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Comparative life cycle analysis of hydrogen fuel cell electric vehicles and battery electric vehicles: An Indian perspective

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ABSTRACT

India aims to decarbonize the transportation sector with 30% penetration of battery-electric vehicles (BEVs) in four-wheeler segment by 2030. Fuel cell electric vehicles (FCEVs) using hydrogen could be alternate solution for achieving the target of GHG emission reduction. This work presents a comparative life cycle GHG emission analysis of FCEVs (for eight hydrogen production pathways) and BEVs (for 2023 and 2030 Indian electricity mix) using GREET model. The results revealed that FCEV powered with green hydrogen has the least emission of 105 gCO_2/km. FCEV with blue hydrogen (CG + CS) has life cycle emissions of 141 gCO_2/km, which is lesser than that of BEV for the present (185 gCO_2/km) and also 2030 (141 gCO_2/km) energy mix. Sensitivity analysis has revealed the impact of lifetime distance, fuel cell degradation, and battery replacement on lifecycle emissions. FCEVs can achieve sustainable transport with blue hydrogen for near future and green hydrogen for long run.

Nomenclature

Abbreviations	
BEV	Battery electric vehicle
CCS	Carbon capture and storage
CCU	Carbon capture and usage
CCUS	Carbon capture utilization and storage
CEA	Central electricity authority
CG	Coal gasification
CNG	Compressed natural gas
DC	Direct current
ECR	Energy consumption rate
EPS	Electrical power survey
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
GHG	Green house gases
GREET	Greenhouse gases, regulated emissions, and energy use in technologies
GWP	Global warming potential
HD	Heavy duty
HEV	Hybrid electric vehicle
ICEV	Internal combustion engine vehicle
IEA	International energy agency
INDC	Intended nationally determined contributions
IPCC	Intergovernmental panel on climate change
IRENA	International renewable energy agency
LCA	Life cycle analysis
MNRE	Ministry of new and renewable energy
MoRTH	Ministry of road transport and highways
MPNG	Ministry of petroleum and natural gases
NG	Natural gas
NHERM	National hydrogen energy road map
NHM	National hydrogen mission
Ni-MH	Nickel metal hydride
NITI	National institution for transforming India
OEM	Original equipment manufacturer
PEMFC	Proton exchange membrane fuel cell
PSA	Pressure swing adsorption
RMI	Rocky mountain institute
SMR	Steam methane reforming
SUV	Sports utility vehicle
TWW	Tank-to-Wheel
WGS	Water-gas-shift
WTT	Well-to-Tank
WTW	Well-to-Wheel

Symbols and units

$E_{life\ cycle}$	Life cycle GHG emissions of a vehicle-fuel system
$E_{vehicle\ cycle}$	GHG emissions of vehicle cycle
$E_{fuel\ cycle}$	GHG emissions of fuel cycle

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(*continued*)

$E_{vehicle\ system}$	GHG emissions due to vehicle system components manufacturing
$E_{battery}$	GHG emissions due to battery manufacturing
E_{tyre}	GHG emissions due to tyre manufacturing
$E_{oil\ and\ fluids}$	GHG emissions due to oil and fluids production
$m_{vehicle\ system}$	Weight of vehicle system components
$m_{battery}$	Weight of battery
m_{tyre}	Weight of tyre
$m_{oil\ and\ fluids}$	Weight of oil and fluids
$e_{vehicle\ system}$	Emission factor of vehicle system components
$e_{battery}$	Emission factor of battery
e_{tyre}	Emission factor of tyre
$e_{oil\ and\ fluids}$	Emission factor of oil and fluids
CO_2	Carbon dioxide
CO	Carbon monoxide
H_2	Hydrogen
Li	Lithium
CH_4	Methane
N_2O	Nitrous oxide
O_2	Oxygen
Ah	Ampere hour
cc	Cubic centimetre
CO_2-eq	Equivalent carbon dioxide
GW	Giga watt
kW	Kilo watt
kWh	Kilo Watt-hour
kg	Kilogram
km	Kilometer
L	Litre
MMT	Million metric tonnes

