Renewable and Sustainable Energy Reviews 199 (2024) 114543

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

Performance, emissions and economic analyses of hydrogen fuel cell vehicles

Pobitra Halder[a,*], Meisam Babaie[b], Farhad Salek[c], Kalpit Shah[d], Svetlana Stevanovic[a], Timothy A. Bodisco[e,f], Ali Zare[a,**]

[a] School of Engineering, Deakin University, Victoria 3216, Australia
[b] School of Mechanical Engineering, University of Leeds, Leeds LS2 9JT, UK
[c] Faculty of Technology, Design and Environment, Oxford Brookes University, Oxford OX3 0BP, UK
[d] School of Engineering, RMIT University, Victoria 3000, Australia
[e] Queensland University of Technology, QLD 4000, Australia
[f] School of Civil Engineering, The University of Sydney, NSW 2006, Australia

ARTICLE INFO

Keywords:
Hydrogen fuel cell vehicles
Vehicle performance
Fuel economy
Energy management
Lifecycle emissions
Economic feasibility

ABSTRACT

The transport sector is considered to be a significant contributor to greenhouse gas emissions, as this sector emits about one-fourth of global CO_2 emissions. Transport emissions contribute toward climate change and have been linked to adverse health impacts. Therefore, alternative and sustainable transport options are urgent for decarbonising the transport sector and mitigating those issues. Hydrogen fuel cell vehicles are a potential alternative to conventional vehicles, which can play a significant role in decarbonising the future transport sector. This study critically analyses the recent works related to hydrogen fuel cell integration into vehicles, modelling and experimental investigations of hydrogen fuel cell vehicles with various powertrains. This study also reviews and analyses the performance, energy management strategies, lifecycle cost and emissions of fuel cell vehicles. Previous literature suggested that the fuel consumption and well-to-wheel greenhouse gas emissions of hydrogen fuel cell-powered vehicles are significantly lower than that of conventional internal combustion vehicles. Hydrogen fuel cell vehicles consume about 29–66 % less energy and cause approximately 31–80 % less greenhouse gas emissions than conventional vehicles. Despite this, the lifecycle cost of hydrogen fuel cell vehicles has been estimated to be 1.2–12.1 times higher than conventional vehicles. Even though there has been recent progress in energy management in hydrogen fuel cell electric vehicles, there are a number of technical and economic challenges to the commercialisation of hydrogen fuel cell vehicles. This study presents current knowledge gaps and details future research directions in relation to the research advancement of hydrogen fuel cell vehicles.

Abbreviations

AFLEET	Alternative Fuel Life-Cycle Environmental and Economic Transportation
BEVs	Battery electric vehicles
CCCS	Coal with carbon capture and storage
CDCS	Charge depleting and charge sustaining
CHTC-HT	China heavy-duty commercial vehicle test cycle-heavy truck
CLTC	China light-duty vehicle test cycle
CNG	Compressed natural gas
COG	Coke oven gas

(continued on next column)

(continued)

DBSD	Depleting – blended – sustaining – depleting
DDP	Determined dynamic programming
DOE	Department of energy
DP	Dynamic programming
FLC	Fuzzy logic controller
GHG	Greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
HFCs	Hydrogen fuel cells
HFCEVs	Hydrogen fuel cell electric vehicles

(continued on next page)

* Corresponding author.
** Corresponding author.
E-mail addresses: p.halder@deakin.edu.au (P. Halder), ali.zare@deakin.edu.au (A. Zare).

https://doi.org/10.1016/j.rser.2024.114543
Received 20 December 2022; Received in revised form 28 January 2024; Accepted 5 May 2024
Available online 10 May 2024
1364-0321/

(*continued*)

HFCHEVs	Hydrogen fuel cell hybrid electric vehicles
ICE	Internal combustion engine
ICEVs	Internal combustion engine vehicles
LPG	Liquid petroleum gas
MLA	Machine learning algorithm
MLPA	Minimum loss power algorithm
MPC	Model predictive control
NEDC	New European driving cycle
NREL	National Renewable Energy Laboratory
PEM	Proton exchange membrane
PMP	Pontryagins minimum principle
RFL	Reinforcement learning
SMR	Steam methane reforming
SOC	State of charge
TTW	Tank-to-wheel
UDDS	Urban dynamometer driving schedule
WLTC	Worldwide light-duty test cycle
WTT	Well-to-tank
WTW	Well-to-wheel
WVUCITY	West Virginia University City
WVUINTER	West Virginia University Interstate
WVUSUB	West Virginia University Suburban

1. Introduction

Owing to being readily available and reliable, road transport usually utilises fossil fuels such as petrol and diesel [1,2]. Road vehicles account for about 74.5 % of transport emissions. Passenger vehicles, including motorcycles, cars, taxis and buses contribute ~45.1 % of road vehicle emissions, whereas heavy-duty trucks and lorries share about 29.4 % [3]. Currently, the decarbonisation of the transport sector is one of the prime focus areas of the vehicle manufacturing industries. A widely implemented mid-term solution is that of gasoline-bioethanol and diesel-biodiesel blends [4,5]. Some countries, including China, Brazil, the European Union, Canada and Australia, already have set gasoline-ethanol blend mandates for light-duty vehicles [6]. However, low energy density, low stability and competition with farming land and their associated emissions are major issues for using bioethanol or biodiesel-based fuels in the transport sector, including heavy-duty applications [7].

Electric vehicles, including battery/plug-in electric, fuel cell electric or hybrid electric vehicles are a promising alternative to conventional diesel or gasoline-powered vehicles due to their high efficiency, low noise, low emission and flexibility [8,9]. Plug-in electric vehicles typically charge from the main electricity grid, affecting grid functionality during peak demand and may have life cycle emissions issues, depending on the electricity generation source [10]. Considering these issues, hydrogen fuel cells (HFCs) could be another energy source for many transport applications, such as heavy-duty vehicles. HFCs use hydrogen and oxygen, converting chemical energy into electrical energy using the movement of the proton across an electrolyte membrane, as shown in Fig. 1.

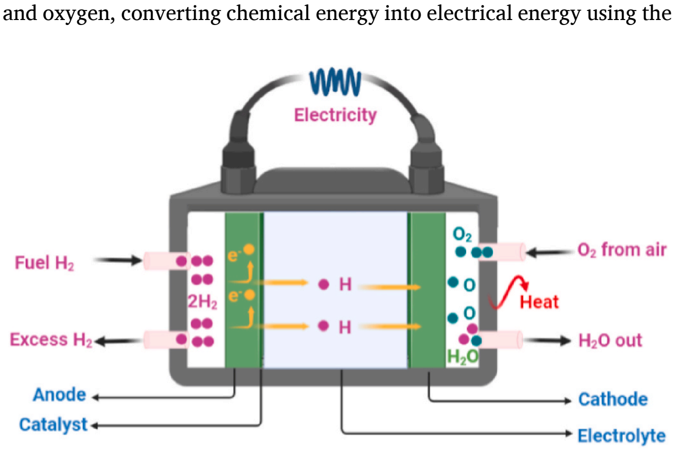

Fig. 1. Key components and working principle of a hydrogen fuel cell.

In recent years, HFCs have received significant attention and can play an important role in the transport sector [11–13]. The integration of HFCs with electric vehicle technologies can bring technological innovation for providing a clean and affordable energy solution to the transport industry and developing the hydrogen economy. Hydrogen fuel cell electric vehicles (HFCEVs) provide a number of benefits over other technologies and thereby are considered potential alternative to conventional vehicles.

- HFCs do not have any moving or frictional parts and require minimum maintenance.
- Produces only water and heat as waste products.
- The energy efficiency of HFCs is around 40–60 %.
- Increased range and comparable refuelling time when compared to diesel-powered vehicles.
- Lighter than battery-electric alternatives for same driving range and has shorter refuelling time than battery charging.
- HFCEVs convert about 60 % of the electrical energy from the source into work at the wheels while conventional diesel or gasoline-powered vehicles covert 20–30 % of fuel energy to wheel work.
- HFCEVs operate quietly even at highway speeds as they do not have any mechanical gears or combustion.
- HFCEVs reduce greenhouse gas (GHG) emissions by 50–90 % compared to gasoline vehicles, depending on the hydrogen production pathway.

Despite several environmental and economic benefits of HFCs, the successful commercialisation of hydrogen fuel cells for vehicle applications still have a number of technical and economic bottlenecks that need to be addressed [14,15]. The fuel cell itself suffer from degradation issues due to frequent change in driving pattern and temperature rise at high loading [16,17]. The challenges associated with HFC-powered vehicles include the high production cost of hydrogen, insufficient refuelling infrastructure, lack of suitable control strategies for effective vehicle operation, onboard storage of hydrogen at high pressure, high cost of the fuel cell system, fuel cell degradation and low durability of the fuel cell stack compared to the required lifetime for competing with fossil fuel-powered vehicles [15,18–22]. In addition to these general issues, there are region-specific issues which impact the life-time and performance of hydrogen fuel cells, such as weather and fine dust particulates (particularly from iron ore) [23,24]. This might challenge the effectiveness of using such technology in different regions.

Research on hydrogen is getting immense interest from the scientific community for increasing the hydrogen economy and system lifetime, and as such, research publications are growing rapidly as shown in

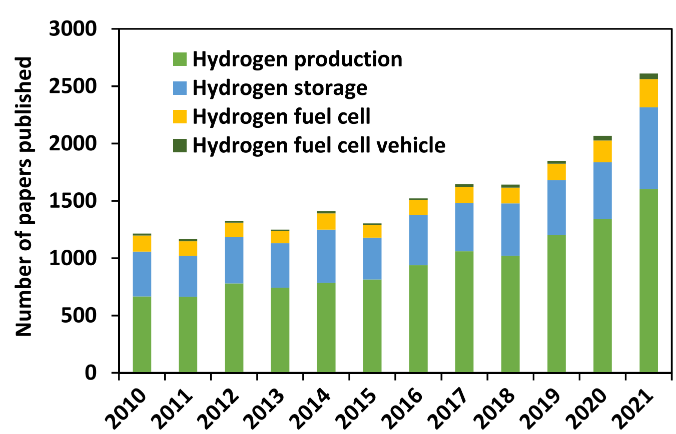

Fig. 2. Literature trend of hydrogen production, storage and application in vehicles.

Fig. 2. The ongoing research is focussing on developing low-cost technology for hydrogen production and low-cost and emerging materials for hydrogen storage and fuel cell stack for reducing the cost and enhancing the durability. The majority of the literature so far focusses on hydrogen production and storage system development. Approximately 61 % of the total literature published in 2021 was dedicated to hydrogen production, followed by research on hydrogen storage (27 %), whereas <2 % of literature focussed on HFCEVs.

A number of reviews on innovation and research progress of hydrogen production and storage systems have been published recently [25–45]. However, only very few reviews in the context of HFCEVs have been published so far [20,46–51]. These reviews have mostly discussed the fundamental description of fuel cells and different vehicle powertrains, the current dissemination status of vehicles and policies in different countries. However, there is a need in the literature for a critical review on other important aspects, including vehicle performance and energy management strategies, emissions and economic footprint, to understand the current state of technological development and formulate future research directions. Accordingly, this study explores several research questions such as (i) how the performance of HFCEVs would be compared to the other technologies, (ii) what would be the optimum energy management strategy for HFCEVs and (iii) can the economic and carbon footprint of HFCEVs be comparable to other vehicle technologies. The aim of this review work is to critically discuss the performance (modelling and experimental), progress on energy management strategies, lifecycle cost and emissions of HFCEVs, which have not been explored in the previous review works.

The structure of this work is organised as follows: Section 2 presents various fuel cell vehicle powertrains and the current global status of hydrogen fuel cell-powered vehicles; Section 3 analyses the performance of hydrogen fuel cell-powered vehicles, which includes the investigation of modelling studies, on-road trials and energy management strategies; Section 4 and 5 present the benchmarking of hydrogen fuel cell-powered vehicles with conventional internal combustion engine vehicles in terms of lifecycle emissions and cost, respectively; finally, the study recommends several future research directions in Section 6.

In this review, a systematic approach was employed to gather, identify and evaluate relevant literature through a comprehensive literature (i.e., journal, conference, books and reports) search in Google Scholar, ScienceDirect, Springer Link, Wiley Online Library, Taylor & Francis Online, IEEE Xplore and MDPI databases. A keyword search was performed initially in title and abstract followed by a full-text screening to select the most relevant literature and identify the knowledge gaps in the existing body of knowledge. The results gathered from the analyses of the literature was primarily narrative which highlighted technological advancements, challenges and areas for future research.

2. Hydrogen fuel cell integration into vehicles: various powertrains and global state-of-the-art

2.1. Hydrogen fuel cell vehicles topology

The transition from diesel engine vehicles to electric vehicle technologies such as battery electric vehicles (BEVs) or HFCEVs is promising to decarbonise the transport sector. The integration of hydrogen fuel cells into vehicles has received significant research interest in recent times due to their extended driving range, fast refuelling and high energy density compared to BEVs [52–54]. Fig. 3 depicts the benchmarking of various electric vehicle powertrains with traditional diesel engine powertrains.

Despite a number of benefits of HFC-powered vehicles over traditional internal combustion engine vehicles (ICEVs), the sole employment of HFC in vehicles still cannot meet all the technical and fuel economy requirements due to their inherent limitations as well as logistic challenges. For instance, an HFCEV is less efficient in terms of the economic aspects compared to BEVs as the cost of electricity, produced through HFC, for HFCEV is higher than that of grid electricity [54]. This high cost is associated with the current high cost of hydrogen production, hydrogen transport, storage and fuelling station infrastructure. However, the production cost of hydrogen is expected to decrease in the near future by developing scale-up production facilities from renewable resources and improving the supply chain infrastructure. Additionally, the degradation of hydrogen fuel cells is one of the key technological challenges [55,56]. Typical degradation, such as mechanical degradation, chemical degradation, membrane degradation, catalyst degradation and carbon corrosion, occur due to the transient load variation, low and high power operation and frequent start-up/shut-down cycles, leading to a reduction of lifespan compared to that of stationary applications (5000 h vs. 40000 h) [56].

HFCs can be employed as the main power source in vehicles along with other auxiliary power sources such as batteries and supercapacitors, usually known as hybrid electric vehicles. The hybridisation can be HFC-battery, HFC-supercapacitor or HFC-battery-supercapacitor. An additional power source in HFC-powered vehicles can reduce the degradation of fuel cells, enhance the fuel economy and provide power during cold starting [57,58]. The hydrogen fuel cell hybrid electric vehicles (HFCHEVs) can be either plug-in or non-plug-in types [59,60]. Fig. 4 presents a typical configuration of a HFCHEV powertrain. Non-plug-in type HFCHEVs usually use smaller-size batteries to assist with the vehicle start and fluctuations during load changes. However, plug-in type HFCHEVs use larger-size batteries for providing flexible driving ranges along with the assistance during vehicle start and load fluctuation.

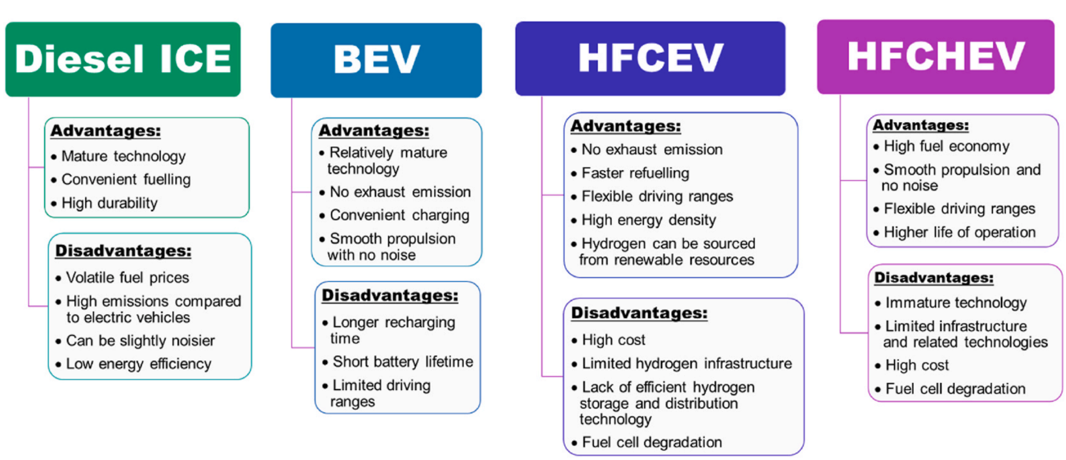

Fig. 3. Comparison of different electric vehicle powertrains with conventional diesel engines.

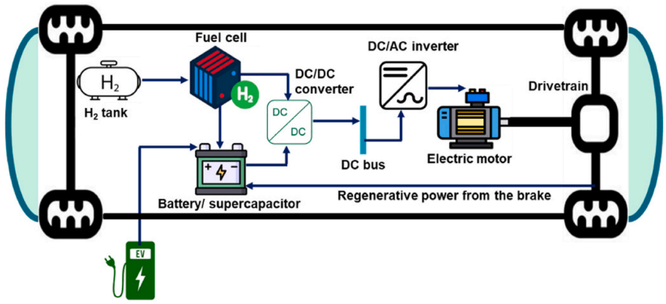

Fig. 4. Configuration of hydrogen fuel cell hybrid electric vehicle powertrain.

2.2. Global state-of-the-art of hydrogen fuel cell vehicles

Fuel cells were first invented in 1839; since then, research and development works have been continued by universities, industries and research institutions. The world's first commercial fuel cell vehicle was launched in 2014 by Toyota [61]. Fig. 5 shows a brief history of fuel cell and fuel cell-powered vehicle advancement.

HFCEVs have now entered into a golden era of improvement in the transport sector through governmental policies towards decarbonising the transport sector and industrial involvement. Hydrogen fuel cells can be used to power forklifts, public busses, and light- and heavy-duty vehicles. Light-duty vehicles can store 4–6 kg of gaseous hydrogen in an onboard tank at high pressure (70 MPa) to avoid the sacrifice of useable vehicle space, whereas heavy-duty vehicles typically store at lower pressure (35 MPa) [65].

