public Health	0.35	0.062
		Employment Opportunities	0.21	0.037
		Training Opportunities	0.18	0.031
		Public Acceptance	0.26	0.046
Technical Performance (C4)	0.32	Energy Efficiency	0.20	0.064
		Exergy Efficiency	0.25	0.080
		Process Control	0.16	0.052
		Start Up Time	0.17	0.056
		Scalability	0.21	0.067

$$\pi_{A1} = \sqrt{\begin{array}{l}(1-0.5^2)^{\frac{1}{5}} \times (1-0.67^2)^{\frac{1}{5}} \times (1-0.67^2)^{\frac{1}{5}} \times (1-0.60^2)^{\frac{1}{5}} \times (1-0.54^2)^{\frac{1}{5}} - \\ (1-0.5^2-0.4^2)^{\frac{1}{5}} \times (1-0.67^2-0.24^2)^{\frac{1}{5}} \times (1-0.67^2-0.24^2)^{\frac{1}{5}} \times (1-0.60^2-0.30^2)^{\frac{1}{5}} \times (1-0.54^2-0.37^2)^{\frac{1}{5}}\end{array}} = 0.311 \tag{27}$$

After calculating μ, v, and π, the score function ($S(\tilde{w}^s_{A_1})$) is calculated for all main criteria by using Eq. (18). The following numerical example illustrates the calculation for the score function of A1.

$$S\left(\tilde{w}^s_{A_1}\right) = \sqrt{\left|100 \times \left[\left((3 \times 0.604) - \left(\frac{0.311}{2}\right)\right)^2 - \left(\left(\frac{0.374}{2}\right) - 0.311\right)^2\right]\right|} = 16.522 \tag{28}$$

In the following step, each of these values is divided by the sum of the score functions ($\sum_{j=1}^{5} S(\tilde{w}^s_{A_j})$) as in Eq. (19) to normalize the values and find the weights of the main criteria.

As a result, spherical fuzzy ($\tilde{w}^s$) weights, score functions, and crisp weights ($\overline{w}^s$) of alternatives, considering initial cost, are calculated as given in Table 8. The crisp values of weights of the main criteria and local and global weights of sub-criteria and alternatives are presented in Table 9. The results are visualized in Figs. 5 and 6. Here, SOFC has the highest overall weight, immediately followed by PEMFC. PAFC has the lowest overall weight, followed by MCFC. SOFC has the highest overall weight because its GHG emissions, water discharge quality, energy and exergy efficiencies, and process performance are better than those of selected fuel cells. However, SOFC has large land requirements and solid waste generation problems. PEMFC has the best performance in terms of initial and running costs, solid waste generation, public acceptance, process control, start-up time, and scalability.

On the other hand, since it has the lowest performance in GHG emissions and water discharge quality, its overall weight is slightly lower than SOFC. PAFC has the lowest performance