1. Introduction

In India, the transportation sector contributes significantly to total energy demand/consumption and its related greenhouse gas emissions (~13% of the total in 2021) [1]. Hence, it is a potential sector that can be decarbonized to reach the future GHG emission reduction targets. India is promoting alternate fuel source vehicles, like battery electric vehicles (BEVs), as potential substitutes for conventional internal combustion engine vehicles (ICEV) since they emit zero tailpipe emissions. The Government of India targets to create demand for BEVs through phase II of the Faster Adoption of Manufacturing of Electric Vehicles (FAME) scheme [2]. The sale of BEV passenger cars has risen at a CAGR of 191% in the last four years, from 1019 units in 2019 to 73,282 units in 2023 [3]. Though BEVs are emerging as an ideal solution for urban mobility, technological constraints like traction battery recharging time, range anxiety, load on the power grid, etc., have questioned BEV's operational feasibility [4]. Though extended-range BEVs and battery-swapping technologies have addressed the issue of range anxiety, the upfront cost of setting up battery-swapping stations, operational cost of BEVs, increased battery material requirements, and battery degradation due to rapid charging are some of the concerns. The present Indian energy mix is dominated by coal-powered thermal power plants (~74% of total electricity generated) [5], with a specific CO_2 emission of 0.91 kg/kWh [6]. Hence, BEV's lifecycle GHG emissions are unlikely to significantly contribute to decarbonizing the transportation sector [7]. Our previous studies [8,9] revealed that the lifecycle GHG emissions of BEVs depend on lifetime travel distance. Until ~120,000 km, BEVs do not benefit in achieving GHG emission reduction targets unless the electricity generation gets cleaner.

A potential alternative to BEVs is electric vehicles powered by fuel cells using hydrogen (H_2), commonly called FCEVs (Fuel Cell Electric Vehicles). In FCEV, hydrogen generates electricity using a fuel cell, which drives the electric motor. Hydrogen is the cleanest fuel, with only water as the combustion product. In addition to being sustainable and having almost zero tailpipe emissions, FCEVs have several advantages over BEVs, such as fast refueling, long travel range, high power density, and less well-to-wheel energy, which makes them highly valued [10,11]. Several researchers globally have already foreseen FCEVs as a viable solution for sustainable transport. Currently, BEVs are superior to FCEVs in terms of costs and infrastructure availability. With rapid development in technology and infrastructure, capital and operating costs of FCEVs are expected to reduce significantly [12]. The IEA analysis finds that the cost of green hydrogen production could be reduced by 30% by 2030 [13]. Vengatesan et al. [14] show that the cost per kg of green hydrogen in India may reduce to INR 100/kg by 2040 compared to the current cost of INR 350/kg. Many automobile companies have engaged in research and development of technologies for manufacturing efficient FCEVs. FCEVs are already operational in Japan, Europe, and the USA. It is speculated that the Hyundai Nexo and Toyota Mirai will be the maiden FCEV models expected to enter the Indian automobile market by 2025 [15].

The government of India announced the launch of the National Hydrogen Mission (NHM), which aims to produce green hydrogen and use it in multiple sectors, including transportation. Currently, in India, conventional methods of bulk hydrogen production are steam methane reforming (SMR) of natural gas and coal gasification (CG), which result in large CO_2 emissions. These emissions can be reduced by carbon capture and storage (CCS) or carbon capture usage (CCU) techniques. Hydrogen produced using SMR coupled with CCS is called blue hydrogen. A potential alternate large-scale hydrogen production route is water electrolysis. However, if the electricity required for the electrolysis is obtained from the grid, mainly contributed by the coal-thermal route in India, it results in significant CO_2 emissions. Hydrogen produced through electrolysis using electricity from renewable routes (like wind and solar), known as green hydrogen, has been found to have the lowest GHG emissions. However, due to higher renewable electricity charges, green hydrogen costs at least double that of the SMR route [16].

FCEV's net life cycle emissions depend on the hydrogen production route and may be greater than BEV's. In this regard, many researchers across the globe have performed and analyzed the life cycle assessment of hydrogen production pathways and FCEVs. A summary of previous literature and critical findings is given in Table S1 of the supplementary material. The referred previous literature concludes that the FCEVs using green hydrogen have the least lifecycle GHG emissions compared to BEVs and FCEVs using either grey or blue hydrogen [10,17–28].