Up to 2021, approximately 51,437 HFCEVs, consisting of 82 % cars followed by 9.2 % buses and 8.7 % trucks (medium- and heavy-duty), and 729 hydrogen fuelling stations have been in operation throughout the world [66] as shown in Fig. 6(A). South Korea is the leader in the number of vehicles used, sharing about 38 % of the global number and 56 % of Asia's total vehicles. The second top disseminator of fuel cell vehicles is the USA, accounting for about 12,358 vehicles, followed by China (8474) and Japan (6741). The number of fuel cell-powered vehicles in 2021 significantly increased by ~7.2 times compared to 2017 (7186); the increasing trend can be defined by a second-degree polynomial [66]. The increasing trend of refuelling stations from the year 2017–2021 also showed a dynamic trend as the number increased from 330 to 729 by 121 % in 2021; therefore, the trend is described in terms of a second-degree polynomial trend. Similar to the increasing trend of fuel cell vehicles and refuelling stations, the increasing trend of fuel cell vehicles per fuelling station followed a second-degree polynomial [66]. The number of fuel cell vehicles per fuelling station was 22 in 2017 and increased to 71 in 2021. The leading countries such as the USA, Japan, Europe and China have set their target as shown in Fig. 6(C) and initiated a number of national strategies to make the refuelling infrastructure more feasible and to meet the global fuel cell-powered vehicles target of ~13 million by 2030 and 400 million by 2050 [67,68]. The current numbers of fuel cell vehicles are far lower than the target numbers; therefore, a third-degree polynomial can describe the trend lines combining the current numbers of fuel cell vehicles with the future target [66], as shown in Fig. 6(D).

3. Performance analysis of HFC–powered vehicles

3.1. Modelling/simulation studies of HFC–powered electric vehicles

A number of modelling/simulation studies have focused on the investigation of HFCEVs' performance and comparison with conventional fuel vehicles in order to optimise the various strategies or vehicle design. Chao et al. [70] simulated a 3.6 kW hydrogen fuel cell-powered scooter of 115 kg in Taiwan using Caspoc software. The simulation results showed that the scooter was able to cover a mileage of 80 km at a constant speed of 30 km/h with hydrogen consumption of 1.6 g H_2/km and fuel economy of 1.34 g/km on hydrogen when compared to a gasoline-powered scooter. The maximum speed limit tested for this scooter was 50 km/h. Han et al. [71] simulated a one-stack fuel cell hybrid passenger car using the parameters of a fourth-generation fuel cell prototype vehicle developed by Tongji University. The simulation results showed 265.3 g hydrogen consumption per New European driving cycle (NEDC) and 2252.82 g hydrogen per 100 km within the entire driving range. Fig. 7 presents the effects of the state-of-charge (SOC) of the battery and various driving cycles on the hydrogen consumption obtained from the modelling studies. Xu et al. [72] observed that the consumption of hydrogen increased linearly with the SOC of the battery and, thereby, the operation cost. Song et al. [73] also noted a similar linear correlation between SOC and hydrogen consumption. Sun et al. [74] reported that the hydrogen consumption of fuel cell-powered cars varies from one driving cycle to another, which depends on several

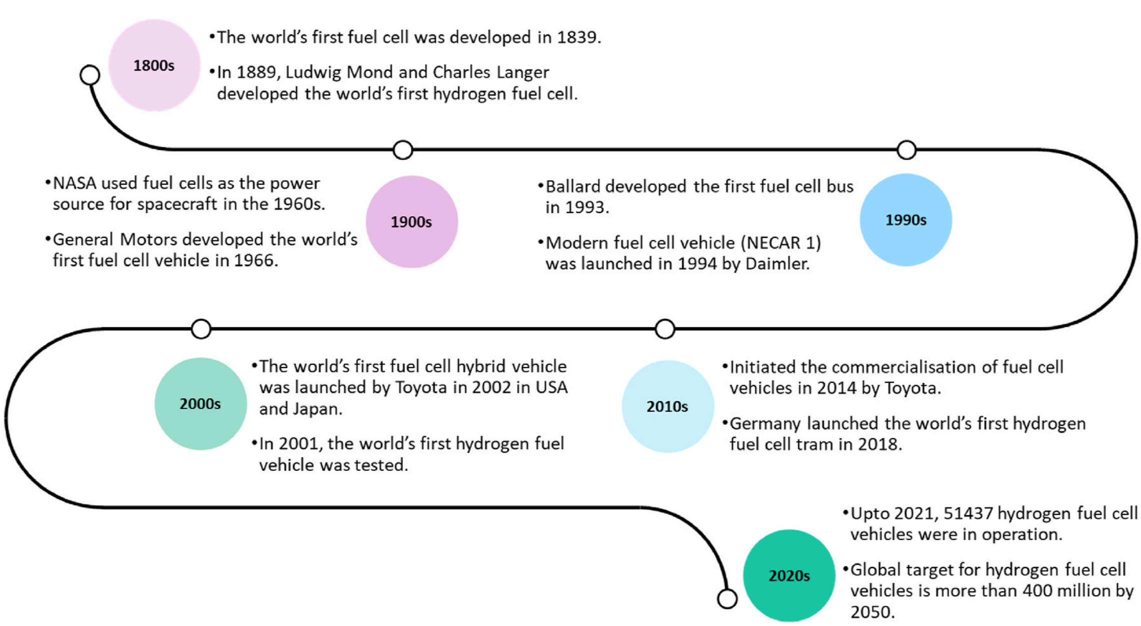

Fig. 5. key milestone on fuel cell and fuel cell-powered vehicle development (data from Refs. [61–64]).

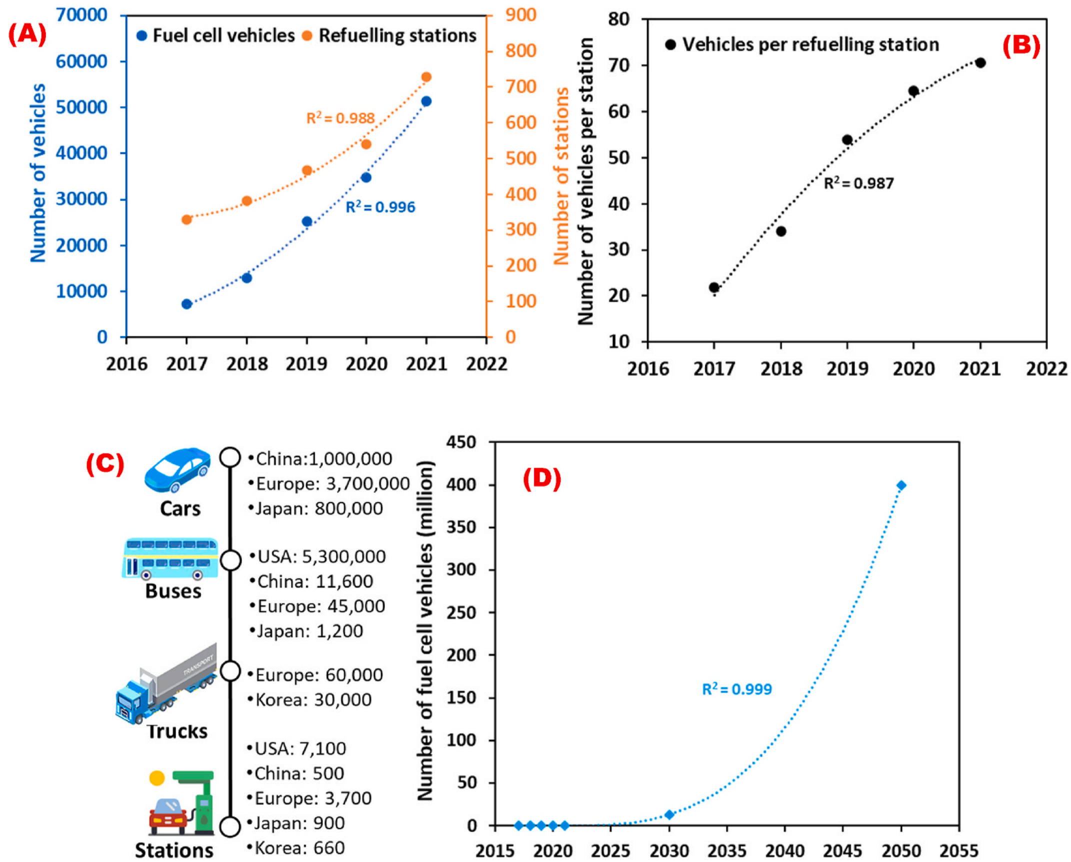

Fig. 6. (A) status of fuel cell vehicle and hydrogen refuelling station (data from Refs. [66,68,69]), (B) vehicles per station (data from Refs. [66,68,69]), (C) 2030 target of HFCEVs and refuelling stations by some key countries and (D) Combination of real and target number of fuel cell vehicles.

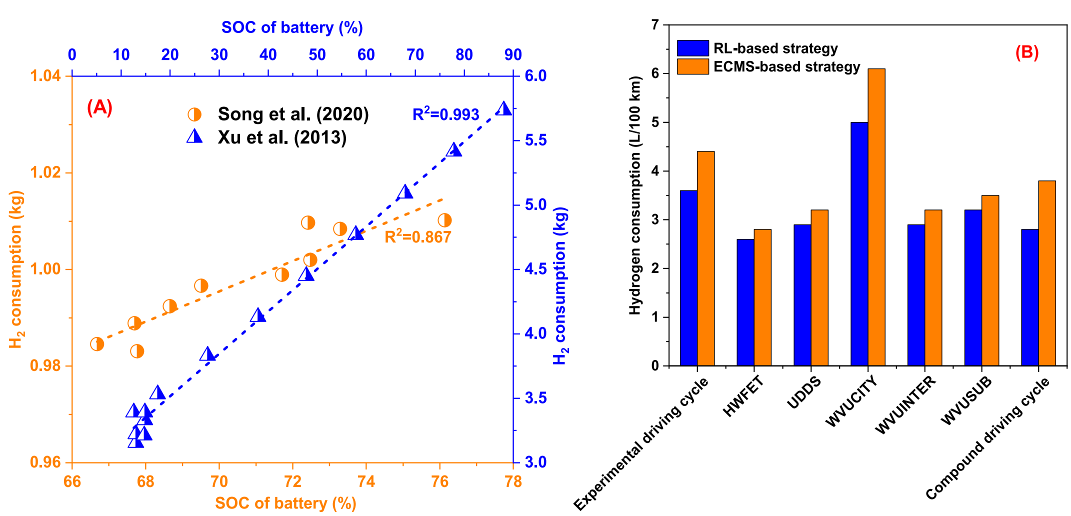

Fig. 7. (A) Effect of SOC on hydrogen consumption (data from Refs. [72,73]) and (B) effect of driving cycle on hydrogen consumption (data from Ref. [74]).

factors, including driving speed and braking energy. The capacities of fuel cell, battery and ultracapacitor, considered in the modelling, were 10 kW, 25.6 kWh and 0.32 kWh, respectively. Ahmadi et al. [17] estimated that the hydrogen consumption per 100 km for highway driving cycle (1514.2 g) was about 9 %, 27 % and 43 % less than that of urban dynamometer driving schedule (UDDS), City of Surrey and New York driving cycle, respectively. Changizian et al. [75] also noted a significant variation in fuel economy among different driving cycles.

Lewis et al. [76] modelled a hybrid delivery van using MATLAB/-Simulink software and the Powertrain System Analysis Toolkit and performed the estimation of vehicle performance for a case in the USA context. They concluded that a 32 kW fuel cell with a 49 kWh battery system and 15 kg hydrogen storage system would be sufficient for Class 6 walk-in delivery vans for a 100–200 km long route. D'Ovidio et al. [77] investigated the effects of the flywheel energy storage system on the performance of HFCEV through the simulation of a city bus with a capacity of 15 passengers over the European urban standard drive cycle. The power of the flywheel energy storage system was about 41.4 % of the electrical energy (1.607 MJ) required to complete the cycle, and the rotational speed of the flywheel increased when the fuel cell power was higher than that of traction power. Zhao [78] established a dynamic model of a gear transmission system for a hydrogen fuel cell-powered car and optimised it using MATLAB/Simulink software to enhance the performance and economy. The optimised gear transmission system increased the speed by 3 % and 4 % under no load and full load conditions, respectively, while the energy consumption was reduced by 3.5 % and 3 % for those conditions respectively.

Turkmen et al. [79] modelled HFC-powered vehicles using Advanced Vehicle Simulator (ADVISOR), developed by National Renewable Energy Laboratory (NREL), in Simulink/Matlab interface. The HFC-powered vehicle with 30 kW and 50 kW fuel cell consumed 123 L H_2 (8.3 L gasoline equivalent)/100 km and 194.6 L H_2 (13.2 L gasoline equivalent)/100 km, respectively. The equivalent gasoline of hydrogen consumed by an HFC-powered vehicle was ~27.1 % less than gasoline (in L) consumed by a gasoline vehicle, irrespective of the fuel cell capacity. Changizian et al. [75] simulated hydrogen fuel cells/battery/ultracapacitor hybrid electric cars for various driving cycles using Amsim software and investigated the vehicle performance. The model reported a reduction of 3.3 % hydrogen consumption and 20.2 % SOC in the battery pack due to the inclusion of an ultracapacitor. Lane et al. [80] modelled a plug-in HFC-powered electric car in the context of California using the FASTSim vehicle simulator developed by the NREL to investigate the performance and fuel economy of the vehicle. The input parameters in the FASTSim simulator were 13 kWh battery storage, 4 kg hydrogen storage, 75 kW fuel cell power and 1665 kg vehicle mass. According to the simulation, the total driving range, hydrogen consumption, average electric efficiency and charge-depleting efficiency were 341 miles, 12.195 g H_2/mile, 0.203 kWh/mile and 0.322 kWh/mile, respectively. The simulation also suggested that a gasoline internal combustion engine (ICE) car consumed ~80 g of gasoline per mile. Compared to the HFC-powered electric car, the plug-in HFC-powered hybrid electric car consumed ~30.7 % less hydrogen per km millage. Hienuki et al. [81] studied the input-output-based model for analysing the lifecycle energy consumption of a HFC passenger car and reported about 1.8 MJ/km less energy consumption by the HFCEV compared to that of a similar-sized gasoline vehicle (large car of 1690 kg weight). Medium sized (1250 kg) gasoline ICE car consumed same amount of energy as of the HFC-powered car; however small sized (940 kg) gasoline ICE car consumed 1.2 MJ/km less energy than the HFC-powered car. Vehicle manufacturing contributed 64 % of total energy consumption for the HFC-powered car compared to 33 % for the gasoline ICE car. Vehicle usage shared 50 % of total energy consumption for the gasoline ICE car, while it is 19 % for the HFC-powered car.

A number of studies [81–86] have investigated the well-to-wheel (WTW) energy consumption of HFCEVs using the Argonne National Laboratory developed Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model in different countries. Although the energy consumption in MJ/kg was different from one study to another due to the variation in driving cycles, hydrogen production pathway and other considerations, all studies exhibited a significant reduction in energy consumption by HFCEV (~29–66 %) when compared to a conventional ICEV, as shown in Fig. 8. A contradiction of this observation was reported by Li and Kimura [87] where they demonstrated a significant increase in energy consumption per km with a hydrogen fuel cell car and truck compared to gasoline ICEVs with an exception for a hydrogen fuel cell bus, in the Association of Southeast Asian Nations context. The higher energy consumption by HFCEVs over gasoline ICEVs can be attributed to the high energy losses/consumption in hydrogen production and transport pathways.

Joseck et al. [88] performed a WTW energy analysis of an HFCHEV with different hydrogen sources, such as natural gas, coal with carbon capture and storage (CCCS) and coke oven gas (COG) and made a comparison to gasoline and diesel vehicles using GREET simulation model. The energy consumption per mile for HFCHEVs was nearly similar to gasoline and diesel hybrid vehicles; however, approximately 32.6–49.8 % lower than that of gasoline-only vehicles (depending on the hydrogen source) due to the reductions in energy use during vehicle operation. Tanç et al. [89] modelled an HFC-powered electric car and an HFC-powered hybrid electric car equipped with a traction battery of capacity of 15 kW using AVL Cruise software and investigated the energy distribution for the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) driving cycle. The energy consumption of HFCHEVs was 8 % less than that of HFCEVs (3.701 kWh vs 4.07 kWh), while the hydrogen consumption was 32 % lower (0.701 kg/100 km vs 1.125 kg/100 km). Another study also reported an ~8.3 % increase in fuel economy due to the hybridisation of the powertrain [90].

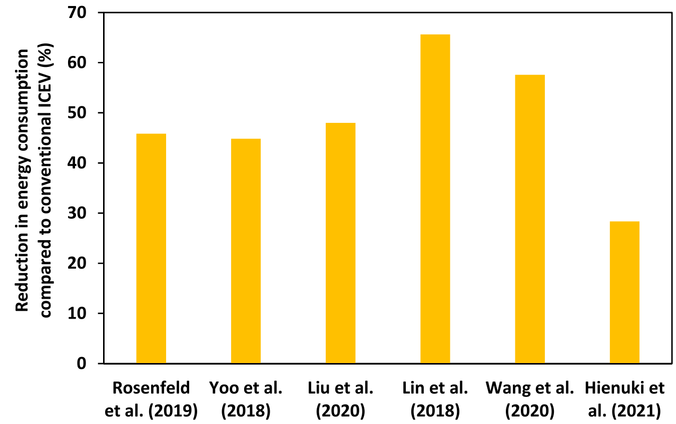

Fig. 8. Reduction in energy consumption by HFCEV compared to that of conventional ICEV.

Kast et al. [91] simulated the performance of medium- and heavy-duty fuel cell trucks using the Autonomie vehicle model from Argonne National Laboratory, considering the truck dimensions, tank design, drive cycles and average payload in order to assess the suitability of the transition from diesel trucks to hydrogen fuel cell trucks in the USA. The trucks required 25 kg or less hydrogen and 180 kW or less fuel cell power to meet daily range and performance needs, as well as to meet the vehicle range requirements of 95–100 % of the routes. Abouelkhair et al. [92] also analysed the energy distribution in a hydrogen fuel cell-powered medium-duty truck using AVL Cruise software and compared it with that of a conventional truck using the Urban Driving Cycle. The power consumption of the hydrogen fuel cell-powered truck was 68 %, 30 %, and 7.12 % less than a conventional truck at low, moderate, and high cruising speeds, respectively.

Therefore, the hybridisation of HFCEVs can be more efficient in terms of energy consumption and fuel economy compared to pure fuel cell vehicles, a modality that demands more investigation.