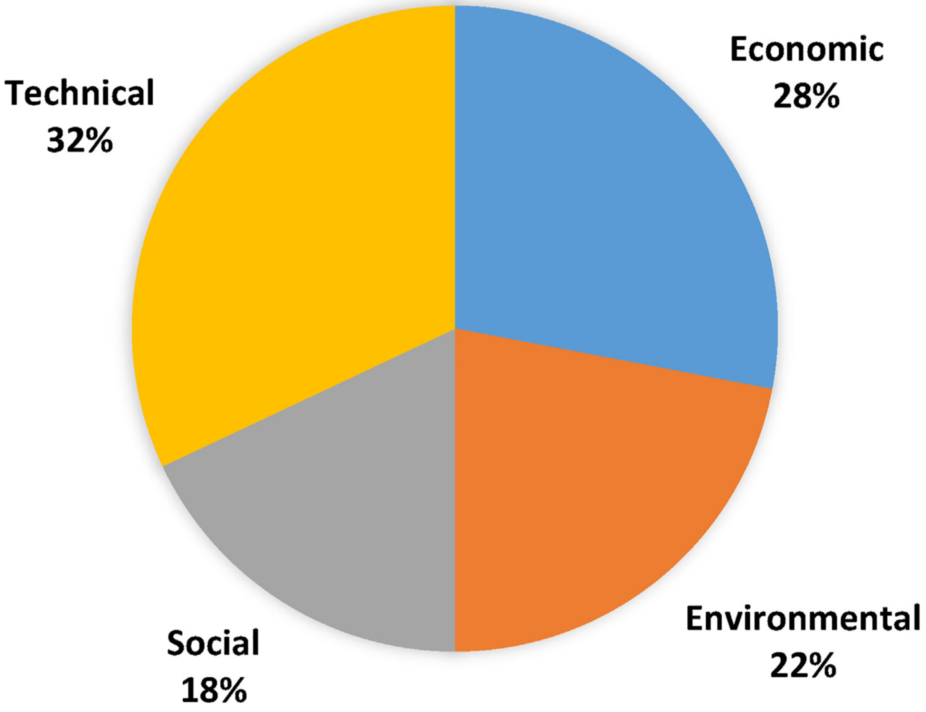


Fig. 3 – The global weights of sustainable fuel cell performance sub-criteria.

Fig. 4 – The global weights of sustainable fuel cell performance sub-criteria.

Table 7 – A sample aggregated decision matrix for the initial cost.

		A1			A2			A3			A4			A5	
A1	0.50	0.40	0.40	0.67	0.34	0.24	0.67	0.34	0.24	0.60	0.40	0.30	0.54	0.40	0.37
A2	0.34	0.67	0.24	0.50	0.40	0.40	0.55	0.42	0.34	0.49	0.50	0.34	0.41	0.64	0.24
A3	0.34	0.67	0.24	0.45	0.53	0.34	0.50	0.40	0.40	0.42	0.58	0.30	0.36	0.66	0.24
A4	0.40	0.60	0.30	0.52	0.46	0.34	0.58	0.42	0.30	0.50	0.40	0.40	0.45	0.53	0.34
A5	0.47	0.48	0.37	0.64	0.41	0.24	0.66	0.36	0.24	0.55	0.42	0.34	0.50	0.40	0.40

in terms of initial and running costs, employment and training opportunities, public acceptance, energy and exergy efficiencies, process control, start-up time, and scalability. Therefore, it has the lowest overall weight.

This study focuses on the sustainability investigation of fuel cells. Although it is critical to select the most sustainable fuel cell for the integration of hydrogen in the energy market, it is essential to produce and store hydrogen in a sustainable manner. In the literature, several studies are focusing on hydrogen production and storage. For instance, Acar et al. [43] have investigated the sustainability of six different hydrogen production options. Another example is Ghorbani et al. [62], who have investigated the potential of electrochemical hydrogen storage. For a truly sustainable future and the dominance of hydrogen in the market, hydrogen must be produced, distributed, stored, and used sustainably.

Sensitivity analysis

The highly dynamic nature of the contemporary business environment results in changing conditions in time, which may influence the experts' evaluations related to the importance of main criteria. The sensitivity analysis shows how robust the alternative selection results are to changing preferences in the main criteria. In this analysis, the weights of the main criteria are varied individually from 0 to 1 by 0.1 at a time. The other weights are changed by keeping the same proportions found in the initial results. In Fig. 7, the results of the sensitivity analysis for the main criteria are given.

Interestingly, the analysis shows that the decision is sensitive only to the changes in social performance. The reason may be the high importance conceptually attached to sustainability in recent years. For instance, although A1 is very

Table 8 – Spherical fuzzy ($\tilde{w}^s$) weights, score functions, and crisp weights ($\overline{w}^s$) of alternatives considering the initial cost.

		$\tilde{w}^s$		$S(\tilde{w}^s_{C_j})$	$\overline{w}^s$
A1	0.604	0.374	0.311	16.522	0.240
A2	0.467	0.513	0.324	12.376	0.180
A3	0.420	0.559	0.316	11.002	0.160
A4	0.499	0.475	0.338	13.229	0.193
A5	0.574	0.412	0.319	15.576	0.227

Table 9 – Local and global weights of fuel cell options regarding sub-criteria.