Yoo et al. [29] determined that FCEVs using hydrogen produced by electrolysis using grid electricity have higher WTW emissions than other hydrogen production methods in Korea. Weger et al. [30] also obtained a similar result due to a possible transition towards a hydrogen economy in German road transport. In Nepal, Joshi et al. [31] revealed that 100% renewable energy-based electricity can reduce upstream emissions by 88%. The study by Ahmadi and Khoshnevisan [25] revealed that after 6000 h of operations, the fuel cell degradation results in an 11.1% voltage drop and a 14.3% increase in fuel consumption. However, the degradation effect is negligible in the case of FCEV using green hydrogen. Stropnik et al. [32] developed a semi-empirical PEMFC model that included cell degradation effects and integrated it into LCA to achieve a more realistic and accurate evaluation of environmental impacts. The study considered green hydrogen produced via., hydro, wind, and PV electricity and compared it with the SMR of NG. The results revealed that green hydrogen with wind electricity has the least environmental effect compared to others. Di Lullo et al. [33] analyzed the possible reduction of CO_2 emissions by transporting blue hydrogen and NG (Hythane). The results revealed that WTW emissions were reduced by 2.8% for hythane with 15% hydrogen incorporating 100% CCS. Kelly and Zhou [26] revealed that the cost of green hydrogen at the pumps in India will be 1.5 times more expensive than blue hydrogen in 2030, and by 2050, it will be cost-competitive. Kumaraswamy et al. [34] showed that the synergistic production of blue hydrogen is important in allowing time for green hydrogen to attain cost parity. Mac Kinnon et al. [35] explained that light-duty FCEVs can reduce ozone and $PM_{2.5}$ levels, aiding decision-makers in developing effective strategies to improve air quality in the transportation sector. Lombardi et al. [36] and Da Costa et al. [37] also revealed that environmental factors like GWP, $PM_{2.5}$, and fossil depletion are reduced due to the FCEV transition over ICEVs.

The Government of India aims to penetrate 30% of the Indian automobile market with electric vehicles (4-wheeler segment) through the FAME scheme. As noted earlier, FECVs can be alternate solutions to the BEVs. To assess the prospects of FCEVs in India, a thorough life cycle assessment of FCEVs fueled by hydrogen produced through different pathways is required. The present study has addressed this critical issue. Relatively small previous literature is available in this context. Das [22] has performed LCA of hydrogen production through proton exchange membrane water electrolysis (PEMWE) using solar electricity and FCEV in Indian conditions without accounting for the vehicle cycle emissions. Mansuri et al. [38] have discussed shifting from ICEVs to FCEVs using solar-powered PEMFC as a case study in an Indian smart city. However, this study could only address the CO_2 emission reduction from tailpipes and did not address tank-to-wheel and vehicle cycle emissions. Vengatesan et al. [14] have compared the potential and prospects of FCEV (as an alternative to BEV) in the Indian transport sector. Although the authors conclude that the total cost of ownership of FCEV would be smaller than BEV for 12 years or more, the study does not account for detailed life cycle emissions of FCEV, which are essential from the viewpoint of their long-term environmental impact. Jayakumar et al. [10] have critically assessed hydrogen as a sustainable fuel for Indian mobility applications in the global context and have also demonstrated various challenges. Wong et al. [26] have estimated the at-the-pump cost of hydrogen produced through SMR with CCS or electrolysis (blue and green hydrogen, respectively) for major Indian cities. The major components contributing to the cost of hydrogen were deduced as production, transport, at-site storage and fueling, and other tariffs in the supply chain. Nonetheless, Wong et al. [26] didn't account for FCEV's complete life cycle emissions. Moreover, the previous literature has also not given an extensive sensitivity analysis of the impact of operational factors on the life cycle emissions of BEVs and FCEVs.

In view of the previous literature, two significant novel contributions of this study are: (1) a rigorous life cycle analysis of FCEV, including GHG emissions in both the vehicle and fuel life cycles (for different hydrogen production pathways, including carbon sequestration) in the Indian context. This analysis is benchmarked against BEV of similar specifications. (2) an in-depth sensitivity analysis of BEV and FCEV for factors like lifetime travel distance, battery lifespan, and fuel cell degradation to verify their impacts on life cycle GHG emissions. In addition, we have also discussed the policy implications of our results for the industry and the Government. Greenhouse gases, Regulated Emissions, and Energy Use in Technologies (GREET) software has been used to estimate both vehicle and fuel lifecycle emissions of BEVs and FCEVs. A brief introduction to this software is given below.

1.1. GREET software: A brief introduction

The GREET software is developed by Argonne National Laboratory and examines the life cycle impacts of vehicle technologies, fuels, products, and energy systems. For any given energy or fuel type and vehicle system, GREET can calculate total energy consumption, air pollutants, emissions of greenhouse gases, and water consumption. GREET software has a vast, inbuilt database of various components and processes required for different types of vehicles and fuel pathways. The models of various vehicle system components and processes related to fuel pathways are available for various scenarios. These models in the GREET are editable as per the user's requirement. We can also use the available database and create a new model using the data editor section of GREET. In our study, the existing models are expanded, and the various input parameter values (like electricity mix, transportation mode and share, distances, weights of various materials, etc.) and any other assumptions are modified in the model and simulated to get the GHG emission values to estimate the Global Warming Potential.