3.2. Experimental/on-road investigations of HFC–powered electric vehicles

The USA department of energy (DOE) conducts research and development works on on-road testing of HFCEVs through a number of laboratories, including Argonne National Laboratory, Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, National Energy Technology Laboratory, NREL, Pacific Northwest National Laboratory and Sandia National Laboratories for improving the performance and durability of vehicle systems. The NREL has completed the on-road evaluation of 230 HFCEVs manufactured by different companies, including Honda, General Motors, Hyundai, Nissan, Mercedes-Benz and Toyota since 2006 after starting the USA DOE Fuel Cell Technologies Office Learning Demonstration project in 2005 [93]. The aim of the on-road testing was to benchmark the HFCEVs against DOE technical targets and typical gasoline vehicle operation as depicted in Fig. 9. The key parameters considered for the on-road evaluation included fuel economy, durability, efficiency, range, system specification, fuelling performance, energy management and emissions.

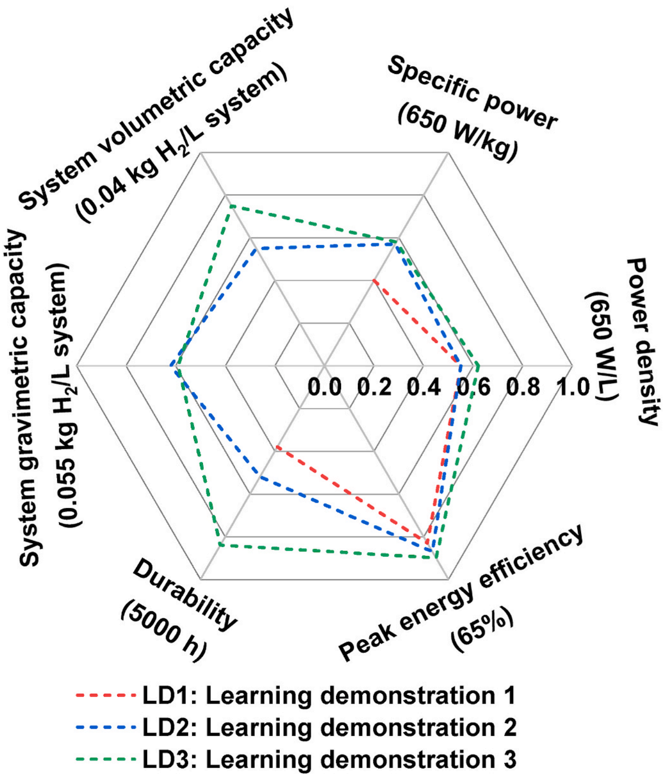

Fig. 9. On-road evaluation results of HFCEV in relation to the DOE target (in parentheses) (redrawn from Kurtz et al. [93]).

In 2002–2003, the fuel economy of HFCEVs was tested at the United States EPA National Vehicle and Fuel Emissions Laboratory and they proposed three methods for estimating hydrogen consumption [94]. Xie et al. [95] developed a test bed for an HFCHEV powertrain with a 10 kWh $LiFeO_4$ battery pack for validating the control strategy, proposed for minimising hydrogen consumption. Weigl et al. [96] designed and developed a hydrogen fuel cell-powered motorcycle with a fuel cell capacity of 7 kW for South East Asia. The performance of the motorcycle was tested at the "South African Solar Challenge" road rally and reported lower energy consumption for a fuel cell powered motorcycle (2.41 L petrol equivalent) than that of petrol motorcycles (3.15–4.1 L) for 100 km millage with a daily average speed of 70 km/h. On-road testing of an HFC-powered scooter in Taiwan showed that the scooter with a 3 kW proton exchange membrane (PEM) fuel cell consumed 1.2 g H_2/km at a speed of 30 km/h [97]. The HFC-powered scooter consumed 35 % less energy than of the equivalent gasoline ICE scooter.

Mubenga and Stuart [98] investigated the feasibility of an HFCHEV powered by hydrogen produced primarily by solar energy. They obtained about a 183 % increase in driving range for a Kronosport electric vehicle when integrated with HFC. Venturi et al. [99] reported the real testing experience of an HFC-powered Mercedes-Benz car for more than 3.3 million kilometres in the USA and Europe in 2001 and reported ~1 kg H_2/100 km and ~1.11 kg H_2/100 km consumption by the car in the USA and Europe, respectively. Following their previous study [76], Lewis et al. [100] later validated the model through the demonstration of a prototype vehicle and observed a variation within 5 %. The University of Texas, in collaboration with the "Center for Transportation and the Environment and Unique Electric Solutions", converted 16 diesel-powered parcel delivery vans to fuel-cell hybrid vehicles in 2017 [76]. The average hydrogen consumption was estimated to be 9.92–10.02 kg and 5.89–6.11 kg for HTUF Class 6 P&D and Sacramento driving cycle, respectively, depending on the fuel cell and battery capacity. A small single-operator HFCEV with a fuel cell capacity of 20 kW and a fuel tank capacity of 5.8 L was fabricated at Kanagawa Institute of Technology, Japan for university education purposes and they experimentally investigated the performance [101]. The required driving power at a constant speed of 3.57 km/h was estimated at about 7 W. In another study, Takahashi validated a control algorithm for determining optimum cruising speed based on remaining hydrogen and distance to destination using a 1 kW HFCEV experimental setup [102]. Şefkat and Özel [103] experimentally validated a fuzzy logic-based energy management model for hydrogen fuel cell/battery hybrid electric vehicles and reported around a 7–11 % increase in energy efficiency, depending on the ambient temperature.

A prototype of a hydrogen fuel cell-powered racing car was designed, developed and tested by a team named "HydRU Racing Team" at the University of Ruse, Bulgaria [104]. According to the trial, the car ran approximately 116 km on 1 m^3 of hydrogen at an average speed of 35 km/h. Martel et al. [105] tested a hydrogen-fuelled light-duty truck with a 271 kg pack of nine 8 V "deep cycle" lead-acid batteries for validating the proposed dynamic model for the management of battery degradation and found good agreement between the model and experimental data. Şefkat and Özel [106] experimentally validated the energy and thermal management model for a mini-hydrogen fuel cell-battery hybrid electric vehicle and noted an approximate 9.1 % reduction in total energy consumption and around 7–11 % increase in energy efficiency depending on the ambient temperature. REVA Electric Car Company developed a hydrogen fuel cell-powered prototype pick-up vehicle with a 1 kW DC motor and 200 Ah lead acid batteries [107]. On-road testing of the prototype vehicle exhibited a power requirement between −1 and 7 kW during the drive, depending on the road conditions and driver. Lohse-Busch et al. [108] performed laboratory testing of a 2016 Toyota Mirai hydrogen fuel cell car using the cold-start North American city drive cycle to investigate the performance of the vehicle. The average vehicle efficiency for the fuel cell vehicle was 62 % compared to 23 % for an equivalent conventional vehicle. The energy consumption at 35 °C (321 Wh/km) was approximately 57.5 % lower than that of −18 °C (758 Wh/km). Recently, the BMW group has started field testing the BMW i Hydrogen NEXT prototype in everyday conditions on European roads to investigate the performance in real-life conditions and is expected to launch this model in late 2022 [109]. Table 1 shows the summary of some key features of HFCEVs currently available in the market.

Laboratory and on-road testing of PEM fuel cell/battery hybrid electric vehicles showed that a hybrid power source was able to meet vehicular energy requirements [110]. Li et al. [111] experimentally investigated the degradation behaviour of the fuel cell system of a plug-in hydrogen fuel cell city bus with a fuel cell capacity of 60 kW and a mass of 80 tons. According to the demonstration operation in China, the average voltage of the fuel cell declined at a rate of approximately 346 mV/h. Tsinghua University developed the first Chinese hydrogen fuel cell/battery hybrid city bus of mass 11600 kg and fuel cell of 100 kW with its partners and completed a 3000 km on-road testing in Beijing in 2004 [112]. The hydrogen consumption of the bus was about 9.68 kg H_2/100 km at a maximum speed of 69.7 km/h. The Research Center for Advanced Science and Technology at Mingdao University in Taiwan developed a light weight HFCEV named Mingdao hydrogen vehicle with a 5 kW PEM hydrogen fuel cell [113]. The performance of the vehicle was tested at the "2004 Taiwan Flower Exposition", and the road test revealed that the vehicle could achieve a maximum velocity of 40 km/h.

Wang et al. [117] experimentally examined the performance of fuel cell vehicles under different drive cycle conditions, including NEDC, worldwide light-duty test cycle (WLTC) and China light-duty vehicle test cycle (CLTC) in the context of China. The hydrogen consumption of CLTC was lower than that of the other driving cycles and ordered as CLTC (0.93 kg/100 km) < NEDC (0.98 kg/100 km) < WLTC (1.05 kg/100 km). Sun et al. [118] also experimentally investigated the effects of constant speed and China heavy-duty commercial vehicle test cycle-heavy truck (CHTC-HT) driving cycle on the driving range, hydrogen and energy consumption of a hydrogen fuel cell truck. The experimental results demonstrated that the hydrogen and electricity

Table 1
Summary of HFCEVs currently available in the market [114–116].

Vehicle model	Driving cycle	Driving range (km)	Fuel tank capacity (kg)	Motor capacity (kW)	FC capacity (kW)	Hydrogen consumption (g/km)
Passenger car						
Toyota MIRAI II	Combined	650	5.6	137.2		7.6
Toyota MIRAI	Combined	650	5.6	137.2		7.6
Hyundai NEXO	Combined	756	6.33	120		8.4
Honda Clarity FC		589	5	130		
Hyundai ix35	NEFZ	594	5.64	100		10
Transporter						
Citroën ë-Jumpy Hydrogen	WLTP combined	400	4.4	100	45	
PEUGEOT e-Expert Hydrogen	WLTP combined	400	4.4	100	45	
Opel Vivaro-e HYDROGEN	WLTP combined	400	4.4	100	45	
HOLTHAUSEN HyMax-75	WLTP combined	350	6	72	40	20
HOLTHAUSEN HyMax-80	WLTP combined	300	6	72	40	20
QUANTRON QLI FCEV	WLTP combined	500	8.2	100	45	
Truck						
FAUN Bluepower		250	16.1	240	90	
FAUN City Power		500	32	140	90	
Hyundai Xcient FC		400	30.08	350	180	
QUANTRON QHM FCEV	WLTP combined	700		500	120	
T680 FCV		725	58.8	309.5		
HYZON HYHD8-200	Hyzon internal testing	563	50	275	200	
HYZON HYHD8-110	Hyzon internal testing	563	50	275	110	
HYZON REFUSE TRUCK		201	25	240	110	
HYZON HYMAX 24 tonne		400	30	160	80	75.19
HYZON HYMAX 46 tonne		680	50–60	190–295	110–200	103.09
HYZON HYMAX 70 tonne		600	50–60	190–295	110–240	153.85

consumption per 100 km increased by approximately 52 and 60.4 %, respectively, under the CHTC-HT driving cycle scenario when compared with those of the 40 km/h constant speed driving cycle scenario. The driving range under the CHTC-HT scenario was reduced by 43.5 % when compared to that of the constant speed scenario.

Therefore, it can be concluded that the driving cycle significantly affects the vehicle's fuel economy, efficiency and driving range and thereby, any reasonable comparison should consider the drive cycle scenarios that resemble real-world driving conditions or perform on-road evaluations.

3.3. Energy management strategies for HFCHEV

In an HFCHEVs powertrain, the hydrogen fuel cell is used as the primary power source, and a battery and/or supercapacitor system is used as the auxiliary power source for the drive system. Energy cost from each of the power sources along with the aging of fuel cell and battery affect the performance of HFCHEVs and their overall implementation. The aging of fuel cell and battery arises due to chemical and mechanical degradation and reduces the lifespan of the power sources [119]. Hydrogen consumption or fuel economy and source aging are important operational parameters which require real time optimisation. Therefore,

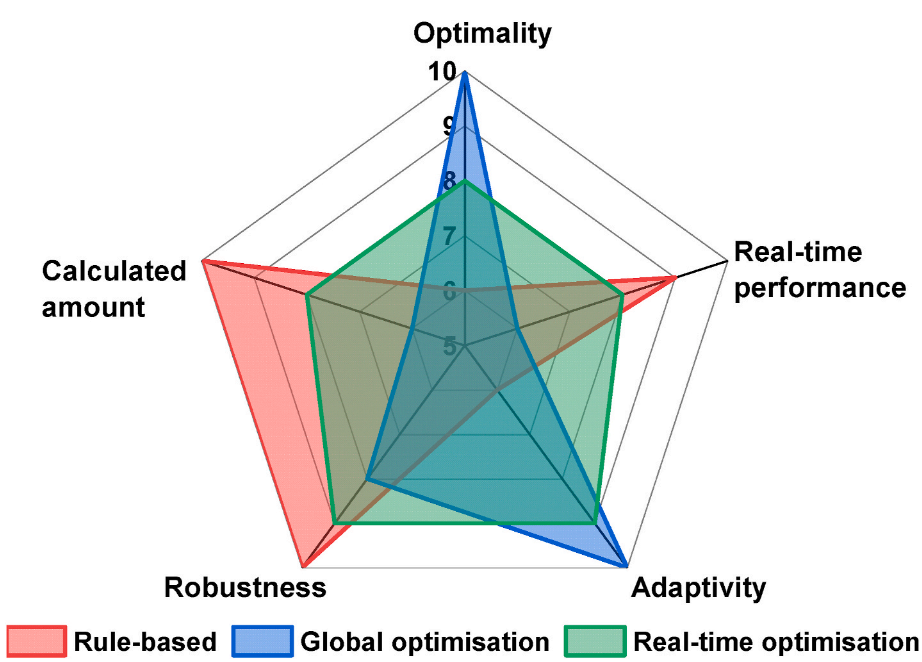

Fig. 10. Performance of the energy management optimisation strategies (modified and redrawn from Teng et al. [121]).

energy management strategies are being employed in the HFCHEVs for assigning the power distribution between the fuel cell and auxiliary power sources, controlling the operation of the power sources as well as mitigating the source aging. In the supervisory level control, the distribution of loads into multiple power sources is maintained while the low-level controllers follow the points set by the supervisory controllers [120]. The implementation of efficient and robust energy management strategies can maximise the fuel economy, performance and lifespan of the power sources, as well as help to retain the battery charge for a longer time. The optimisation strategies can be global, real-time or rule-based. The most commonly used optimisation algorithms for controlling the energy management in HFCHEVs include dynamic programming (DP), pontryagins minimum principle (PMP), fuzzy logic controller (FLC) and equivalent consumption minimisation. The performance comparisons of the optimisation strategies are shown in Fig. 10.

DP optimisation has been employed by a number of studies in order to reduce energy consumption and enhance fuel cell lifespan [122–127]. Zohu et al. [125] developed an open DP software package-based on MATLAB Object Oriented Programming and compared it with basic DP and level-set DP. The optimisation problem was solved by setting the fuel cell power, battery SOC, gears and working modes as state variables. The proposed open DP method outperformed the basic DP and level-set DP models in terms of calculation time and computational accuracy. Optimisation using the open DP method resulted in a 3.7 % and 1.4 % lower hydrogen consumption compared to that of the level-set DP and basic DP optimisation, respectively, as presented in Table 2. Tao et al. [126] reported 18.4–21.7 % lower hydrogen consumption with the DP-based strategy compared to the state machine strategy for a fuel cell hybrid tramway. Ravey et al. [124] investigated the performance of the DP algorithm-based offline strategy and FLC-based online strategy and compared it with the on-road testing of HFCHEV. The DP-based energy management strategy exhibited about 36.5 % and 18.4 % lower hydrogen consumption using the same driving cycle compared to that of the FLC and optimised FLC-based strategy, respectively. The experimental benchmarking suggested 24 % higher hydrogen consumption than the simulation owing to a lack of penalty for hydrogen purge in the fuel cell model during the simulation. A novel rule-based strategy was developed by Chen et al. [123] from the DP solution to enhance fuel economy. The proposed model was capable of maintaining the SOC of the battery near 95 % during the charge-sustaining period.

Xu et al. [122] proposed a determined dynamic programming (DDP)-based novel real-time optimal energy management strategy, called charge depleting – blended – sustaining – depleting (DBSD), and compared with DDP and charge depleting and charge sustaining (CDCS) strategies. The operating cost with the DBSD strategy was 6.4 % lower compared to that with the CDCS strategy and 3.4 % higher compared to that with the DDP strategy. The study also reported that the SOC significantly affected the operation cost; the operation cost per 100 km driving distance increased by 28.7 % (from 496 to 638.5 Sig. $) when the SOC increased from 10 % to 90 %. The validation of the DBSD strategy was investigated through the on-road performance testing of Singapore Bus Route 179. The hydrogen consumption in real vehicle testing was 10.6 % higher than that of the simulation value. Xu et al. [130] proposed a DP-based energy management strategy for HFCHEVs for simultaneous optimisation of hydrogen economy and system durability. The model was further integrated with multi-objective optimisation for sizing the parameters of the vehicle in the China context. The simulation results suggested a 150 Ah battery and 40 kW fuel cell for a China city typical bus cycle. Hu et al. [131] also minimised source aging and hydrogen consumption using DP-based energy strategy. The lifecycle cost of the system was improved significantly due to the prolonged service life of fuel cell. The model was further validated in a three months demonstration operation of a fuel cell city bus.

Minimum loss power algorithm (MLPA)-based instantaneous strategy reduced hydrogen consumption by a 35.9 % for a dual-stack fuel cell hybrid vehicle within NEDC compared to a one stack fuel cell hybrid vehicle [71]. Min et al. [132] proposed a genetic algorithm-optimised neural network-based energy management strategy for HFCHEVs under start/stop conditions and observed a 33 % reduction in hydrogen consumption as well as an enhancement in fuel cell lifespan. Air flow global extremum search algorithm-based load servo control loop and optimised loop strategy also improved the hydrogen economy for HFCHEVs [133].

Considering the good real-time controllability advantage of a wavelet-based model, Erdinc et al. [134,135] proposed an integrated strategy consisting of wavelet-based load sharing and a fuzzy logic-based control algorithm for energy management of fuel cell/ultra-capacitor hybrid vehicles and fuel cell/battery/ultra-capacitor hybrid vehicles. The simulation was performed using the MATLAB, Simulink and SimPowerSystems environments. The energy management strategy ensured the operation of the fuel cell in part loading conditions avoided transients and sharp peak loads, leading to the enhancement of the lifespan and efficiency of the fuel cell. Hydrogen consumption of the fuel cell/battery/ultra-capacitor

Table 2
Summary of energy management studies.