Sub-Criteria	Global Weights of Sub-Criteria	Crisp Local Weights of Fuel Cell Options					Crisp Global Weights of Fuel Cell Options				
		A1	A2	A3	A4	A5	A1	A2	A3	A4	A5
Initial Cost	0.136	0.240	0.180	0.160	0.193	0.227	0.033	0.025	0.022	0.026	0.031
Running Cost	0.145	0.246	0.161	0.140	0.156	0.298	0.036	0.023	0.020	0.023	0.043
GHG Emissions	0.069	0.136	0.201	0.192	0.197	0.273	0.009	0.014	0.013	0.014	0.019
Land Use	0.048	0.192	0.226	0.218	0.203	0.160	0.009	0.011	0.011	0.010	0.008
Water Discharge Quality	0.056	0.163	0.177	0.176	0.222	0.262	0.009	0.010	0.010	0.012	0.015
Solid Waste Generation	0.051	0.212	0.210	0.209	0.192	0.177	0.011	0.011	0.011	0.010	0.009
Impact on Public Health	0.062	0.231	0.148	0.163	0.236	0.222	0.014	0.009	0.010	0.015	0.014
Employment Opportunities	0.037	0.252	0.175	0.154	0.161	0.257	0.009	0.007	0.006	0.006	0.010
Training Opportunities	0.031	0.285	0.171	0.154	0.163	0.228	0.009	0.005	0.005	0.005	0.007
Public Acceptance	0.046	0.265	0.195	0.152	0.153	0.235	0.012	0.009	0.007	0.007	0.011
Energy Efficiency	0.064	0.229	0.182	0.142	0.143	0.304	0.014	0.012	0.009	0.009	0.019
Exergy Efficiency	0.080	0.235	0.201	0.145	0.139	0.279	0.019	0.016	0.011	0.011	0.022
Process Control	0.052	0.230	0.195	0.177	0.173	0.225	0.012	0.010	0.009	0.009	0.012
Start Up Time	0.056	0.236	0.222	0.177	0.179	0.185	0.013	0.012	0.010	0.010	0.010
Scalability	0.067	0.231	0.224	0.153	0.175	0.217	0.016	0.015	0.010	0.012	0.015
Overall Weights							0.226	0.188	0.164	0.178	0.244

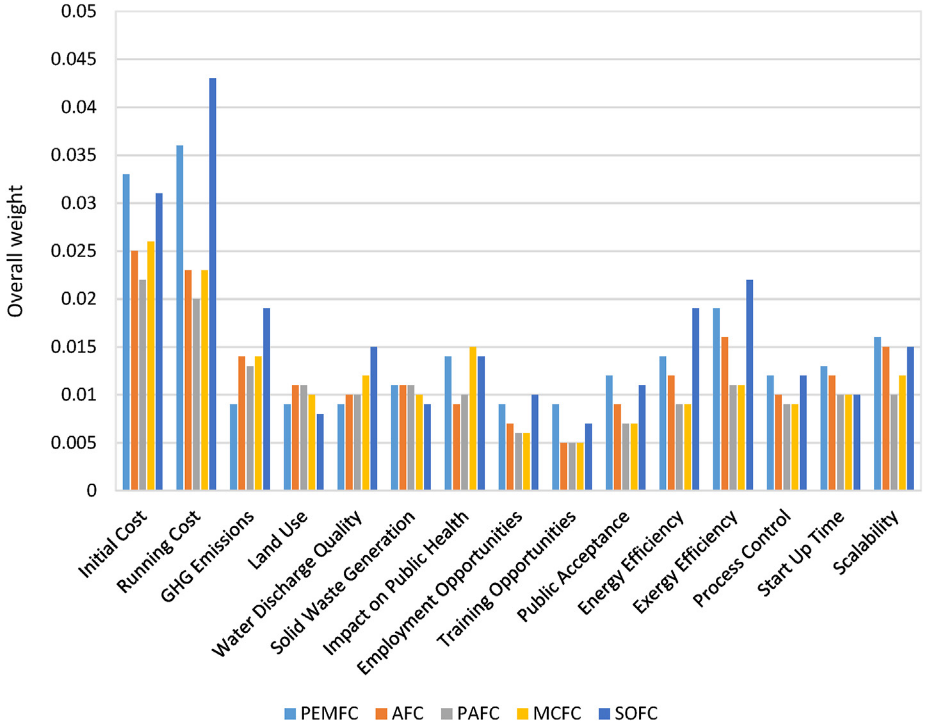


Fig. 5 – The detailed sustainability performance results of the selected fuel cells.

close to the leader at the beginning of the environmental performance sensitivity analysis (as seen in part (a) of Fig. 7), the weight of it has been dramatically decreased. At the point of 0.8, it becomes the last.

It is also noticeable that A5 has been the best alternative for all main criteria except for the further points of 0.6 at the social performance. On the other hand, A3 is the least important for all main criteria except for the further points of 0.8 at the environmental performance. The rankings are mostly affected by the changes in the importance of environmental and social performance.