Each pathway in a system (for example, vehicle cycle or fuel cycle in the present context) is a sequence of processes (stationery processes - for example, the hydrogen production plant, and transportation – which includes transportation of natural gas to the plant and hydrogen from the plant). Each process has one or more inputs and a single output – which is hydrogen in the present context. Besides the main output, a process might produce coproducts – for example, CO_2 emissions. Every input, output, and coproduct is a resource. There might be a loss (leakage, boil-off, etc.) associated with any of the inputs or outputs of a process. Within a process, inputs might be associated with technologies comprising different kinds of reactors, heat transfer systems, condensers, and other downstream processes. The flow of the calculations in the GREET model accounts for all the resources and technologies used in the processes of a pathway and then combines them to calculate the energy and emissions associated with each pathway. Each pathway has a single main product. The calculated energy and emissions of a pathway are used as upstream values for the corresponding product when the product is used as an input to any process within the model. Iterative calculations are used to converge the solution with improvement in accuracy.

2. Life cycle analysis (LCA) – methodology

LCA is essentially an estimation of the GHG emissions by a particular vehicle-fuel system during its lifetime. As per the GREET model, the LCA of a vehicle-fuel system includes estimating total GHG emissions by assessing both vehicle and fuel life cycles from cradle to grave under a single system boundary. The main lifecycle stages covered in the vehicle and fuel cycle models are shown in Fig. 1 [21,39,40]. The total life cycle GHG emissions of a vehicle $E_{life\ cycle}$ can be calculated as

$$E_{life\ cycle} = E_{vehicle\ cycle} + E_{fuel\ cycle} \tag{1}$$

$E_{vehicle\ cycle}$ and $E_{fuel\ cycle}$ being the GHG emissions of vehicle and fuel cycles.

The vehicle (equipment) life cycle estimates GHG emissions during the raw material recovery and extraction, material processing and fabrication, components manufacturing, vehicle assembly, maintenance, recycling, and disposal. The fuel cycle consists of two pathways: well-to-tank (WTT) and tank-to-wheel (TTW). WTT pathway estimates GHG emissions during recovery and extraction of primary feedstock, feedstock transportation, fuel production from feedstock, and transportation and distribution of fuel. The TTW pathway estimates the GHG emissions from fuel use during vehicle operation.

The functional unit for measuring GHG emissions is gCO_2-eq. per km travel, which compares the potential of emitted gases to cause global warming relative to CO_2. Referring to the equivalent CO_2 values for CO_2, CH_4, and N_2O from the latest 6th Assessment report by IPCC [42,43], the total Global Warming Potential can be calculated in terms of CO_2-eq. as given in equation (2).

$$Eq.CO_2(g) = CO_2(g) + CH_4(g) \times 29.8 + N_2O(g) \times 273 \tag{2}$$

This comparative LCA study investigates whether hydrogen-powered FCEVs can be a suitable replacement for ICEVs instead of BEVs to reduce CO_2 emissions and global warming potential. For this analysis, this study has considered eight different combinations of hydrogen production pathways: (i) Steam Methane Reforming (SMR), (ii) SMR with CO_2 Sequestration (SMR-CS), (iii) Coal Gasification (CG), (iv) CG with CO_2 Sequestration (CG-CS), (v) Electrolysis using 2023 Grid electricity (EG23), (vi) Electrolysis using 2030 Grid electricity (EG30), (vii) Electrolysis using Solar electricity (ES), and (viii) Electrolysis using Wind electricity (EW). The fuel-cycle GHG emissions of all eight hydrogen production pathways are compared to identify the technology with the lowest carbon footprint. Later, FCEV, with selected hydrogen production pathways, is benchmarked with BEV on total life cycle GHG emissions.

2.1. Fuel cycle (well-to-wheel) analysis of hydrogen production pathways

Hydrogen offers massive potential for decarbonizing the

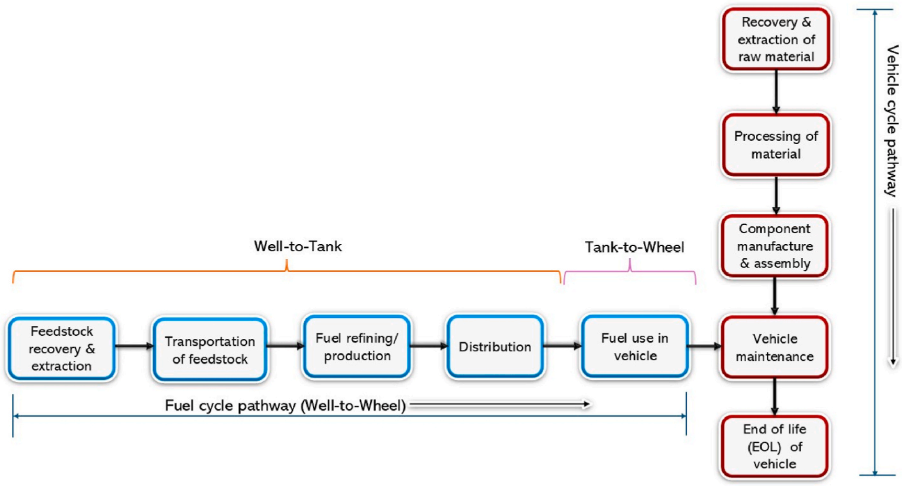

Fig. 1. Vehicle and Fuel cycle under a single system boundary [9,41].