Key considerations	Software	Algorithm	Key findings	Reference
Vehicle mass: 2000 kg; Drive ratio: 8.298; Battery capacity: 16 Ah; Fuel cell power: 45 kW	MATLAB/ Simulink	Level-set DP	H_2 consumption: 1065.60 g/100 km; Calculation time: 48.1126 s	[125]
		Basic DP	H_2 consumption: 1040.96 g/100 km; Calculation time: 28.7839 s	
		Open DP	H_2 consumption: 1026.19 g/100 km; Calculation time: 22.3491 s	
Vehicle mass: 15000 kg; Mass factor: 1.1; Battery capacity: 180 Ah; Fuel cell power: 40 kW; SOC: 10 %	MATLAB/ Simulink	CDCS	H_2 consumption: 10965.91 g/100 km	[122]
		DBSD	H_2 consumption: 10227.27 g/100 km	
		DDP	H_2 consumption: 9886.36 g/100 km	
Vehicle mass: 13000 kg; Mass factor: 1.1; Drive ratio: 6.3; Battery capacity: 175 Ah; Fuel cell power: 60 kW; Gear ratio: 1.65	MATLAB/ Simulink	PMP	H_2 consumption: 4800 g/100 km	[72]
Vehicle mass: 2000 kg; Battery capacity: 8 Ah; Fuel cell power: 70 kW;		MLPA	H_2 consumption: 1503.76 g/100 km	[71]
Vehicle mass: 2064 kg; Drive ratio: 8.867; Battery capacity: 37 Ah; Fuel cell power: 65 kW; SOC: 67.77 %		PMP	H_2 consumption: 1050.9 g/100 km	[73]
Vehicle mass: 2000 kg; Gear ratio: 7; Transmission efficiency: 95 %	MATLAB	MPC	H_2 consumption reduction: 6.67 % Accuracy improvement: 5.7 %	[128]
Vehicle mass: 1850 kg; Battery capacity: 1.6 kWh; Fuel cell power: 114 kW	Simcenter Amesim	MLA	H_2 consumption: 912.19 g/100 km	[129]

hybrid vehicle was 0.06962 kmol H_2 with a wavelet-based strategy during the UDDS cycle, which further reduced to 0.06421 kmol H_2 (~7.8 % reduction), when FLC was integrated with the wavelet-based strategy [135]. The SOC of the battery and ultra-capacitor was 0.659–0.7 and 0.588–0.711, respectively, which helped to maintain enough charge in the battery and ultra-capacitor, leading to a decrease in hydrogen consumption.

Xu et al. [72] studied the PMP strategy for energy management of PEM HFCHEVs due to the advantages of considering more state variables and real-time control over DP and CDCS strategies. The operation cost with the PMP control strategy was 5.9 % lower compared to that with the CDCS strategy while 1.4 % higher than the DP strategy. The validation of the proposed PMP strategy on 30 China city bus cycles revealed a 20.8 % higher hydrogen consumption than the simulation result. Song et al. [73] developed a suboptimal real-time PMP-based energy management strategy, considering both hydrogen economy and power source durability. The study reported an improvement in fuel cell durability with a slight increase in hydrogen consumption and battery degradation using a PMP-based real-time energy management strategy for HFCHEVs. Zheng et al. [136] also considered degradation effect of fuel cell in PMP-based strategy. The results of the model revealed that there is a trade-off between the fuel cell lifetime and hydrogen consumption although the strategy increased the lifetime of fuel cell. Ou et al. [137] proposed and simulated an adapted-PMP model for a fuel cell/battery hybrid system in the MATLAB/Simulink environment, which prevented the battery from deep discharging or overcharging.

Model predictive control (MPC)-based energy management strategies have been studied for the improvement in fuel economy and lifetime due to its capability to simultaneously deal with various constraints [128,138–141]. Ma et al. [128] proposed an MPC-based strategy, which reduced hydrogen consumption by 6.67 % while avoiding fuel cell degradation. Considering velocity forecast in the model further reduced hydrogen consumption by 3 %, compared to that of a traditional non-forecast energy management strategy. Wang et al. [141] also reported an 8 % reduction in hydrogen consumption using an MPC-based approach compared to that of a rule-based energy management system. Zhou et al. [138] proposed a multi-mode MPC approach and observed an over 87 % reduction in fuel cell power transients and a 2.1 % decrease in hydrogen consumption in the single-mode MPC strategy.

Learning-based energy management, such as a machine learning algorithm (MLA) or reinforcement learning (RFL), has received widespread attention due to its satisfactory optimisation performance and good adaptability [74,129,142–144]. Raeesi et al. [129] investigated the impact of fuel cell degradation on the hydrogen consumption of a hydrogen fuel cell hybrid passenger vehicle using an MLA-based energy management technique. The hydrogen consumption of the degraded fuel cell was increased by 14.32 % within the NEDC and 13.9 % within the FTP-75 driving cycle. Tang et al. [142] also reported a decrease in hydrogen fuel economy in the case of degraded fuel cells within the UDDS cycle. The proposed deep RFL energy management framework resulted in 10.8 % higher hydrogen consumption than that with the DP-based approach; however, the proposed learning technique was 78.8 % faster in computation than the DP-based technique. Based on the findings of Ahmadi et al. [17], it can be concluded that the power recovery from the regenerative braking system is not enough to compensate the degradation effect of fuel cell, irrespective of driving cycle. This indicates the higher hydrogen consumption of degraded fuel cell-powered vehicle even with regenerative braking system. Sun et al. [74] noted a 75 % faster computation of the data-driven RFL-based hierarchical energy management approach compared to that of the DP-based method. Lee and Cha [144] reported 4.6 % lower hydrogen consumption with model-based RFL compared to that of a rule-based approach and 9.5 % higher consumption than the DP-based technique.

Although the DP-based energy management strategy for HFCHEVs exhibited better performance in terms of reduction of hydrogen consumption over most other strategies, the major issue of the DP-based strategy are its large computational loads and difficulties in real-time control, which require further improvement.

4. Environmental assessment of HFC–powered vehicles

The lifecycle cradle-to-grave emissions of vehicle powertrains include the emissions analysis of fuel and vehicle cycles. The fuel cycle-termed as WTW analysis, is comprised of fuel production to its delivery to the vehicle's fuel tank (known as the well-to-tank (WTT) stage) and consumption of fuel during the operation of vehicles (known as the tank-to-wheel (TTW) stage). The vehicle cycle consists of the manufacturing of vehicles and end-of-life (i.e., disposal and recycling) analysis. In the case of HFCEV and BEV, the TTW stage GHG emissions are zero as there are no emissions associated with the operation phase of electric vehicles [145,146].

Hwang [97] stated 58 % less GHG emissions from an HFC-powered scooter in Taiwan compared to a gasoline ICE scooter. Offer et al. [147] reported the positive impact of decarbonising electricity generation on the lifecycle emissions of HFCHEV, as the lifecycle emissions significantly reduced from 85 to 90 gCO_2/km to 40–50 gCO_2/km when the carbon emissions from electricity generation reduced from 20 to 80 %. Zhang et al. [148] estimated that the substitution of all diesel buses at Zhangjiakou in North China by hydrogen fuel cell transit buses could reduce approximately 17,524 tons of CO_2 in 2035, considering the CO_2 emission from a 12 m transit bus as 125.72 kg/100 km [149]. Huang and Zhang [150] evaluated WTW emission impacts of various hydrogen pathways in China using the GREET fuel-cycle model and found that an inefficient hydrogen pathway coupled with HFCEV may not provide GHG emissions benefits. Li and Hesary [151] performed a WTW lifecycle analysis of various HFCEV powertrains with different storage and supply systems (i.e., pipeline, compressed hydrogen, liquid hydrogen and liquid organic hydrogen carrier) in the context of China and compared it with that of a conventional vehicle powertrain. The analysis showed that the carbon emissions (kg/km) of hydrogen fuel cell powertrains with all storage and supply systems except liquid hydrogen were significantly lower than BEV and conventional vehicle powertrains. Additionally, Ugurlu [152] demonstrated that gaseous hydrogen-powered fuel cell vehicles were associated with the lowest total emissions, whereas fuel cell vehicles using liquid hydrogen showed the lowest VOC, CO and NOx emissions. Table 3 presents the findings of the key literature on lifecycle emissions analysis.

Li et al. [153] conducted a lifecycle emissions analysis of HFCEVs and compared it with that of BEVs and conventional fuel vehicles. The WTW CO_2 emissions of HFCEVs were similar to BEVs; both HFCEVs and BEVs emitted significantly less WTW CO_2 than a conventional vehicle. However, the total lifecycle (cradle-to-grave) CO_2 emissions of an HFCEV was 31.2 % higher than a conventional vehicle and 84.2 % higher than a BEV owing to the higher emissions associated with the vehicle cycle for HFCEVs, as it contributes approximately 59.1 % of the total lifecycle CO_2 emissions. Hienuki et al. [81] also reported that approximately 65 % of total GHG emissions from HFC-powered passenger car was associated with vehicle manufacturing, whereas 45 % of emission from gasoline ICE car was attributed to vehicle usage. The HFC-powered car exhibited ~0.14 kg-CO_2eq./km less emissions than the same-sized gasoline vehicle (large car of 1690 kg weight). Ahmadi et al. [17] showed that fuel cycle shares the highest portion of GHG emissions per km from the HFCEV followed by vehicle cycle. The GHG emissions associated with fuel cycle of HFCEV was significantly higher than ICEV; however, the total lifecycle GHG emissions of HFCEV was less than ICEV, due to the zero tailpipe emissions of HFCEV.

The WTW lifecycle analysis of various car powertrains in the Australian context showed the highest CO_2 emissions for battery electric vehicles followed by ethanol, gasoline, biodiesel, diesel, liquid petroleum gas (LPG) and compressed natural gas (CNG) vehicles and was lowest for HFCEVs [154]. The highest emissions for battery electric vehicles were associated with the higher emissions (nearly 10–70 % of

Table 3
Summary of some literature on lifecycle analysis.

Location (year)	Vehicle type	System boundary	Model	Hydrogen pathways	GHG emission (gCO_2-eq/km)			Reference
					HFCEV/ HFCHEV	BEV	ICEV	
USA (2007)		WTW	GREET	SMR of natural gas	161.6			[88]
				Coal gasification with CCS	74.6			
				Coke oven gas separation	49.7–136.7			
China (2020)		Cradle-to-grave	GREET		374	203	285	[153]
		WTW			154	149	249	
Australia (2016)	Car	WTW	Eco-invent 3.2 and GREET		32.4	364	136	[154][a]
China (2017)	light-duty passenger vehicle	WTW	GREET	SMR of natural gas	173	189	309	[86]
				Electrolysis by renewable electricity	35			
				Electrolysis by grid electricity	431			
				Coke oven gas separation	98			
Europe (2018)	Passenger car	Cradle-to-grave	GREET	SMR of natural gas	147		225	[82]
				Electrolysis by renewable electricity	38			
Korea (2015)		WTW	GREET	SMR of natural gas	218		220	[83]
				Electrolysis by grid electricity	388			
China (2016)		WTW	GREET	SMR of natural gas	140		295	[84]
				Electrolysis by grid electricity	390			
USA (2018)		WTW	GREET	SMR of natural gas	145		228	[85]
				Electrolysis by renewable electricity	28			
Japan (2020)	Passenger car	WTW	Input-output	Crude oil steam reforming	340		480	[81]
Korea (2020)		WTW	GREET	SMR of natural gas	110			[155]
Canada (2015)	Passenger car	WTW	Eco-invent 2.2 and GREET	Coal gasification	57	165		[156]
Finland (2014)	Bus	WTW	GREET	SMR of natural gas	95		121	[157][b]
USA (2014)	Bus	WTW	GREET	SMR of natural gas	120		182	[157][c]
USA (2015)	Light-duty vehicle	Cradle-to-grave	GREET	SMR of natural gas	196		263	[158][d]
China (2017)	Passenger vehicle	WTW	GREET	Electrolysis by wind electricity	36	233	307	[159]
				Electrolysis by grid electricity	495			
				Biomass gasification	49			
				SMR of natural gas	173			
USA (2016)	Passenger vehicle	WTW	FASTSim	33 % renewable hydrogen from biogas	100	87	174	[80]
USA (2021)	Passenger vehicle	WTW	GREET	SMR of natural gas	79.53	123.34	329.64	[160]
China (2020)	Heavy-duty truck	Cradle-to-grave	AFLEET	Coal gasification	1.63	1.49	1.21	[161][e]
Canada (2020)	Heavy-duty truck	WTW		Electrolysis by grid electricity	419		325	[162][f]
USA (2016)	Heavy-duty truck	WTW	GREET	SMR of natural gas	0.85		1.05	[163][g,e]

[a] gCO_2/MJ and average of diesel and gasoline.
[b] Average of Espoo11 and H550 driving cycles.
[c] Average of Line18 and Line51B driving cycles.
[d] Average of diesel and gasoline.
[e] $kgCO_2$-eq/km.
[f] gCO_2/kWh.
[g] Tractor trailer; SMR: Steam methane reforming.

the manufacturing GHG emissions [164]) from battery production. The WTW CO_2 emissions for a hydrogen fuel cell car were about 78.8 and 72.8 % lower than that of a gasoline vehicle and diesel vehicle, respectively. Liu et al. [85] reported 15–45 % less WTW GHG emissions for HFCEVs compared to gasoline ICEVs in the context of the USA. Rosenfeld et al. [82] and Yoo et al. [83] estimated about 35 and 65 % lower WTW GHG emissions for HFCEVs compared to gasoline ICEVs for Austria and South Korea, respectively. In another lifecycle emissions study, the WTW GHG emissions of hydrogen fuel cell passenger cars were reported as 65.5 % and 81 % lower than that of battery electric and methanol cars, respectively [156]. Zamel and Li [165] reported a nearly similar amount of CO_2 emissions reductions (~32 %) by HFCEVs compared to that of conventional ICEVs in Canada and the USA.

Wang et al. [86] noted slightly higher WTW GHG emissions of HFCEVs powered by hydrogen from coal gasification compared to that of gasoline ICEVs. Whereas HFCEVs with hydrogen produced from on-site water electrolysis using grid electricity exhibited about 2.3 and 1.4 times higher WTW GHG emissions compared to BEVs and gasoline ICEVs, respectively. The TTW stage contributed about 80 % of the WTW GHG emissions by gasoline ICEVs while the majority of the WTW GHG emissions by HFCEVs (~63–80 %) were associated with the hydrogen production pathway (i.e., coal gasification and steam methane reforming) and transport (i.e., pipeline and tube trailer). Joseck et al. [88] performed a WTW emission analysis of HFCHEVs using hydrogen from COG and compared it with that of HFCHEVs using hydrogen from natural gas and CCCS, as well as with gasoline vehicles and diesel vehicles. HFCHEVs using hydrogen from COG outperformed the gasoline vehicles, gasoline hybrid vehicles, diesel hybrid vehicles, HFCHEVs using hydrogen from natural gas and CCCS in terms of WTW GHG emissions and ordered them as HFCHEV-COG (0.08 gCO_2/mi) < HFCHEV-CCCS (12 gCO_2/mi) < HFCHEV-natural gas (26 gCO_2/mi) < diesel hybrid (29 gCO_2/mi) < gasoline hybrid (34 gCO_2/mi) < gasoline vehicle (47 gCO_2/mi).

Nguyen et al. [166] analysed the WTW GHG emissions of HFCEVs, BEVs, and plug-in hybrid vehicles and compared them with that of gasoline ICEVs. The HFCEVs powered by hydrogen sourced from wind energy exhibited the lowest carbon emissions among the vehicle options, shown was: HFCEV-wind ≤ HFCEV-biomass < HFCEV-natural gas < HFCEV-CCCS. Lee et al. [167] reported a 22–80 % WTW air emissions reduction on a hydrogen fuel cell bus using hydrogen from a central steam methane reforming pathway and around 54–97 % reduction with a wind electrolysis pathway, compared to that of a diesel bus in a USA scenario. According to Wong et al. [168], the WTT CO_2 emissions of gasoline ICEVs were 49.5 % lower than HFCEVs with natural gas reforming pathway and 200 % higher than HFCEVs with a renewable electricity water electrolysis route. The WTW CO_2 emissions of gasoline ICEVs were 3.37–20 times higher than HFCEVs, depending on the hydrogen production pathway. A recent study in China demonstrated that an HFCEV operated by hydrogen from electrolysis using solar power reduced global warming potential by 76.4 % (in terms of CO_2 emissions) when compared to a steam reforming route; however, electrolysis using the Chinese electricity grid mix resulted in almost 158.3 % higher global warming potential [169]. The GHG emissions per 100 km travel of HFCEV in USA using electrolysis hydrogen, produced from grid electricity, was higher than that in Canada due to the variation in electricity grid mix [170]. Hydrogen production using solar power electrolysis exhibited the lowest GHG emissions among the other hydrogen producing approaches. Other studies also showed significantly lower WTW GHG emissions for HFCEV with solar power electrolysis, hydropower electrolysis and wind power electrolysis compared to that of conventional ICEV [129,146,171–173].

A case study on the lifecycle assessment of HFCEVs in Korea under the NEDC driving cycle reported about 47.1 % lower GHG emissions for HFCEVs powered by hydrogen sourced from off-site natural gas reforming, compared to that of a naphtha and electricity mix [155]. An approximate 11–29 % variation in GHG emissions in California under NEDC, worldwide light vehicle test, procedure federal test and procedure highway fuel economy test driving cycles was observed, irrespective of production pathways. Lajunen and Lipman [157] also reported a variation in CO_2 emissions from a hydrogen fuel cell bus between two driving cycles in the context of Finland and California, USA.