In the economic performance (as seen in Fig. 7-a), and environmental performance (as seen in Fig. 7-b), the positions of A2 and A4 changed at point 0.9. The same thing occurs at point 0.6 in the social performance (as seen in Fig. 7-c) and at point 0.1 in the technical performance (as seen in Fig. 7-d).

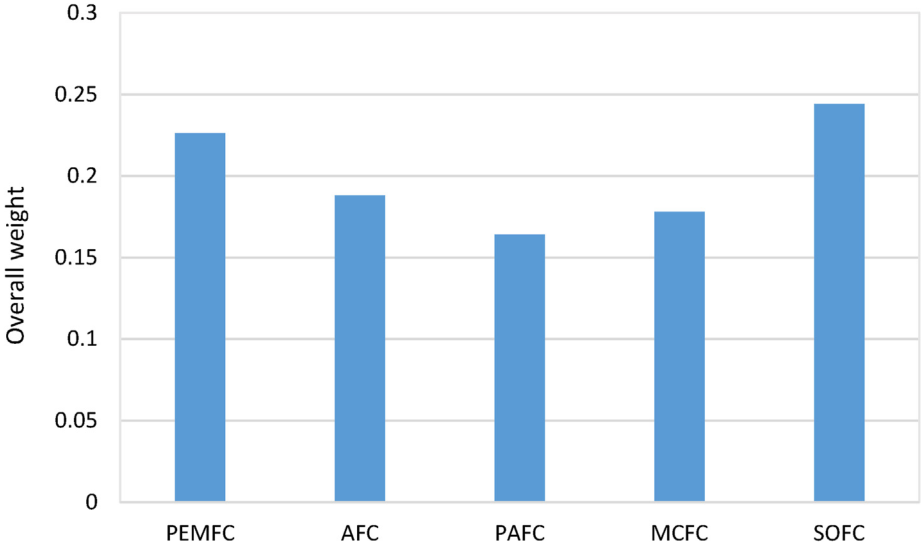


Fig. 6 – The overall sustainability weights of the selected fuel cells.