Zhang et al. [161] conducted a lifecycle emissions analysis of a heavy-duty truck in China using the Argonne National Laboratory-developed Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) model and observed 9.4 and 34.7 % higher CO_2 emissions than that of conventional ICEVs and BEVs, respectively. Lajevardi et al. [174] quantified the WTW GHG emissions of sixteen different heavy-duty truck drivetrains powered by hydrogen, natural gas, diesel and electricity in the context of Canada and recorded the hydrogen fuel cell hybrid electric truck as the second lowest WTW GHG emissions contributor, with BEVs as the lowest for both short and long-haul cycles. Forrest et al. [175] assessed the technical feasibility of hydrogen fuel cell heavy-duty trucks in California, USA and estimated a more than three times higher energy requirement for hydrogen fuel cell heavy-duty trucks. The study suggested building high-capacity refuelling infrastructure with a zero-emission hydrogen production pathway in California to meet the travel demand of hydrogen fuel cell heavy-duty trucks. The substitution of diesel with a hydrogen fuel cell in a heavy-duty tractor in China reported 80.50, 87.83, 91.30 and 97.22 kg/100 km GHG emissions reduction for the truck tonnage of 14-24t, 24-25t, 25-29t and 31-60t, respectively [176]. The annual GHG emissions of a tractor and freight truck were quite similar; however, they were significantly higher than that of a dump truck and a special truck. In another study, a 28, 19 and 7 % reduction in CO_2, NOx and particulate matter emissions, respectively, were reported by using a hydrogen fuel cell/battery electric heavy-duty trucks in Germany [177]. Gustafsson et al. [162] investigated the effect of different energy carriers on WTW GHG emissions of heavy-duty trucks. Energy carriers with a high electricity dependency showed high per kWh WTW GHG emissions, as hydrogen from electrolysis using grid electricity mix exhibited about 28.9 % higher per kWh WTW GHG emissions than that of diesel. Liu et al. [178] noted that a heavy-duty truck using hydrogen from steam methane reforming and renewable power (both solar and wind) electrolysis routes were associated with lower per km GHG emissions than a diesel truck, while coal gasification and grid electricity pathways showed significantly higher emissions. Ren et al. [179] also showed that electrolysis using renewable electricity could reduce the WTW GHG emissions of a heavy-duty truck by 29–52.4 %.

It can be concluded from the literature that the GHG emissions of HFCEVs are largely dependent on the hydrogen production pathway and transport system. Although the assumptions of these studies were different, the same trend of WTW GHG emissions of HFCEVs with different hydrogen production pathways was observed when compared to other vehicles, as HFCEVs fuelled with hydrogen from renewable electricity showed the lowest WTW GHG emissions.

5. Economic analysis of HFC–powered vehicles

Despite a number of advantages of HFC, a comprehensive economic feasibility study and synergies in road vehicle applications are required to understand the future potential of HFC-powered vehicles as an alternative to ICEVs, and to develop policy accordingly, as high cost is still the major bottleneck of HFC-based transport. According to the NREL, the current cost of a medium size HFC-powered passenger vehicle is approximately $53.1k and is expected to reduce to $33.1k by 2050 [65]. The current cost of a hydrogen fuel cell is around $160 per kW and is expected to go down to $40 per kW by 2050. Offer et al. [180] performed the cost analysis of HFCEVs and compared it to that of BEVs and HFCHEVs over 100,000 miles. According to the cost analysis, the lifecycle cost of an HFCEV, BEV and HFCHEV for 2030 was estimated in the range of $7360-$22,580, $6460-$11,420 and $4310-$12,540, respectively. The lifecycle cost of an HECHEV was around 1.75 times lower than that of a conventional IC powertrain. The HFCHEVs and HFCVs were significantly cost-sensitive to capital and hydrogen costs. In another study, Offer et al. [147] conducted an economic assessment of HFCEV, BEV and HFCHEV powertrains in the context of the UK using cost prediction analysis for 2030 and reported a 5–15 kWh battery as the optimum battery size for an HFCHEV depending on the size of the vehicle and their usage pattern. The cost of hydrogen had a significant impact on the returns from an HFCEV, whereas hydrogen cost had a large impact on HFCHEV only with a small battery size (<10 kWh). The cost of an HFCHEV, even with a large battery size, was much lower than that of an HFCEV due to the compensating of cost by downsizing the fuel cell. In another techno-economic analysis, it was observed that the economic profitability of both fuel cell powertrains and conventional internal combustion engine powertrains are highly sensitive to fuel price [181]. Table 4 shows the findings of the economic assessment from some key literature.

Chen and Meliana [182] and Cox et al. [183] developed a techno-economic assessment framework for future HFCEVs to compare the cost of HFCEVs with ICEVs and BEVs in the context of Switzerland and the USA, respectively. De Miranda et al. [184] performed an economic analysis of a plug-in type hybrid electric-hydrogen fuel cell city bus in the context of Brazil. The capital cost of the bus contributed approximately 65 % of the total cost of ownership of a plug-in hybrid electric-hydrogen fuel cell bus followed by the cost of hydrogen (22 %) and maintenance (13 %). The capital cost of a plug-in hybrid electric-hydrogen fuel cell city bus is about 386 % higher than that of a diesel bus. A lifecycle cost analysis conducted by Jeong and Oh [185] showed that the lifecycle cost of HFCHEVs is significantly affected by hydrogen production costs, fuel cell size and fuel cell cost. Whiston et al. [186] estimated the total cost of ownership as $0.26/km in 2017, but expected this to reduce to $0.12/km by 2035, which will make it competitive with ICEVs and BEVs. Wróblewski et al. [187] studied the potential of HFCEVs market development in Poland through a total cost of ownership analysis. Jones et al. [188] performed an economic

Table 4
Summary of economic assessment from some key literature.

Location (year)	Vehicle type	System boundary	Hydrogen pathways	Lifecycle cost/Total cost of ownership ($/km)				Reference
				HFCEV/ HFCHEV	BEV	PHEV	ICEV	
China (2020)		Cradle-to-grave		0.23	0.25		0.31	[153]
Australia (2016)	Passenger car	WTW		0.24	0.71		0.33	[154][a]
USA (2015)	Light-duty vehicles	Cradle-to-grave	SMR of natural gas	0.24			0.16	[158]
China (2017)	Passenger vehicles	WTW	Electrolysis by wind electricity	0.41	0.49		0.29	[159]
			SMR of natural gas	0.38				
China (2018)	Passenger car	WTW	Electrolysis by solar PV electricity	0.295	0.466	0.504	0.414	[151][b]
	Bus			3.495	1.607	2.085	1.733	
	Truck			3.082	0.858	0.944	1.017	
Indonesia (2017)	Passenger car	WTW	SMR of natural gas + gasification of lignite and biomass + renewable electricity from solar and wind	0.66	0.49	0.41	0.28	[87]
	Bus			2.76	1.12	1.53	1.17	
	Truck			2.20	0.60	0.64	0.64	
Malaysia (2017)	Passenger car	WTW	SMR of natural gas + gasification of lignite and biomass + renewable electricity from solar and wind	0.75	0.57	0.46	0.32	[87]
	Bus			2.61	1.14	1.51	1.19	
	Truck			1.99	0.64	0.62	0.64	
Thailand (2017)	Passenger car	WTW	SMR of natural gas + gasification of lignite and biomass + renewable electricity from solar and wind	0.55	0.42	0.38	0.27	[87]
	Bus			2.26	1.00	1.40	1.27	
	Truck			1.89	0.64	0.67	0.73	
Philippines (2017)	Passenger car	WTW	SMR of natural gas + gasification of lignite and biomass + renewable electricity from solar and wind	0.57	0.45	0.39	0.27	[87]
	Bus			2.34	1.21	1.48	1.3	
	Truck			1.96	0.82	0.69	0.74	
Brazil (2016)	Bus	WTW		2.61			1.12	[184]
Australia (2015)	Bus		Electrolysis by grid electricity	2.66			1.36	[189]
Finland (2014)	Bus	WTW	SMR of natural gas	1.93			0.97	[157][c]
USA (2014)	Bus	WTW	SMR of natural gas	2.21			1.05	[157][d]
China (2020)	Heavy-duty truck	Cradle-to-grave	Coal gasification	1.3	0.9		0.7	[161][e]

[a] Average of diesel and gasoline.
[b] Hydrogen transport through pipeline.
[c] Average of Espoo11 and H550 driving cycles.
[d] Average of Line18 and Line51B driving cycles.
[e] Average of fast and slow charging; SMR: Steam methane reforming.

analysis of thirteen vehicles in order to investigate the economic competitiveness of HFCEVs in a UK scenario in 2017 and found that the lifetime cost of HFCEVs was within the range of some diesel ICEVs when considering the tax benefits and subsidies for HFCEVs. However, diesel ICEVs still remained the most competitive transport for commercial use in the UK.

Li and Kimura [87] assessed the economic competitiveness of different HFCEVs (i.e., passenger cars, buses and trucks) with BEVs and conventional ICEVs in Association of Southeast Asian Nations countries, including Indonesia, Malaysia, Philippines and Thailand. The total cost of ownership for all categories of HFCEVs was significantly higher than that of BEVs and ICEVs. De Miranda et al. [184] reported a 133 % higher total cost of ownership for a plug-in hybrid electric-hydrogen fuel cell bus in Brazil, compared to a diesel bus, due to the significantly higher cost of the initial purchase of the fuel cell bus. According to Lajunen and Lipman [157], the capital cost of a HFC bus was higher than a diesel bus, irrespective of the driving cycle for both Finland and California scenarios. The higher total cost of ownership for a hydrogen fuel cell bus than a diesel bus was also noted by Ally and Pryor [189] in Australia. Li and Taghizadeh-Hesary [151] studied the total cost of ownership model of various HFCEV powertrains with hydrogen produced from renewable energy sources in the context of China and compared them with conventional internal combustion engine vehicles. The total cost of ownership ($/km) of a bus and a truck with an HFCEV powertrain were around 117.5 and 259.2 %, respectively, higher than that of a BEV powertrain. A bus and truck with HFCEV powertrains showed a 101.7 and 203 %, respectively, higher total cost of ownership than a conventional gasoline vehicle powertrain. A fuel cell-powered passenger car exhibited 36.7 and 28.7 % lower total cost of ownership than a battery electric passenger car and a conventional gasoline passenger car, respectively.

A comparative economic assessment of different car powertrains with various fuels in the context of Australia performed by Sharma and Strezov [154] also reported a lower per km cost for fuel cell-powered cars than other vehicles. The economic cost (in per km) of different car powertrains was ordered as battery electric car > ethanol car > biodiesel car > diesel car > gasoline car > CNG car > hydrogen fuel cell car > LPG car. The higher economic cost per km of a battery electric car was due to the higher capital costs of battery electric cars [180,190]. The total economic cost per km of a hydrogen fuel cell car was approximately 66.2 % lower than that of a battery electric car, but about 16.8 % higher than an LPG car. Li et al. [153] proposed a lifecycle cost model for an HFCEV and compared it with a conventional vehicle and a BEV in the context of China. The average lifecycle cost for the HFCEV was approximately 25.8 % lower than that of a conventional vehicle and 8 % lower than that of a BEV due to local government subsidies for the HFCEV.

The sensitivity analysis suggested that the annual average mileage was the most sensitive to lifecycle cost. A recent case study in Brazil using an ADVISOR model in MATLAB/Simulink software showed that subsidies and fuel credits together reduced the total cost of an HFCEV by up to 27.2 %, whereas mass production reduced the cost by up to 38 % [90]. Therefore, the total cost of an HFCEV can be reduced by introducing subsidies and fuel credits, as well as increasing the production volume, which will further reduce the total cost of ownership. The total cost of ownership can also be reduced by employing an effective energy management strategy [191].

The techno-economic analysis of heavy-duty truck powertrains demonstrated a significantly higher lifecycle cost for hydrogen fuel cell-powered trucks compared to that of BEVs and conventional ICEVs [161]. The charging mode of BEV affected the lifecycle cost, fast-charging resulted in a higher lifecycle cost than slow-charging due to the higher cost of fast-charging infrastructure. The integration of a hydrogen fuel cell in a tractor instead of using diesel provided a considerable economic benefit as the cost per 100 km was reduced by $22.2, $24.2, $25.1 and $26.8 for truck tonnages of 14-24t, 24-25t, 25-29t and 31-60t, respectively [176].

As can be seen from the literature, although the total cost of ownership of HFCEVs varies with the hydrogen production pathway (i.e., hydrogen production cost), the capital cost of fuel cell vehicles plays a key role in the significant variation of the total cost of ownership of HFCEVs compared to that of conventional ICEVs. Therefore, both the production cost of hydrogen and the cost of fuel cell vehicles will need to be mitigated to make the technology more economically attractive.

6. Future research perspectives and implications of this study

6.1. Limitations of the previous studies and future research directions

In this study, some of the key aspects of HFCEVs such as modelling and experimental trial, performance improvement strategies, economic and environmental impacts were critically discussed in relation to the findings of previous studies from different nationalities. Significant progress has been made so far on these aspects in terms of technological advancements and policy framework as discussed in the respective sections. However, there are still several limitations in modelling assumptions and challenges which require to be addressed to make the technology more affordable and long-term competitive to other options. Therefore, taking into account the recent advances in HFCEV research and limitations of previous studies, the study has summarised some suggestions for future research directions as follows.

- The hybridisation of HFCEVs by integrating HFCs with battery/supercapacitor systems ensures rapid energy exchange during acceleration and deceleration and high energy availability for a prolonged drive range. Therefore, hybridisation improves the overall fuel economy and efficiency of hybrid vehicles compared to pure HFCEVs. However, the degree of hybridisation is required to be optimised, considering the various driving cycles closer to real-world driving conditions for different vehicle types and combinations of different secondary power sources with HFC.
- Energy management of hydrogen fuel cell hybrid electric vehicles is an important factor to enhance the fuel economy, performance and lifetime of the vehicles' operation. So far, a number of optimisation approaches have been developed and investigated for efficient energy management. Only a few studies have integrated optimisation of hydrogen economy with mitigation of power source durability without consideration of both factors at the same time in the model. The validation of optimisation models with experimental studies has not been investigated extensively in the literature, though it is important to understand the real-time applicability of the models. Therefore, a lack of comparative studies between models and experimental investigations is demanding more research on benchmarking the optimisation tools with experimental data to understand the practical applicability of the approach. Future optimisation approaches should also consider various driving cycles and precisely capture the time-varying behaviour of fuel cells to implement a real-time optimal control policy.
- Based on the current literature, the majority of lifecycle assessment studies investigated the well-to-wheel emissions; however, more research should focus on considering the vehicle cycle emissions, as it could significantly affect the total lifecycle emissions. The recycling of vehicle components can add positive environmental benefits to the lifecycle emissions by avoiding the manufacturing of vehicle parts. This will help to understand the actual contribution of HFCEV to decarbonising the transport sector. The well-to-wheel emissions of HFCEVs are also significantly dependent on the hydrogen production pathway and transport system. On-site hydrogen production from renewable electricity integrated sustainable process, particularly from electrolysis, could be an excellent option where future optimisation research should focus on, considering the hydrogen demand and overall cost. Emissions associated with other important factors including fuel supply chain and required infrastructure are also required to be considered to make complex decisions on planning and developing refuelling infrastructure.
- Vehicle manufacturing shared more than 60 % of the total energy consumed by fuel cell vehicles, which is associated with a huge capital cost. The recycling of vehicle components can add a significant economic benefit in terms of reducing the vehicle's capital costs. Both direct use of recycled components for vehicle manufacturing and second life use (alternative use) of components can compensate the manufacturing cost of vehicle. Therefore, the end-of-life salvage value of the vehicle should be considered in the economic model for providing accurate information about best scenarios to the policymakers.
- The total cost of ownership for HFCHEVs depends on the production volume of vehicle and infrastructure components, hydrogen production pathway, charging mode and energy management strategy. Therefore, more studies are required for optimising energy management strategy and production volume as well as for identifying the best hydrogen production route suitable for the specific country or location to get the target total cost of ownership competitive to ICEVs. Additionally, some other aspects such as uncertainties in costs associated with the supply chain of hydrogen production, distribution and storage and vehicle manufacturing along with country specific government policies and incentives needs to be considered in the model for exploring more realistic evaluation and competitiveness with other technologies.
- The transformation of fossil fuels-powered heavy-duty vehicles to sustainable low-emissions power technologies is emerging for decarbonising the transport sector, where the automobile industries and scientists are currently looking at. However, the modelling, economic and environmental studies so far reported in the literature have mostly focussed on light to medium-duty vehicles. It is not well understood how the optimum energy distribution would be when hybrid power sources are used for long range driving of heavy-duty vehicles considering variable weather conditions and driving cycles. Spatiotemporal multi-objective optimisation model would be helpful to establish the optimal hydrogen supply chain for long range driving of heavy-duty vehicles. Therefore, there is a considerable future research scope in the heavy-duty vehicles sector to identify the country-specific feasibility.

6.2. Practical implementations of the study

This work systematically analyses the findings of the previous research on energy management, economic and environmental aspects of HFCEVs and gives insight into technological and scientific advancements of these aspects from a global perspective. The assumptions and considerations of the previous studies vary from one nationality/region to another. Therefore, comparative analyses were conducted discussing the effect of each assumed parameters on the performance, total cost of ownership and GHG emissions. The total cost of ownership was converted to US dollar ($) from other currency considering relevant year for better comparison. The strategic discussions presented in this work reasonably generalises the findings of the previous studies and provides benchmarking comparison despite of variation in assumptions.

However, the limitation of this study lies on the comparison of total cost of ownership which could be further improved by adjusting the total cost of ownership estimated in different years to a specific year using the gross domestic product inflation/deflation factor.

This study gathers the dispersed knowledge on performance, energy management, emissions and cost of HFCEVs and consolidates on a single platform to support policymakers involved in the development of HFCEV infrastructure and vehicle owners. The comparative analysis of this study can be useful information for policymakers and vehicle owners to understand the benefits of HFCEVs in terms of performance, emissions and ownership cost. The discussions and findings of the work can also provide useful insights for identifying key challenging areas to be addressed and policy design through research and development in the future as follows. The discussions on energy management of HFCHEV can help to design effective strategy for optimising power usage with extended fuel cell life. The comparative economic and emissions analyses at various scenarios can guide policymakers to find out hotspot i.e., the most critical parameter affecting the total cost of ownership and GHG emissions and help to rethink on how to reduce the total cost of ownership and emissions to make HFCEV more affordable, sustainable and comparable to other technologies. The emissions data of HFCEV from previous studies revealed a promise for long term alternative in terms of environmental sustainability despite of higher costs associated with hydrogen production, storage and refuelling infrastructure. Therefore, the Environmental, Social, and Governance (ESG) practice through implementing HFCEVs is linked to the United Nations (UN) Sustainable Development Goals (SDGs) – 13: Climate action. The consolidated findings and discussion of this review can help the policymakers to take decision whether the HFCEV technology will be adopted as a disruptive technology for the respective country/region; accordingly, to develop short- and long-term plan to enhance public acceptance and awareness and support other organisations and new start-ups.