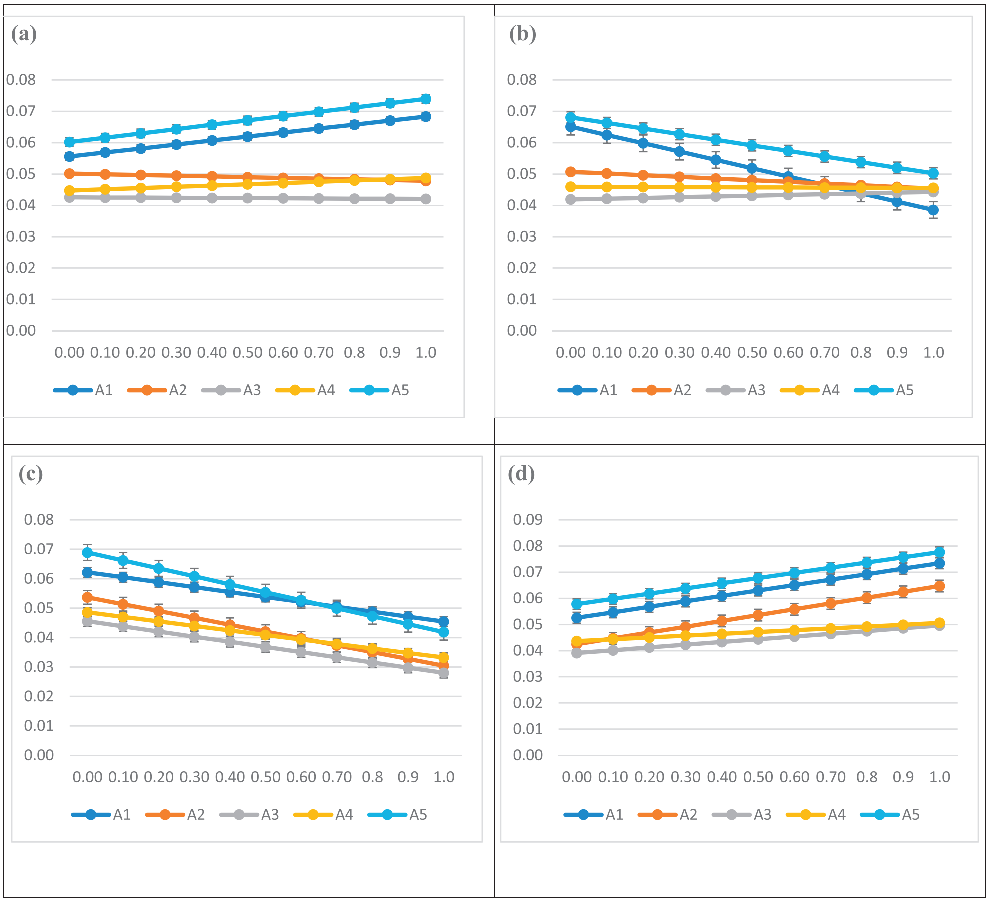


Fig. 7 – Sensitivity analysis of (a) economic, (b) environmental, (c) social, and (d) technical performance (x-axis refers to the unit increase in weights of main criteria; y-axis refers to the importance scores of alternatives).

Conclusion

This study is one of a kind example in the literature with its comprehensive and whole approach in terms of evaluating the economic, environmental, social, and technical performance of fuel cells for better sustainability. Using a novel approach called SFAHP contributes to the relevant literature by providing a model that allows experts to define their judgments comprehensively. The originality of the proposed methodology is depending on its success in dealing with uncertainties in the industry.

Here, five different fuel cells have been investigated, namely, PEMFC, AFC, PAFC, MCFC, and SOFC. The results show that when selecting the most sustainable fuel cell:

- The most critical main criterion to consider is technical performance.
- The main criterion with the lowest weight is social performance.
- Initial and running costs have the highest sub-criteria weight.
- Training opportunities have the lowest sub-criteria weight.

The comparative sustainability assessment results show that SOFC has the highest performance, and PEMFC has the second-highest performance, which is very close to SOFC. On the other hand, PAFC has the lowest performance.

The aim of this study is not only to conduct a one-of-a-kind sustainability investigation of fuel cell technologies but also to provide a comprehensive and detailed overview of their current social, economic, technical, and environmental performances. By presenting the selected fuel cell technologies' strengths and weaknesses, this study can become a guide to researchers, industry professionals, and policymakers on the next steps and possible research and development directions. Using an MCDM method, SFAHP, lets researchers utilize both qualitative and quantitative criteria simultaneously in an evaluation model. Also, a more extensive domain set coming from the spherical fuzzy set extension allows a better mathematical representation of experts' judgments. This, in turn, results in criteria weights and scores of alternatives that reflect the experts’ preferences better than the outputs of alternative methods.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature

AFC	Alkaline fuel cell
AHI	Absolutely higher importance
AHP	Analytic hierarchy process
ALI	Absolutely lower importance
APU	Auxiliary power units
CCHP	Combined cooling, heat, and power
CHP	Combined heat and power
CI	Consistency index
CR	Consistency ratio
EI	Equally Important
ELECTRE	Elimination and choice expressing the reality
FCEV	Fuel cell electric vehicles
FCV	Fuel cell vehicles
HFAHP	Hesitant fuzzy analytic hierarchy process
HFTOPSIS	Hesitant fuzzy TOPSIS
HI	High importance
LI	Low importance
MCDM	Multi-criteria decision making
MCFC	Molten carbonate fuel cell
PAFC	Phosphoric acid fuel cell
PEMFC	Polymer electrolyte membrane fuel cell
P2G	Power-to-Gas
PROMETHEE	Preference ranking organization method for enrichment evaluation
RI	Random index
SHI	Slightly Higher Importance
SI	Score Index
SLI	Slightly Lower Importance
SOFC	Solid Oxide Fuel Cell
SFAHP	Spherical Fuzzy Analytic Hierarchy Process
SWAM	Spherical Weighted Arithmetic Mean
SWGM	Spherical Weighted Geometric Mean
TOPSIS	Technique for order preference by similarity to the ideal solution
UPS	Uninterruptible power supplies
VHI	Very high importance
VLI	Very low importance

REFERENCES

[1] Donateo T, Ficarella A, Spedicato L, Arista A, Ferraro M. A new approach to calculating endurance in electric flight and comparing fuel cells and batteries. Appl Energy 2017;187:807–19.

[2] Liu X, Reddi K, Elgowainy A, Lohse-Busch H, Wang M, Rustagi N. Comparison of well-to-wheels energy use and emissions of a hydrogen fuel cell electric vehicle relative to a conventional gasoline-powered internal combustion engine vehicle. Int J Hydrogen Energy 2020;45(1):972–83.

[3] Wang S, Jiang SP. Prospects of fuel cell technologies. Natl Sci Rev 2017;4(2):163–6.

[4] Dekel DR. Review of cell performance in anion exchange membrane fuel cells. J Power Sources 2018;375:158–69.

[5] Yoshida T, Kojima K. Toyota MIRAI fuel cell vehicle and progress toward a future hydrogen society. Electrochem Soc Interface 2015;24(2):45–9.

[6] Kim DJ, Jo MJ, Nam SY. A review of polymer–nanocomposite electrolyte membranes for fuel cell application. J Ind Eng Chem 2015;21:36–52.

[7] Pandey RP, Shukla G, Manohar M, Shahi VK. Graphene oxide based nanohybrid proton exchange membranes for fuel cell applications: an overview. Adv Colloid Interface Sci 2017;240:15–30.

[8] Rosli RE, Sulong AB, Daud WRW, Zulkifley MA, Husaini T, Rosli MI, Haque MA. A review of high-temperature proton exchange membrane fuel cell (HT-PEMFC) system. Int J Hydrogen Energy 2017;42(14):9293–314.

[9] Marino MG, Kreuer KD. Alkaline stability of quaternary ammonium cations for alkaline fuel cell membranes and ionic liquids. ChemSusChem 2015;8(3):513–23.

[10] Mahato N, Banerjee A, Gupta A, Omar S, Balani K. Progress in material selection for solid oxide fuel cell technology: a review. Prog Mater Sci 2015;72:141–337. https://doi.org/10.1016/j.pmatsci.2015.01.001.

[11] Bi L, Da'as EH, Shafi SP. Proton-conducting solid oxide fuel cell (SOFC) with Y-doped $BaZrO_3$ electrolyte. Electrochem Commun 2017;80:20–3.

[12] Lototskyy MV, Tolj I, Pickering L, Sita C, Barbir F, Yartys V. The use of metal hydrides in fuel cell applications. Prog Nat Sci: Mater Int 2017;27(1):3–20.

[13] Wang Y, Leung DY, Xuan J, Wang H. A review on unitized regenerative fuel cell technologies, part-A: unitized regenerative proton exchange membrane fuel cells. Renew Sustain Energy Rev 2016;65:961–77.

[14] Wang Y, Leung DY, Xuan J, Wang H. A review on unitized regenerative fuel cell technologies, part B: unitized regenerative alkaline fuel cell, solid oxide fuel cell, and microfluidic fuel cell. Renew Sustain Energy Rev 2017;75:775–95.

[15] Alaswad A, Baroutaji A, Achour H, Carton J, Al Makky A, Olabi AG. Developments in fuel cell technologies in the transport sector. Int J Hydrogen Energy 2016;41(37):16499–508.

[16] Wang W, Lv F, Lei B, Wan S, Luo M, Guo S. Tuning nanowires and nanotubes for efficient fuel-cell electrocatalysis. Adv Mater 2016;28(46):10117–41.

[17] Das V, Padmanaban S, Venkitusamy K, Selvamuthukumaran R, Blaabjerg F, Siano P. Recent advances and challenges of fuel cell based power system architectures and control–A review. Renew Sustain Energy Rev 2017;73:10–8.

[18] Wilberforce T, Alaswad A, Palumbo A, Dassisti M, Olabi AG. Advances in stationary and portable fuel cell applications. Int J Hydrogen Energy 2016;41(37):16509–22.

[19] Wilberforce T, El-Hassan Z, Khatib FN, Al Makky A, Baroutaji A, Carton JG, Olabi AG. Developments of electric cars and fuel cell hydrogen electric cars. Int J Hydrogen Energy 2017;42(40):25695–734.

[20] Sulaiman N, Hannan MA, Mohamed A, Majlan EH, Daud WW. A review on energy management system for fuel cell hybrid electric vehicle: issues and challenges. Renew Sustain Energy Rev 2015;52:802–14.

[21] Dodds PE, Staffell I, Hawkes AD, Li F, Grünewald P, McDowall W, Ekins P. Hydrogen and fuel cell technologies for heating: a review. Int J Hydrogen Energy 2015;40(5):2065–83.