7. Conclusions

This study provides a comprehensive state-of-the-art review on hydrogen fuel cell electric vehicles (HFCEVs). The HFCEV is a low-emission power technology which can help to decarbonise the future transport sector and to achieve sustainable development goals. Despite a number of benefits, the commercialisation of HFCEVs is associated with several issues, including the cost of hydrogen production and fuel cells, and hence the vehicle itself, refuelling infrastructure and energy management, where ongoing research is focussing on.

This study critically reviewed the recent research on the performance of HFCEVs, lifecycle costs and emissions. From the detailed literature review, it was observed that HFCEVs outperformed conventional internal combustion engine vehicles (ICEVs) in terms of fuel economy and well-to-wheel greenhouse gas (GHG) emissions. The lower GHG emissions of HFCEVs can help to attain the UN SDG – 13: Climate action. The fuel economy and efficiency of HFCEVs depend on the driving cycle, whereas the GHG emissions are affected by the hydrogen production pathway and transport system. However, the total cost of ownership of HFCEVs is still significantly higher than that of ICEVs due to the higher production cost of hydrogen and capital cost of fuel cell vehicles. Fig. 11 presents the benchmarking of HFCEVs with conventional ICEVs in terms of fuel economy, GHG emissions and total cost of ownership based on the average data of light-duty vehicles of different categories from the available literature. The study suggested that the higher lifecycle cost of HFCEVs can be reduced by increasing the production volume of station equipment and fuel cell components and incorporating low-cost resources and technologies for hydrogen production and transport.

The study has offered suggestions for further research on performance improvement of HFCHEVs through hybridisation and proper energy management strategy and improvement of emissions and economic models for understanding best scenarios. The practical implementation of this study in relation with policy implications has also been discussed.

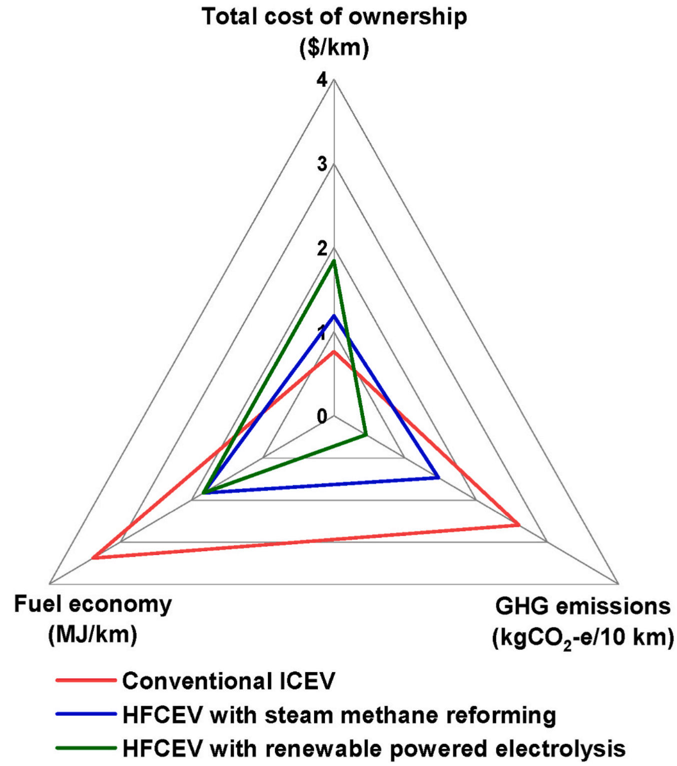

Fig. 11. Benchmarking of HFCEV with conventional ICEV.

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.

Data availability

No data was used for the research described in the article.

Acknowledgement

The authors would like to acknowledge the support of Deakin University, Australia through the Alfred Deakin Postdoctoral Research Fellowship.

References

[1] Navas-Anguita Z, García-Gusano D, Iribarren D. A review of techno-economic data for road transportation fuels. Renew Sustain Energy Rev 2019;112:11–26. https://doi.org/10.1016/J.RSER.2019.05.041.

[2] Ajanovic A, Haas R. Renewable energy systems implementation in road transport: prospects and impediments. Renewable Energy and Environmental Sustainability 2021;6:39. https://doi.org/10.1051/REES/2021042.

[3] Ritchie H. Cars, planes, trains: where do CO2 emissions from transport come from? - Our World in Data. https://ourworldindata.org/co2-emissions-from-transport. [Accessed 29 June 2022].

[4] Azad AK, Adhikari J, Halder P, Rasul MG, Hassan NMS, Khan MMK, et al. Performance, emission and combustion Characteristics of a diesel engine powered by macadamia and grapeseed biodiesels. Energies 2020;13:2748. https://doi.org/10.3390/EN13112748.

[5] Bodisco TA, Rahman SMA, Hossain FM, Brown RJ. On-road NOx emissions of a modern commercial light-duty diesel vehicle using a blend of tyre oil and diesel. Energy Rep 2019;5:349–56. https://doi.org/10.1016/J.EGYR.2019.03.002.

[6] Halder P, Azad K, Shah S, Sarker E. Prospects and technological advancement of cellulosic bioethanol ecofuel production. In: Azad K, editor. Advances in eco-fuels

for a sustainable environment. Elsevier Science & Technology; 2019. p. 211–36. https://doi.org/10.1016/B978-0-08-102728-8.00008-5.
[7] Azad AK, Rasul MG, Khan MMK, Sharma SC, Mo M, Bhuiya MMK. Prospects, feedstocks and challenges of biodiesel production from beauty leaf oil and castor oil : a nonedible oil sources in Australia. Renew Sustain Energy Rev 2016;61: 302–18. https://doi.org/10.1016/j.rser.2016.04.013.
[8] Shafique M, Azam A, Rafiq M, Luo X. Life cycle assessment of electric vehicles and internal combustion engine vehicles: a case study of Hong Kong. Res Transport Econ 2021:101112. https://doi.org/10.1016/J.RETREC.2021.101112.
[9] Das HS, Rahman MM, Li S, Tan CW. Electric vehicles standards, charging infrastructure, and impact on grid integration: a technological review. Renew Sustain Energy Rev 2020;120. https://doi.org/10.1016/j.rser.2019.109618.
[10] Alavi F, Park Lee E, van de Wouw N, De Schutter B, Lukszo Z. Fuel cell cars in a microgrid for synergies between hydrogen and electricity networks. Appl Energy 2017;192:296–304. https://doi.org/10.1016/J.APENERGY.2016.10.084.
[11] Staffell I, Scamman D, Abad AV, Balcombe P, Dodds PE, Ekins P, et al. The role of hydrogen and fuel cells in the global energy system. Energy Environ Sci 2019;12: 463–91. https://doi.org/10.1039/C8EE01157E.
[12] Li J, Zhu X, Djilali N, Yang Y, Ye D, Chen R, et al. Comparative well-to-pump assessment of fueling pathways for zero-carbon transportation in China: hydrogen economy or methanol economy? Renew Sustain Energy Rev 2022;169:112935. https://doi.org/10.1016/J.RSER.2022.112935.
[13] Fayaz H, Saidur R, Razali N, Anuar FS, Saleman AR, Islam MR. An overview of hydrogen as a vehicle fuel. Renew Sustain Energy Rev 2012;16:5511–28. https://doi.org/10.1016/J.RSER.2012.06.012.
[14] Emadi A, Williamson SS. Fuel cell vehicles: opportunities and challenges. In: 2004 IEEE power engineering society general meeting, vol. 2; 2004. p. 1640–5. https://doi.org/10.1109/PES.2004.1373150.
[15] Greene DL, Ogden JM, Lin Z. Challenges in the designing, planning and deployment of hydrogen refueling infrastructure for fuel cell electric vehicles. ETransportation 2020;6:100086. https://doi.org/10.1016/J.ETRAN.2020.100086.
[16] İnci M, Büyük M, Demir MH, İlbey G. A review and research on fuel cell electric vehicles: topologies, power electronic converters, energy management methods, technical challenges, marketing and future aspects. Renew Sustain Energy Rev 2021;137:110648. https://doi.org/10.1016/J.RSER.2020.110648.
[17] Ahmadi P, Torabi SH, Afsaneh H, Sadegheih Y, Ganjehsarabi H, Ashjaee M. The effects of driving patterns and PEM fuel cell degradation on the lifecycle assessment of hydrogen fuel cell vehicles. Int J Hydrogen Energy 2020;45: 3595–608. https://doi.org/10.1016/J.IJHYDENE.2019.01.165.
[18] Mori D, Hirose K. Recent challenges of hydrogen storage technologies for fuel cell vehicles. Int J Hydrogen Energy 2009;34:4569–74. https://doi.org/10.1016/J.IJHYDENE.2008.07.115.
[19] Garland NL, Papageorgopoulos DC, Stanford JM. Hydrogen and fuel cell technology: progress, challenges, and future directions. Energy Proc 2012;28: 2–11. https://doi.org/10.1016/J.EGYPRO.2012.08.034.
[20] Hosseini SE, Butler B. An overview of development and challenges in hydrogen powered vehicles. Int J Green Energy 2020;17:13–37. https://doi.org/10.1080/15435075.2019.1685999.
[21] Zhang B, Zhang SX, Yao R, Wu YH, Qiu JS. Progress and prospects of hydrogen production: opportunities and challenges. Journal of Electronic Science and Technology 2021;19:100080. https://doi.org/10.1016/J.JNLEST.2021.100080.
[22] DOE. Fuel cell vehicles - benefits and challenges. 2022. https://www.fueleconomy.gov/feg/fcv_benefits.shtml. [Accessed 16 November 2022].
[23] Haraldsson K, Alvfors P. Effects of ambient conditions on fuel cell vehicle performance. J Power Sources 2005;145:298–306. https://doi.org/10.1016/J.JPOWSOUR.2004.12.080.
[24] Salam MA, Habib S, Arefin P, Ahmed K, Uddin S, Hossain T, et al. Effect of temperature on the performance factors and durability of proton exchange membrane of hydrogen fuel cell: a narrative review. Material Science Research India 2020;17:179–91. https://doi.org/10.13005/MSRI/170210.
[25] Ramprakash B, Lindblad P, Eaton-Rye JJ, Incharoensakdi A. Current strategies and future perspectives in biological hydrogen production: a review. Renew Sustain Energy Rev 2022;168:112773. https://doi.org/10.1016/J.RSER.2022.112773.
[26] Usman MR. Hydrogen storage methods: review and current status. Renew Sustain Energy Rev 2022;167:112743. https://doi.org/10.1016/J.RSER.2022.112743.
[27] Tashie-Lewis BC, Nnabuife SG. Hydrogen production, distribution, storage and power conversion in a hydrogen economy - a technology review. Chemical Engineering Journal Advances 2021;8:100172. https://doi.org/10.1016/J.CEJA.2021.100172.
[28] Yukesh Kannah R, Kavitha S, Preethi Parthiba Karthikeyan O, Kumar G, Dai-Viet NV, et al. Techno-economic assessment of various hydrogen production methods – a review. Bioresour Technol 2021;319:124175. https://doi.org/10.1016/J.BIORTECH.2020.124175.
[29] Nikolaidis P, Poullikkas A. A comparative overview of hydrogen production processes. Renew Sustain Energy Rev 2017;67:597–611. https://doi.org/10.1016/J.RSER.2016.09.044.
[30] El-Emam RS, Özcan H. Comprehensive review on the techno-economics of sustainable large-scale clean hydrogen production. J Clean Prod 2019;220: 593–609. https://doi.org/10.1016/J.JCLEPRO.2019.01.309.
[31] Abdalla AM, Hossain S, Nisfindy OB, Azad AT, Dawood M, Azad AK. Hydrogen production, storage, transportation and key challenges with applications: a review. Energy Convers Manag 2018;165:602–27. https://doi.org/10.1016/J.ENCONMAN.2018.03.088.
[32] Pinsky R, Sabharwall P, Hartvigsen J, O'Brien J. Comparative review of hydrogen production technologies for nuclear hybrid energy systems. Prog Nucl Energy 2020;123:103317. https://doi.org/10.1016/J.PNUCENE.2020.103317.
[33] Kayfeci M, Keçebaş A, Bayat M. Hydrogen production. Solar Hydrogen Production: Processes, Systems and Technologies 2019:45–83. https://doi.org/10.1016/B978-0-12-814853-2.00003-5.
[34] Singla S, Shetti NP, Basu S, Mondal K, Aminabhavi TM. Hydrogen production technologies - membrane based separation, storage and challenges. J Environ Manage 2022;302:113963. https://doi.org/10.1016/J.JENVMAN.2021.113963.
[35] Dawood F, Anda M, Shafiullah GM. Hydrogen production for energy: an overview. Int J Hydrogen Energy 2020;45:3847–69. https://doi.org/10.1016/J.IJHYDENE.2019.12.059.
[36] Martinez-Burgos WJ, de Souza Candeo E, Pedroni Medeiros AB, Cesar de Carvalho J, Oliveira de Andrade Tanobe V, Soccol CR, et al. Hydrogen: current advances and patented technologies of its renewable production. J Clean Prod 2021;286:124970. https://doi.org/10.1016/J.JCLEPRO.2020.124970.
[37] Nnabuife SG, Ugbeh-Johnson J, Okeke NE, Ogbonnaya C. Present and projected developments in hydrogen production: a technological review. Carbon Capture Science & Technology 2022;3:100042. https://doi.org/10.1016/J.CCST.2022.100042.
[38] Kumar A, Muthukumar P, Sharma P, Kumar EA. Absorption based solid state hydrogen storage system: a review. Sustain Energy Technol Assessments 2022;52: 102204. https://doi.org/10.1016/J.SETA.2022.102204.
[39] Zeleňák V, Saldan I. Factors affecting hydrogen adsorption in metal–organic frameworks: a short review. Nanomaterials 2021;11:1638. https://doi.org/10.3390/NANO11071638.
[40] Li H, Cao X, Liu Y, Shao Y, Nan Z, Teng L, et al. Safety of hydrogen storage and transportation: an overview on mechanisms, techniques, and challenges. Energy Rep 2022;8:6258–69. https://doi.org/10.1016/J.EGYR.2022.04.067.
[41] Ma Y, Wang XR, Li T, Zhang J, Gao J, Sun ZY. Hydrogen and ethanol: production, storage, and transportation. Int J Hydrogen Energy 2021;46:27330–48. https://doi.org/10.1016/J.IJHYDENE.2021.06.027.
[42] Moradi R, Groth KM. Hydrogen storage and delivery: review of the state of the art technologies and risk and reliability analysis. Int J Hydrogen Energy 2019;44: 12254–69. https://doi.org/10.1016/J.IJHYDENE.2019.03.041.
[43] Rimza T, Saha S, Dhand C, Dwivedi N, Patel SS, Singh S, et al. Carbon-based sorbents for hydrogen storage: challenges and sustainability at operating conditions for renewable energy. ChemSusChem 2022:e202200281. https://doi.org/10.1002/CSSC.202200281.
[44] Bellosta von Colbe J, Ares JR, Barale J, Baricco M, Buckley C, Capurso G, et al. Application of hydrides in hydrogen storage and compression: achievements, outlook and perspectives. Int J Hydrogen Energy 2019;44:7780–808. https://doi.org/10.1016/J.IJHYDENE.2019.01.104.
[45] Yue M, Lambert H, Pahon E, Roche R, Jemei S, Hissel D. Hydrogen energy systems: a critical review of technologies, applications, trends and challenges. Renew Sustain Energy Rev 2021;146:111180. https://doi.org/10.1016/J.RSER.2021.111180.
[46] Bethoux O. Hydrogen fuel cell road vehicles and their infrastructure: an option towards an environmentally friendly energy transition. Energies 2020;13:6132. https://doi.org/10.3390/EN13226132.
[47] Manoharan Y, Hosseini SE, Butler B, Alzhahrani H, Senior BTF, Ashuri T, et al. Hydrogen fuel cell vehicles; current status and future prospect. Appl Sci 2019;9: 2296. https://doi.org/10.3390/APP9112296.
[48] Cunanan C, Tran MK, Lee Y, Kwok S, Leung V, Fowler M. A review of heavy-duty vehicle powertrain technologies: diesel engine vehicles, battery electric vehicles, and hydrogen fuel cell electric vehicles. Clean Technologies 2021;3:474–89. https://doi.org/10.3390/CLEANTECHNOL3020028.
[49] Bethoux O. Hydrogen fuel cell road vehicles: state of the art and perspectives. Energies 2020;13:5843. https://doi.org/10.3390/EN13215843.
[50] Li S, Djilali N, Rosen MA, Crawford C, Sui PC. Transition of heavy-duty trucks from diesel to hydrogen fuel cells: opportunities, challenges, and recommendations. Int J Energy Res 2022;46:11718–29. https://doi.org/10.1002/ER.8066.
[51] Olabi AG, Wilberforce T, Abdelkareem MA. Fuel cell application in the automotive industry and future perspective. Energy 2021;214:118955. https://doi.org/10.1016/J.ENERGY.2020.118955.
[52] Kast J, Vijayagopal R, Gangloff JJ, Marcinkoski J. Clean commercial transportation: medium and heavy duty fuel cell electric trucks. Int J Hydrogen Energy 2017;42:4508–17. https://doi.org/10.1016/J.IJHYDENE.2016.12.129.
[53] Liu F, Zhao F, Liu Z, Hao H. The impact of fuel cell vehicle deployment on road transport greenhouse gas emissions: the China case. Int J Hydrogen Energy 2018; 43:22604–21. https://doi.org/10.1016/J.IJHYDENE.2018.10.088.
[54] Lee DY, Elgowainy A, Kotz A, Vijayagopal R, Marcinkoski J. Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium- and heavy-duty trucks. J Power Sources 2018;393:217–29. https://doi.org/10.1016/J.JPOWSOUR.2018.05.012.
[55] 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. https://doi.org/10.1016/J.ENCONMAN.2019.112022.
[56] Ren P, Pei P, Li Y, Wu Z, Chen D, Huang S. Degradation mechanisms of proton exchange membrane fuel cell under typical automotive operating conditions. Prog Energy Combust Sci 2020;80:100859. https://doi.org/10.1016/J.PECS.2020.100859.
[57] Dépature C, Macías A, Jácome A, Boulon L, Solano J, Trovão JP. Fuel cell/supercapacitor passive configuration sizing approach for vehicular applications.