[22] Ellamla HR, Staffell I, Bujlo P, Pollet BG, Pasupathi S. Current status of fuel cell based combined heat and power systems for residential sector. J Power Sources 2015;293:312–28.

[23] Elmer T, Worall M, Wu S, Riffat SB. Fuel cell technology for domestic built environment applications: state of-the-art review. Renew Sustain Energy Rev 2015;42:913–31.

[24] Geng K, Tang H, Ju Q, Qian H, Li N. Symmetric sponge-like porous polybenzimidazole membrane for high temperature proton exchange membrane fuel cells. J Membr Sci 2021;620:118981.

[25] Liu R, Dai Y, Li J, Chen X, Pan C, Yang J, Li Q. 1-(3-Aminopropyl) imidazole functionalized poly (vinyl chloride) for high temperature proton exchange membrane fuel cell applications. J Membr Sci 2021;620:118873.

[26] Zhao J, Li X. A review of polymer electrolyte membrane fuel cell durability for vehicular applications: degradation modes and experimental techniques. Energy Convers Manag 2019;199:112022.

[27] Wang G, Yu Y, Liu H, Gong C, Wen S, Wang X, Tu Z. Progress on design and development of polymer electrolyte membrane fuel cell systems for vehicle applications: a review. Fuel Process Technol 2018;179:203–28.

[28] Sohani A, Naderi S, Torabi F. Comprehensive comparative evaluation of different possible optimization scenarios for a polymer electrolyte membrane fuel cell. Energy Convers Manag 2019;191:247–60.

[29] Sun Z, Lin B, Yan F. Anion-exchange membranes for alkaline fuel-cell applications: the effects of Cations. ChemSusChem 2018;11(1):58–70.

[30] Ran J, Ding L, Chu C, Liang X, Pan T, Yu D, Xu T. Highly conductive and stabilized side-chain-type anion exchange membranes: ideal alternatives for alkaline fuel cell applications. J Mater Chem 2018;6(35):17101–10.

[31] Liu W, Liu L, Liao J, Wang L, Li N. Self-crosslinking of comb-shaped polystyrene anion exchange membranes for alkaline fuel cell application. J Membr Sci 2017;536:133–40.

[32] Verhaert I, Mulder G, De Paepe M. Evaluation of an alkaline fuel cell system as a micro-CHP. Energy Convers Manag 2016;126:434–45.

[33] Wu M, Zhang H, Zhao J, Wang F, Yuan J. Performance analyzes of an integrated phosphoric acid fuel cell and thermoelectric device system for power and cooling cogeneration. Int J Refrig 2018;89:61–9.

[34] Açıkkalp E, Ahmadi MH. Parametric investigation of phosphoric acid fuel cell-Thermally regenerative electro chemical hybrid system. J Clean Prod 2018;203:585–600.

[35] Strickland K, Pavlicek R, Miner E, Jia Q, Zoller I, Ghoshal S, Liang W, Mukerjee S. Anion resistant oxygen reduction electrocatalyst in phosphoric acid fuel cell. ACS Catal 2018;8(5):3833–43.

[36] Ghorbani B, Mehrpooya M, Mousavi SA. Hybrid molten carbonate fuel cell power plant and multiple-effect desalination system. J Clean Prod 2019;220:1039–51.

[37] Mehrpooya M, Sayyad S, Zonouz MJ. Energy, exergy and sensitivity analyses of a hybrid combined cooling, heating, and power (CCHP) plant with molten carbonate fuel cell (MCFC) and Stirling engine. J Clean Prod 2017;148:283–94.

[38] Jokar MA, Ahmadi MH, Sharifpur M, Meyer JP, Pourfayaz F, Ming T. Thermodynamic evaluation and multi-objective optimization of molten carbonate fuel cell-supercritical CO2 Brayton cycle hybrid system. Energy Convers Manag 2017;153:538–56.

[39] Da Silva FS, de Souza TM. Novel materials for solid oxide fuel cell technologies: a literature review. Int J Hydrogen Energy 2017;42(41):26020–36.

[40] Ramadhani F, Hussain MA, Mokhlis H, Hajimolana S. Optimization strategies for solid oxide fuel cell (SOFC) application: a literature survey. Renew Sustain Energy Rev 2017;76:460–84.