Int J Hydrogen Energy 2020;45:26501–12. https://doi.org/10.1016/J.IJHYDENE.2020.05.040.
[58] Das HS, Tan CW, Yatim AHM. Fuel cell hybrid electric vehicles: a review on power conditioning units and topologies. Renew Sustain Energy Rev 2017;76: 268–91. https://doi.org/10.1016/J.RSER.2017.03.056.
[59] Martel F, Kelouwani S, Dubé Y, Agbossou K. Optimal economy-based battery degradation management dynamics for fuel-cell plug-in hybrid electric vehicles. J Power Sources 2015;274:367–81. https://doi.org/10.1016/J.JPOWSOUR.2014.10.011.
[60] Martel F, Dube Y, Kelouwani S, Agbossou K. Economy-focused PHEV battery lifetime management through optimal fuel cell load sharing. In: 2015 IEEE vehicle power and propulsion conference, VPPC 2015 - proceedings; 2015. https://doi.org/10.1109/VPPC.2015.7352934.
[61] Whiston MM, Azevedo IL, Litster S, Whitefoot KS, Samaras C, Whitacre JF. Expert assessments of the cost and expected future performance of proton exchange membrane fuel cells for vehicles. Proc Natl Acad Sci U S A 2019;116:4899–904. https://doi.org/10.1073/PNAS.1804221116/SUPPL_FILE/PNAS.1804221116.SAPP.PDF.
[62] Interplex. The first hydrogen fuel cell vehicle was created in 1966. https://interplex.com/resources/the-first-hydrogen-fuel-cell-vehicle-was-created-in-1966/. [Accessed 16 August 2022].
[63] FASTECH. The surprising history of hydrogen vehicles. https://www.fastechus.com/blog/the-surprising-history-of-hydrogen-vehicles. [Accessed 16 August 2022].
[64] Heritage Center. General motors hydrogen fuel cell vehicles. 2022. 10.2/JQUERY.MIN.JS.
[65] Kurtz J, Sprik S, Bradley TH. Review of transportation hydrogen infrastructure performance and reliability. Int J Hydrogen Energy 2019;44:12010–23. https://doi.org/10.1016/J.IJHYDENE.2019.03.027.
[66] Samsun RC, Rex M, Antoni L, Stolten D. Deployment of fuel cell vehicles and hydrogen refueling station infrastructure: a global overview and perspectives. Energies 2022;15:4975. https://doi.org/10.3390/EN15144975.
[67] Asif U, Schmidt K. Fuel cell electric vehicles (FCEV): policy advances to enhance commercial success. Sustainability 2021;13:5149. https://doi.org/10.3390/SU13095149.
[68] Deloitte China. Fueling the future of mobility. Hydrogen and fuel cell solutions for transportation 2020.
[69] Samsun RC, Antoni L, Rex M. Mobile fuel cell application: tracking market trends. 2020.
[70] Chao DCH, Van Duijsen PJ, Hwang JJ, Liao CW. Modeling of a Taiwan fuel cell powered scooter. In: Proceedings of the international conference on power electronics and drive systems; 2009. p. 913–9. https://doi.org/10.1109/PEDS.2009.5385788.
[71] Han X, Li F, Zhang T, Zhang T, Song K. Economic energy management strategy design and simulation for a dual-stack fuel cell electric vehicle. Int J Hydrogen Energy 2017;42:11584–95. https://doi.org/10.1016/J.IJHYDENE.2017.01.085.
[72] Xu L, Ouyang M, Li J, Yang F, Lu L, Hua J. Application of Pontryagin's Minimal Principle to the energy management strategy of plugin fuel cell electric vehicles. Int J Hydrogen Energy 2013;38:10104–15. https://doi.org/10.1016/J.IJHYDENE.2013.05.125.
[73] Song K, Wang X, Li F, Sorrentino M, Zheng B. Pontryagin's minimum principle-based real-time energy management strategy for fuel cell hybrid electric vehicle considering both fuel economy and power source durability. Energy 2020;205: 118064. https://doi.org/10.1016/J.ENERGY.2020.118064.
[74] Sun H, Fu Z, Tao F, Zhu L, Si P. Data-driven reinforcement-learning-based hierarchical energy management strategy for fuel cell/battery/ultracapacitor hybrid electric vehicles. J Power Sources 2020;455:227964. https://doi.org/10.1016/J.JPOWSOUR.2020.227964.
[75] Changizian S, Ahmadi P, Raeesi M, Javani N. Performance optimization of hybrid hydrogen fuel cell-electric vehicles in real driving cycles. Int J Hydrogen Energy 2020;45:35180–97. https://doi.org/10.1016/J.IJHYDENE.2020.01.015.
[76] Lewis M, Hearn C, Feng X, Hanlin J, Levin J, Ambrosio J, et al. Design and modeling for hydrogen fuel cell conversion of parcel delivery trucks. In: 2017 IEEE transportation and electrification conference and expo, ITEC 2017; 2017. p. 674–8. https://doi.org/10.1109/ITEC.2017.7993350.
[77] D'Ovidio G, Masciovecchio C, Rotondale N. City bus powered by hydrogen fuel cell and flywheel energy storage system. In: IEEE international electric vehicle conference, IEVC 2014; 2014. https://doi.org/10.1109/IEVC.2014.7056107.
[78] Zhao A. Research on transmission system optimization of hydrogen fuel cell vehicle based on Simulink. In: Proceedings of 2021 IEEE international conference on emergency science and information technology. ICESIT; 2021. p. 946–50. https://doi.org/10.1109/ICESIT53460.2021.9696694. 2021.
[79] Turkmen AC, Solmaz S, Celik C. Analysis of fuel cell vehicles with advisor software. Renew Sustain Energy Rev 2017;70:1066–71. https://doi.org/10.1016/J.RSER.2016.12.011.
[80] Lane B, Shaffer B, Samuelsen GS. Plug-in fuel cell electric vehicles: a California case study. Int J Hydrogen Energy 2017;42:14294–300. https://doi.org/10.1016/J.IJHYDENE.2017.03.035.
[81] Hienuki S, Mitoma H, Ogata M, Uchida I, Kagawa S. Environmental and energy life cycle analyses of passenger vehicle systems using fossil fuel-derived hydrogen. Int J Hydrogen Energy 2021;46:36569–80. https://doi.org/10.1016/J.IJHYDENE.2021.08.135.
[82] Rosenfeld DC, Lindorfer J, Fazeni-Fraisl K. Comparison of advanced fuels—which technology can win from the life cycle perspective? J Clean Prod 2019;238: 117879. https://doi.org/10.1016/J.JCLEPRO.2019.117879.
[83] Yoo E, Kim M, Song HH. Well-to-wheel analysis of hydrogen fuel-cell electric vehicle in Korea. Int J Hydrogen Energy 2018;43:19267–78. https://doi.org/10.1016/J.IJHYDENE.2018.08.088.
[84] Lin T, Wu Y, He XY, Zhang SJ, Hao JM. Well-to-Wheels fossil energy consumption and CO 2 emissions of hydrogen fuel cell vehicles in China. Huanjing Kexue/Environmental Science 2018;39:3946–53. https://doi.org/10.13227/J.HJKX.201712113.
[85] 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;45:972–83. https://doi.org/10.1016/J.IJHYDENE.2019.10.192.
[86] Wang Q, Xue M, Lin B Le, Lei Z, Zhang Z. Well-to-wheel analysis of energy consumption, greenhouse gas and air pollutants emissions of hydrogen fuel cell vehicle in China. J Clean Prod 2020;275:123061. https://doi.org/10.1016/J.JCLEPRO.2020.123061.
[87] Li Y, Kimura S. Economic competitiveness and environmental implications of hydrogen energy and fuel cell electric vehicles in ASEAN countries: the current and future scenarios. Energy Pol 2021;148:111980. https://doi.org/10.1016/J.ENPOL.2020.111980.
[88] Joseck F, Wang M, Wu Y. Potential energy and greenhouse gas emission effects of hydrogen production from coke oven gas in U.S. steel mills. Int J Hydrogen Energy 2008;33:1445–54. https://doi.org/10.1016/J.IJHYDENE.2007.10.022.
[89] Tanç B, Arat HT, Conker Ç, Baltacioğlu E, Aydin K. Energy distribution analyses of an additional traction battery on hydrogen fuel cell hybrid electric vehicle. Int J Hydrogen Energy 2020;45:26344–56. https://doi.org/10.1016/J.IJHYDENE.2019.09.241.
[90] Nassif GG, Almeida SCA de. Impact of powertrain hybridization on the performance and costs of a fuel cell electric vehicle. Int J Hydrogen Energy 2020; 45:21722–37. https://doi.org/10.1016/J.IJHYDENE.2020.05.138.
[91] Kast J, Vijayagopal R, Gangloff JJ, Marcinkoski J. Clean commercial transportation: medium and heavy duty fuel cell electric trucks. Int J Hydrogen Energy 2017;42:4508–17. https://doi.org/10.1016/J.IJHYDENE.2016.12.129.
[92] Abouelkhair E, Salek F, Babaie M. Comparative energy analysis of the conventional and fuel cell electric powertrains for a medium-duty truck. SAE International Journal of Electrified Vehicles 2022;12. https://doi.org/10.4271/14-12-01-0004.
[93] Kurtz J, Sprik S, Saur G, Onorato S. On-road fuel cell electric vehicles evaluation. 2019. Overview.
[94] Paulina CM. Hydrogen fuel cell vehicle fuel economy testing at the U.S. EPA national vehicle and fuel emissions laboratory. SAE Technical Papers 2004. https://doi.org/10.4271/2004-01-2900.
[95] Xie C, Ogden JM, Quan S, Chen Q. Optimal power management for fuel cell–battery full hybrid powertrain on a test station. Int J Electr Power Energy Syst 2013;53:307–20. https://doi.org/10.1016/J.IJEPES.2013.05.016.
[96] Weigl JD, Saidi H. Inayati. Design, testing and optimisation of a hydrogen fuel cell motorcycle for South East Asia. In: 8th international conference and exhibition on ecological vehicles and renewable energies, EVER 2013; 2013. https://doi.org/10.1109/EVER.2013.6521632.
[97] Hwang JJ. Review on development and demonstration of hydrogen fuel cell scooters. Renew Sustain Energy Rev 2012;16:3803–15. https://doi.org/10.1016/J.RSER.2012.03.036.
[98] Mubenga NS, Stuart T. A case study on the hybridization of an electric vehicle into a fuel cell hybrid vehicle and the development of a solar powered hydrogen generating station. IEEE Power and Energy Society General Meeting; 2011. https://doi.org/10.1109/PES.2011.6039198.
[99] Venturi M, Mohrdieck C, Friedrich J. Mercedes-Benz B-Class Fuel Cell: the world largest hydrogen vehicle fuel cell fleet experience. In: 2013 world electric vehicle symposium and exhibition, EVS 2014; 2014. https://doi.org/10.1109/EVS.2013.6915019.
[100] Lewis M, Feng X, Hanlin J, Field M, Ambrosio J, Mabrey A. Model validation and demonstration of a hydrogen fuel cell parcel delivery truck. In: 2020 IEEE transportation electrification conference and expo, ITEC 2020; 2020. p. 1075–80. https://doi.org/10.1109/ITEC48692.2020.9161548.
[101] Takahashi Y. Running experiments of small single-operator electric vehicle using 20W hydrogen fuel cell. In: International conference on control, automation and systems; 2014. p. 704–9. https://doi.org/10.1109/ICCAS.2014.6987870.
[102] Takahashi Y. Simple optimum energy management control system for small fuel cell vehicle regarding remaining hydrogen and distance to destination. In: IEEE vehicle power and propulsion conference, VPPC 2017 - proceedings 2018; 2018-Janua. p. 1–5. https://doi.org/10.1109/VPPC.2017.8330982.
[103] Şefkat G, Özel MA. Experimental and numerical study of energy and thermal management system for a hydrogen fuel cell-battery hybrid electric vehicle. Energy 2022;238:121794. https://doi.org/10.1016/J.ENERGY.2021.121794.
[104] Ravchev J, Hristov G, Zahariev P, Kinaneva D. Design, development and evaluation of an electric urban concept vehicle prototype powered by a hydrogen fuel cell. In: 28th EAEEIE annual conference, EAEEIE 2018; 2018. https://doi.org/10.1109/EAEEIE.2018.8534240.
[105] Martel F, Kelouwani S, Dubé Y, Agbossou K. Optimal economy-based battery degradation management dynamics for fuel-cell plug-in hybrid electric vehicles. J Power Sources 2015;274:367–81. https://doi.org/10.1016/J.JPOWSOUR.2014.10.011.
[106] Şefkat G, Özel MA. Experimental and numerical study of energy and thermal management system for a hydrogen fuel cell-battery hybrid electric vehicle. Energy 2022;238:121794. https://doi.org/10.1016/J.ENERGY.2021.121794.

[107] Pathak S, Das JN, Rangarajan J, Choudhury SR, Prakash R. Development of prototype phosphoric acid fuel cell pick-up electric vehicle. In: 2006 IEEE conference on electric and hybrid vehicles, ICEHV; 2006. https://doi.org/10.1109/ICEHV.2006.352292.

[108] Lohse-Busch H, Stutenberg K, Duoba M, Liu X, Elgowainy A, Wang M, et al. Automotive fuel cell stack and system efficiency and fuel consumption based on vehicle testing on a chassis dynamometer at minus 18 °C to positive 35 °C temperatures. Int J Hydrogen Energy 2020;45:861–72. https://doi.org/10.1016/J.IJHYDENE.2019.10.150.

[109] BMW Group. Everyday testing of BMW i Hydrogen NEXT with hydrogen fuel cell drive train begins. https://www.press.bmwgroup.com/global/article/detail/T0334225EN/everyday-testing-of-bmw-i-hydrogen-next-with-hydrogen-fuel-cell-drive-train-begins?language=en. [Accessed 28 September 2022].

[110] Tang Y, Yuan W, Pan M, Wan Z. Experimental investigation on the dynamic performance of a hybrid PEM fuel cell/battery system for lightweight electric vehicle application. Appl Energy 2011;88:68–76. https://doi.org/10.1016/J.APENERGY.2010.07.033.

[111] Li J, Hu Z, Xu L, Ouyang M, Fang C, Hu J, et al. Fuel cell system degradation analysis of a Chinese plug-in hybrid fuel cell city bus. Int J Hydrogen Energy 2016;41:15295–310. https://doi.org/10.1016/J.IJHYDENE.2016.06.136.

[112] Jia Y, Wang H, Ouyang M. Electric power system for Chinese fuel cell city bus. Fuel Cell Bull 2006;2006:12–5. https://doi.org/10.1016/S1464-2859(06)71025-2.

[113] Hwang JJ, Wang DY, Shih NC. Development of a lightweight fuel cell vehicle. J Power Sources 2005;141:108–15. https://doi.org/10.1016/J.JPOWSOUR.2004.08.056.

[114] Motors Hyzon. Zero emission, hydrogen-powered vehicles. https://www.hyzonmotors.com/. [Accessed 27 January 2024].

[115] H2. Hydrogen vehicles. All models at a glance. https://h2.live/en/. [Accessed 27 January 2024].

[116] Kenworth. T680 Fuel cell electric vehicle. 2024. https://www.kenworth.com/. [Accessed 27 January 2024].

[117] Mizutani C, Shiozawa M, Maruo T, al Yunzhe J, Bowei Z, et al. Experimental study on the performance of FCV in standard test cycle. IOP Conf Ser Earth Environ Sci 2021;632:032014. https://doi.org/10.1088/1755-1315/632/3/032014.

[118] Sun T, Chen G, Lan H, Guo J, Wang X, Hao D. Experimental study on fuel economy of fuel cell truck under different driving cycle. In: 4th Asia conference on energy and electrical engineering. ACEEE; 2021. p. 38–43. https://doi.org/10.1109/ACEEE51855.2021.9575149. 2021.

[119] Kabir MM, Demirocak DE. Degradation mechanisms in Li-ion batteries: a state-of-the-art review. Int J Energy Res 2017;41:1963–86. https://doi.org/10.1002/ER.3762.

[120] Ferrara A, Jakubek S, Hametner C. Energy management of heavy-duty fuel cell vehicles in real-world driving scenarios: robust design of strategies to maximize the hydrogen economy and system lifetime. Energy Convers Manag 2021;232:113795. https://doi.org/10.1016/J.ENCONMAN.2020.113795.

[121] Teng T, Zhang X, Dong H, Xue Q. A comprehensive review of energy management optimization strategies for fuel cell passenger vehicle. Int J Hydrogen Energy 2020;45:20293–303. https://doi.org/10.1016/J.IJHYDENE.2019.12.202.

[122] Xu L, Yang F, Li J, Ouyang M, Hua J. Real time optimal energy management strategy targeting at minimizing daily operation cost for a plug-in fuel cell city bus. Int J Hydrogen Energy 2012;37:15380–92. https://doi.org/10.1016/J.IJHYDENE.2012.07.074.

[123] Chen Z, Guo N, Zhang Q, Shen J, Xiao R. An optimized rule based energy management strategy for a fuel cell/battery vehicle. In: 2017 IEEE vehicle power and propulsion conference, VPPC 2017 - proceedings 2018; 2018-Janua:1–6. https://doi.org/10.1109/VPPC.2017.8330991.

[124] Ravey A, Blunier B, Miraoui A. Control strategies for fuel-cell-based hybrid electric vehicles: from offline to online and experimental results. IEEE Trans Veh Technol 2012;61:2452–7. https://doi.org/10.1109/TVT.2012.2198680.

[125] Zhou W, Yang L, Cai Y, Ying T. Dynamic programming for new energy vehicles based on their work modes Part II: fuel cell electric vehicles. J Power Sources 2018;407:92–104. https://doi.org/10.1016/J.JPOWSOUR.2018.10.048.

[126] Tao S, Chen W, Gan R, Li L, Zhang G, Han Y, et al. Energy management strategy based on dynamic programming with durability extension for fuel cell hybrid tramway. Railway Engineering Science 2021;29:299–313. https://doi.org/10.1007/S40534-021-00247-W/TABLES/4.