[41] Oryshchyn D, Harun NF, Tucker D, Bryden KM, Shadle L. Fuel utilization effects on system efficiency in solid oxide fuel cell gas turbine hybrid systems. Appl Energy 2018;228:1953–65.

[42] Saaty T. In: The analytic hierarchy process (AHP) for decision making. Japan: Kobe; 1980.

[43] Acar C, Beskese A, Temur GT. Sustainability analysis of different hydrogen production options using hesitant fuzzy AHP. Int J Hydrogen Energy 2018;43(39):18059–76.

[44] Acar C, Beskese A, Temur GT. A novel multi-criteria sustainability investigation of energy storage systems. Int J Energy Res 2019;43(12):6419–41.

[45] Beskese A, Camci A, Temur GT, Erturk E. Wind turbine evaluation using the hesitant fuzzy AHP-TOPSIS method with a case in Turkey. J Intell Fuzzy Syst 2020;38(1):997–1011.

[46] Yildiz D, Temur GT, Beskese A, Bozbura FT. A spherical fuzzy analytic hierarchy process based approach to prioritize career management activities improving employee retention. J Intell Fuzzy Syst 2020;39(5):6603–18.

[47] Zadeh LA. Information and control. Fuzzy Sets 1965;8(3):338–53.

[48] Kutlu Gündoğdu F, Kahraman C. A novel VIKOR method using spherical fuzzy sets and its application to warehouse site selection. J Intell Fuzzy Syst 2019;37(1):1197–211.

[49] Kutlu Gündoğdu F, Kahraman C. Extension of WASPAS with spherical fuzzy sets. Informatica 2019;30(2):269–92.

[50] Kutlu Gündoğdu F, Kahraman C. A novel fuzzy TOPSIS method using emerging interval-valued spherical fuzzy sets. Eng Appl Artif Intell 2019;85:307–23.

[51] Kutlu Gündoğdu F, Kahraman C. Hospital performance assessment using interval-valued spherical fuzzy analytic hierarchy process. In: Decision Making with Spherical Fuzzy Sets. Cham: Springer; 2020. p. 349–73.

[52] Kutlu Gundogdu F, Kahraman C. A novel spherical fuzzy analytic hierarchy process and its renewable energy application. Soft Comput 2020;24:4607–21.

[53] Shanian A, Savadogo O. A non-compensatory compromised solution for material selection of bipolar plates for polymer electrolyte membrane fuel cell (PEMFC) using ELECTRE IV. Electrochim Acta 2006;51(25):5307–15.

[54] Shanian A, Savadogo O. TOPSIS multiple-criteria decision support analysis for material selection of metallic bipolar plates for polymer electrolyte fuel cell. J Power Sources 2006;159(2):1095–104.

[55] Lee S, Mogi G, Lee S, Kim J. Prioritizing the weights of hydrogen energy technologies in the sector of the hydrogen economy by using a fuzzy AHP approach. Int J Hydrogen Energy 2011;36(2):1897–902.

[56] Nikouei MA, Oroujzadeh M, Mehdipour-Ataei S. The PROMETHEE multiple criteria decision-making analysis for selecting the best membrane prepared from sulfonated poly (ether ketone) s and poly (ether sulfone) s for proton exchange membrane fuel cell. Energy 2017;119:77–85.

[57] Akash BA, Mamlook R, Mohsen MS. Multi-criteria selection of electric power plants using analytical hierarchy process. Elec Power Syst Res 1999;52(1):29–35.

[58] Barda OH, Dupuis J, Lencioni P. Multicriteria location of thermal power plants. Eur J Oper Res 1990;45(2–3):332–46.

[59] Goumas M, Lygerou V. An extension of the PROMETHEE method for decision making in fuzzy environment: ranking of alternative energy exploitation projects. Eur J Oper Res 2000;123(3):606–13.

[60] Erdoğan M, Kaya İ. A combined fuzzy approach to determine the best region for a nuclear power plant in Turkey. Appl Soft Comput 2016;39:84–93.

[61] Camci A, Temur GT, Beskese A. CNC router selection for SMEs in woodwork manufacturing using hesitant fuzzy AHP method. J Enterprise Inf Manag 2018;31:529–49.

[62] Ghorbani R, Behrangi S, Aghajani H, Tabrizi AT, Abdian N. Application of synthesized porous 3D graphene structure for electrochemical hydrogen storage. Mater Sci Eng, B 2021;268:115139.