[127] Meng X, Li Q, Zhang G, Chen W. Efficient multidimensional dynamic programming-based energy management strategy for global composite operating cost minimization for fuel cell trams. IEEE Transactions on Transportation Electrification 2022;8:1807–18. https://doi.org/10.1109/TTE.2021.3120425.

[128] Ma Y, Li C, Wang S. Multi-objective energy management strategy for fuel cell hybrid electric vehicle based on stochastic model predictive control. ISA Trans 2022. https://doi.org/10.1016/J.ISATRA.2022.04.045.

[129] Raeesi M, Changizian S, Ahmadi P, Khoshnevisan A. Performance analysis of a degraded PEM fuel cell stack for hydrogen passenger vehicles based on machine learning algorithms in real driving conditions. Energy Convers Manag 2021;248:114793. https://doi.org/10.1016/J.ENCONMAN.2021.114793.

[130] Xu L, Mueller CD, Li J, Ouyang M, Hu Z. Multi-objective component sizing based on optimal energy management strategy of fuel cell electric vehicles. Appl Energy 2015;157:664–74. https://doi.org/10.1016/J.APENERGY.2015.02.017.

[131] Hu Z, Li J, Xu L, Song Z, Fang C, Ouyang M, et al. Multi-objective energy management optimization and parameter sizing for proton exchange membrane hybrid fuel cell vehicles. Energy Convers Manag 2016;129:108–21. https://doi.org/10.1016/J.ENCONMAN.2016.09.082.

[132] Min D, Song Z, Chen H, Wang T, Zhang T. Genetic algorithm optimized neural network based fuel cell hybrid electric vehicle energy management strategy under start-stop condition. Appl Energy 2022;306:118036. https://doi.org/10.1016/J.APENERGY.2021.118036.

[133] Bizon N, Lopez-Guede JM, Kurt E, Thounthong P, Mazare AG, Ionescu LM, et al. Hydrogen economy of the fuel cell hybrid power system optimized by air flow control to mitigate the effect of the uncertainty about available renewable power and load dynamics. Energy Convers Manag 2019;179:152–65. https://doi.org/10.1016/J.ENCONMAN.2018.10.058.

[134] Erdinc O, Vural B, Uzunoglu M, Ates Y. Modeling and analysis of an FC/UC hybrid vehicular power system using a wavelet-fuzzy logic based load sharing and control algorithm. Int J Hydrogen Energy 2009;34:5223–33. https://doi.org/10.1016/J.IJHYDENE.2008.10.039.

[135] Erdinc O, Vural B, Uzunoglu M. A wavelet-fuzzy logic based energy management strategy for a fuel cell/battery/ultra-capacitor hybrid vehicular power system. J Power Sources 2009;194:369–80. https://doi.org/10.1016/J.JPOWSOUR.2009.04.072.

[136] Zheng CH, Xu GQ, Park YI, Lim WS, Cha SW. Prolonging fuel cell stack lifetime based on Pontryagin's Minimum Principle in fuel cell hybrid vehicles and its economic influence evaluation. J Power Sources 2014;248:533–44. https://doi.org/10.1016/J.JPOWSOUR.2013.09.110.

[137] Ou K, Yuan WW, Choi M, Yang S, Jung S, Kim YB. Optimized power management based on adaptive-PMP algorithm for a stationary PEM fuel cell/battery hybrid system. Int J Hydrogen Energy 2018;43:15433–44. https://doi.org/10.1016/J.IJHYDENE.2018.06.072.

[138] Zhou Y, Ravey A, Péra MC. Multi-mode predictive energy management for fuel cell hybrid electric vehicles using Markov driving pattern recognizer. Appl Energy 2020;258:114057. https://doi.org/10.1016/J.APENERGY.2019.114057.

[139] Pereira DF, Lopes FDC, Watanabe EH. Nonlinear model predictive control for the energy management of fuel cell hybrid electric vehicles in real time. IEEE Trans Ind Electron 2021;68:3213–23. https://doi.org/10.1109/TIE.2020.2979528.

[140] Pereira DF, Da Costa Lopes F, Watanabe EH. Neural generalized predictive control for tracking maximum efficiency and maximum power points of PEM fuel cell stacks. In: 44th annual conference of the IEEE industrial electronics society; 2018. p. 1878–83. https://doi.org/10.1109/IECON.2018.8591290.

[141] Wang H, Huang Y, Khajepour A, Song Q. Model predictive control-based energy management strategy for a series hybrid electric tracked vehicle. Appl Energy 2016;182:105–14. https://doi.org/10.1016/J.APENERGY.2016.08.085.

[142] Tang X, Zhou H, Wang F, Wang W, Lin X. Longevity-conscious energy management strategy of fuel cell hybrid electric Vehicle Based on deep reinforcement learning. Energy 2022;238:121593. https://doi.org/10.1016/J.ENERGY.2021.121593.

[143] Venkatasatish R, Dhanamjayulu C. Reinforcement learning based energy management systems and hydrogen refuelling stations for fuel cell electric vehicles: an overview. Int J Hydrogen Energy 2022;47:27646–70. https://doi.org/10.1016/J.IJHYDENE.2022.06.088.

[144] Lee H, Cha SW. Energy management strategy of fuel cell electric vehicles using model-based reinforcement learning with data-driven model update. IEEE Access 2021;9:59244–54. https://doi.org/10.1109/ACCESS.2021.3072903.

[145] Onat NC, Abdella GM, Kucukvar M, Kutty AA, Al-Nuaimi M, Kumbaroğlu G, et al. How eco-efficient are electric vehicles across Europe? A regionalized life cycle assessment-based eco-efficiency analysis. Sustain Dev 2021;29:941–56. https://doi.org/10.1002/SD.2186.

[146] Candelaresi D, Valente A, Iribarren D, Dufour J, Spazzafumo G. Comparative life cycle assessment of hydrogen-fuelled passenger cars. Int J Hydrogen Energy 2021;46:35961–73. https://doi.org/10.1016/J.IJHYDENE.2021.01.034.

[147] Offer GJ, Contestabile M, Howey DA, Clague R, Brandon NP. Techno-economic and behavioural analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system in the UK. Energy Pol 2011;39:1939–50. https://doi.org/10.1016/J.ENPOL.2011.01.006.

[148] Zhang G, Zhang J, Xie T. A solution to renewable hydrogen economy for fuel cell buses – a case study for Zhangjiakou in North China. Int J Hydrogen Energy 2020;45:14603–13. https://doi.org/10.1016/J.IJHYDENE.2020.03.206.

[149] Wang X, Zhang LW-FL. CO2 emission reduction effect of electric Bus Based on energy chain in life cycle. Journal of Transportation Systems Engineering and Information Technology 2019;19:19–25.

[150] Huang Z, Zhang X. Well-to-wheels analysis of hydrogen based fuel-cell vehicle pathways in Shanghai. Energy 2006;31:471–89. https://doi.org/10.1016/J.ENERGY.2005.02.019.

[151] Li Y, Taghizadeh-Hesary F. The economic feasibility of green hydrogen and fuel cell electric vehicles for road transport in China. Energy Pol 2022;160:112703. https://doi.org/10.1016/J.ENPOL.2021.112703.

[152] Ugurlu A. An emission analysis study of hydrogen powered vehicles. Int J Hydrogen Energy 2020;45:26522–35. https://doi.org/10.1016/J.IJHYDENE.2020.05.156.

[153] Li J, Liang M, Cheng W, Wang S. Life cycle cost of conventional, battery electric, and fuel cell electric vehicles considering traffic and environmental policies in China. Int J Hydrogen Energy 2021;46:9553–66. https://doi.org/10.1016/J.IJHYDENE.2020.12.100.

[154] Sharma A, Strezov V. Life cycle environmental and economic impact assessment of alternative transport fuels and power-train technologies. Energy 2017;133:1132–41. https://doi.org/10.1016/J.ENERGY.2017.04.160.

[155] Wei QS, Zhang X, Oh BS. The effect of driving cycles and H2 production pathways on the lifecycle analysis of hydrogen fuel cell vehicle: a case study in South Korea. Int J Hydrogen Energy 2021;46:7622–33. https://doi.org/10.1016/J.IJHYDENE.2020.09.024.

[156] Bicer Y, Dincer I. Comparative life cycle assessment of hydrogen, methanol and electric vehicles from well to wheel. Int J Hydrogen Energy 2017;42:3767–77. https://doi.org/10.1016/J.IJHYDENE.2016.07.252.
[157] Lajunen A, Lipman T. Lifecycle cost assessment and carbon dioxide emissions of diesel, natural gas, hybrid electric, fuel cell hybrid and electric transit buses. Energy 2016;106:329–42. https://doi.org/10.1016/J.ENERGY.2016.03.075.
[158] Elgowainy A, Han J, Ward J, Joseck F, Gohlke D, Lindauer A, et al. Current and future United States light-duty vehicle pathways: cradle-to-grave lifecycle greenhouse gas emissions and economic assessment. Environ Sci Technol 2018; 52:2392–9. https://doi.org/10.1021/ACS.EST.7B06006/SUPPL_FILE/ES7B06006_SI_002.XLSX.
[159] He X, Wang F, Wallington TJ, Shen W, Melaina MW, Kim HC, et al. Well-to-wheels emissions, costs, and feedstock potentials for light-duty hydrogen fuel cell vehicles in China in 2017 and 2030. Renew Sustain Energy Rev 2021;137: 110477. https://doi.org/10.1016/J.RSER.2020.110477.
[160] Teimouri A, Zayer Kabeh K, Changizian S, Ahmadi P, Mortazavi M. Comparative lifecycle assessment of hydrogen fuel cell, electric, CNG, and gasoline-powered vehicles under real driving conditions. Int J Hydrogen Energy 2022. https://doi.org/10.1016/J.IJHYDENE.2022.08.298.
[161] Zhang X, Lin Z, Crawford C, Li S. Techno-economic comparison of electrification for heavy-duty trucks in China by 2040. Transp Res D Transp Environ 2022;102: 103152. https://doi.org/10.1016/J.TRD.2021.103152.
[162] Gustafsson M, Svensson N, Eklund M, Dahl Öberg J, Vehabovic A. Well-to-wheel greenhouse gas emissions of heavy-duty transports: influence of electricity carbon intensity. Transp Res D Transp Environ 2021;93:102757. https://doi.org/10.1016/J.TRD.2021.102757.
[163] Lee DY, Elgowainy A, Kotz A, Vijayagopal R, Marcinkoski J. Life-cycle implications of hydrogen fuel cell electric vehicle technology for medium- and heavy-duty trucks. J Power Sources 2018;393:217–29. https://doi.org/10.1016/J.JPOWSOUR.2018.05.012.
[164] Nealer R, Hendrickson TP. Review of recent lifecycle assessments of energy and greenhouse gas emissions for electric vehicles. Current Sustainable/Renewable Energy Reports 2015;2:66–73. https://doi.org/10.1007/S40518-015-0033-X/FIGURES/1.
[165] Zamel N, Li X. Life cycle comparison of fuel cell vehicles and internal combustion engine vehicles for Canada and the United States. J Power Sources 2006;162: 1241–53. https://doi.org/10.1016/J.JPOWSOUR.2006.08.007.
[166] Nguyen T, Ward J, Johnson K. Well-to-Wheels greenhouse gas emissions and petroleum use for mid-size light-duty vehicles. 2013.
[167] Lee DY, Elgowainy A, Vijayagopal R. Well-to-wheel environmental implications of fuel economy targets for hydrogen fuel cell electric buses in the United States. Energy Pol 2019;128:565–83. https://doi.org/10.1016/J.ENPOL.2019.01.021.
[168] Wong CEY, Ho DCK, So S, Tsang C-W, Chan EMH. Life cycle assessment of electric vehicles and hydrogen fuel cell vehicles using the GREET model—a comparative study. Sustainability 2021;13:4872. https://doi.org/10.3390/SU13094872.
[169] Chen Y, Lan L, Hao Z, Fu P. Cradle-grave energy consumption, greenhouse gas and acidification emissions in current and future fuel cell vehicles: study based on five hydrogen production methods in China. Energy Rep 2022;8:7931–44. https://doi.org/10.1016/J.EGYR.2022.06.021.
[170] Ahmadi P, Khoshnevisan A. Dynamic simulation and lifecycle assessment of hydrogen fuel cell electric vehicles considering various hydrogen production methods. Int J Hydrogen Energy 2022;47:26758–69. https://doi.org/10.1016/J.IJHYDENE.2022.06.215.
[171] Pereira SR, Coelho MC. Life cycle analysis of hydrogen – a well-to-wheels analysis for Portugal. Int J Hydrogen Energy 2013;38:2029–38. https://doi.org/10.1016/J.IJHYDENE.2012.12.029.
[172] Hwang JJ, Kuo JK, Wu W, Chang WR, Lin CH, Wang SE. Lifecycle performance assessment of fuel cell/battery electric vehicles. Int J Hydrogen Energy 2013;38: 3433–46. https://doi.org/10.1016/J.IJHYDENE.2012.12.148.
[173] Ren L, Zhou S, Ou X. Life-cycle energy consumption and greenhouse-gas emissions of hydrogen supply chains for fuel-cell vehicles in China. Energy 2020; 209:118482. https://doi.org/10.1016/J.ENERGY.2020.118482.
[174] Lajevardi MS, Axsen J, Crawford C. Comparing alternative heavy-duty drivetrains based on GHG emissions, ownership and abatement costs: simulations of freight routes in British Columbia. Transp Res D Transp Environ 2019;76:19–55. https://doi.org/10.1016/J.TRD.2019.08.031.
[175] Forrest K, Mac Kinnon M, Tarroja B, Samuelsen S. Estimating the technical feasibility of fuel cell and battery electric vehicles for the medium and heavy duty sectors in California. Appl Energy 2020;276:115439. https://doi.org/10.1016/J.APENERGY.2020.115439.
[176] Lao J, Song H, Wang C, Zhou Y, Wang J. Reducing atmospheric pollutant and greenhouse gas emissions of heavy duty trucks by substituting diesel with hydrogen in Beijing-Tianjin-Hebei-Shandong region, China. Int J Hydrogen Energy 2021;46:18137–52. https://doi.org/10.1016/J.IJHYDENE.2020.09.132.
[177] Breuer JL, Samsun RC, Stolten D, Peters R. How to reduce the greenhouse gas emissions and air pollution caused by light and heavy duty vehicles with battery-electric, fuel cell-electric and catenary trucks. Environ Int 2021;152:106474. https://doi.org/10.1016/J.ENVINT.2021.106474.
[178] Liu F, Mauzerall DL, Zhao F, Hao H. Deployment of fuel cell vehicles in China: greenhouse gas emission reductions from converting the heavy-duty truck fleet from diesel and natural gas to hydrogen. Int J Hydrogen Energy 2021;46: 17982–97. https://doi.org/10.1016/J.IJHYDENE.2021.02.198.
[179] Ren L, Zhou S, Peng T, Ou X. Greenhouse gas life cycle analysis of China's fuel cell medium- and heavy-duty trucks under segmented usage scenarios and vehicle types. Energy 2022;249:123628. https://doi.org/10.1016/J.ENERGY.2022.123628.
[180] Offer GJ, Howey D, Contestabile M, Clague R, Brandon NP. Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. Energy Pol 2010;38:24–9. https://doi.org/10.1016/J.ENPOL.2009.08.040.
[181] Horvath S, Fasihi M, Breyer C. Techno-economic analysis of a decarbonized shipping sector: technology suggestions for a fleet in 2030 and 2040. Energy Convers Manag 2018;164:230–41. https://doi.org/10.1016/J.ENCONMAN.2018.02.098.
[182] Chen Y, Melaina M. Model-based techno-economic evaluation of fuel cell vehicles considering technology uncertainties. Transp Res D Transp Environ 2019;74: 234–44. https://doi.org/10.1016/J.TRD.2019.08.002.
[183] Cox B, Bauer C, Mendoza Beltran A, van Vuuren DP, Mutel CL. Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios. Appl Energy 2020;269:115021. https://doi.org/10.1016/J.APENERGY.2020.115021.
[184] de Miranda PEV, Carreira ES, Icardi UA, Nunes GS. Brazilian hybrid electric-hydrogen fuel cell bus: improved on-board energy management system. Int J Hydrogen Energy 2017;42:13949–59. https://doi.org/10.1016/J.IJHYDENE.2016.12.155.
[185] Jeong KS, Oh BS. Fuel economy and life-cycle cost analysis of a fuel cell hybrid vehicle. J Power Sources 2002;105:58–65. https://doi.org/10.1016/S0378-7753(01)00965-X.
[186] Whiston MM, Azevedo I, Litster S, Whitefoot K, Samaras C, Whitacre J. Total cost of ownership of fuel cell electric vehicles using expert assessments. ECS Meeting Abstracts 2018:1419. https://doi.org/10.1149/MA2018-02/42/1419. MA2018-02.
[187] Wróblewski P, Drożdż W, Lewicki W, Dowejko J. Total cost of ownership and its potential consequences for the development of the hydrogen fuel cell powered vehicle market in Poland. Energies 2021;14:2131. https://doi.org/10.3390/EN14082131.
[188] Jones J, Genovese A, Tob-Ogu A. Hydrogen vehicles in urban logistics: a total cost of ownership analysis and some policy implications. Renew Sustain Energy Rev 2020;119:109595. https://doi.org/10.1016/J.RSER.2019.109595.
[189] Ally J, Pryor T. Life cycle costing of diesel, natural gas, hybrid and hydrogen fuel cell bus systems: an Australian case study. Energy Pol 2016;94:285–94. https://doi.org/10.1016/J.ENPOL.2016.03.039.
[190] Wood E, Wang L, Gonder J, Ulsh M. Overcoming the range limitation of medium-duty battery electric vehicles through the use of hydrogen fuel-cells. SAE Int J Commer Veh 2013;6:563–74. https://doi.org/10.4271/2013-01-2471.
[191] Lorenzo C, Mendoza DS, Rey JM, Bouquain D, Hibon S, Hissel D, et al. Sizing and energy management strategy impact on the total cost of ownership in fuel cell electric vehicles. In: IEEE vehicle power and propulsion conference, VPPC 2020 - proceedings; 2020. https://doi.org/10.1109/VPPC49601.2020.9330961.