transportation sector and moving towards a sustainable energy future since it is a flexible and the cleanest energy source. A study from the Rocky Mountain Institute (RMI) and National Institution for Transforming India (NITI) Aayog suggests that hydrogen demand in India will increase from 6 million tons in 2020 to around 29 million tons by 2050 [44]. Hydrogen production has several routes. The primary hydrogen production methods are SMR of natural gas, coal gasification, and water electrolysis. A brief description of these technologies, schematic diagrams of their models and pathways in the GREET, and assumption details are given in section S2 of the supplementary material. The process used to manufacture hydrogen significantly impacts the environment, ranging from significant GHG emissions to almost zero emissions. To estimate the total environmental impact of each hydrogen production pathway, this study has estimated the FCEVs' complete fuel cycle (WTW) emissions from the early stages of raw material extraction to the final hydrogen consumption.

2.1.1. CO_2 sequestration

The SMR and CG processes fulfil most of the worldwide hydrogen demand much cheaper than alternative approaches. As these fossil fuel-based hydrogen production processes are associated with substantial CO_2 emissions, integrating these processes with carbon capture utilization and storage (CCUS) technology is necessary for minimizing CO_2 emissions. As noted earlier, hydrogen produced from SMR and CG plants integrated with CCUS is called blue hydrogen, which essentially is a transition towards a clean energy system. Various CCUS technologies are available for the sequestration of CO_2 during multiple stages of the hydrogen production process, such as adsorption, absorption, cryogenic separation, membrane separation, calcium looping, etc.

There are several stages where CO_2 can be captured in an SMR or CG plant. CO_2 can be separated from the high-pressure synthesis gas stream and tail gas, reducing emissions by up to 60% and 55%, respectively. CO_2 can also be captured from the more diluted furnace flue gas. This can boost the level of overall emission reduction to 90% or more. It must be noted that CO_2 capture and storage involves additional capital investment, and this increases hydrogen production costs. However, the study by Ref. [45] has revealed that with >90% CO_2 capture, the specific cost of hydrogen production (per kg) rises by ~13%. Pressure swing adsorption (PSA) is a popular technology for hydrogen purification, while the widely used technology for CO_2 capture is absorption using suitable solvents such as ethanolamines. A general H_2 production route for SMR and CG plants with CO_2 capture is shown in Fig. S3 in the supplementary material. Though blue hydrogen is associated with higher GHG emissions than green hydrogen, the technology for green hydrogen is still in development. Therefore, in the immediate future, hydrogen production through mature technologies of SMR (Kemperdick and Letmathe, 2024) and CG integrated with CCUS will be an economically and environmentally viable solution. The natural gas market is developing quickly, from 6.2% of the total energy consumption share in 2017 to a projected share of 20% by 2025. Given these contemplations, our analysis is based on hydrogen production from SMR and CG routes with a CO_2 sequestration rate of 95%.

2.1.2. Transportation, distribution, compression, and refueling

The distribution process is applicable for offsite hydrogen-producing plants. It comprises transporting the hydrogen produced in the central gaseous hydrogen production plant to the bulk terminal and then to refueling stations via pipelines or heavy-duty (HD) trucks. Usually, the hydrogen produced from the plant is first transported to a distribution company, which is also called bulk terminals, via pipelines. These bulk terminals are very close to the production plants, so the average transportation distance is very short and is assumed to be 3 km in this study. The distribution company then delivers the hydrogen to local refueling stations through pipelines or HD trucks. As these distribution data are unavailable, hydrogen is assumed to be delivered through HD trucks to refueling stations with an average transportation distance of 200 km.

The density of hydrogen is very low, 0.0824 kg/m^3 [46], at standard atmospheric pressure and 25 $^\circ$C. This low density of hydrogen results in an extremely low volumetric energy content of hydrogen that is 0.01 MJ/L H_2, which is undoubtedly a major barrier to both the viability of the hydrogen economy and the cost-effective storage of hydrogen. Concerning FCEV, storing sufficient hydrogen onboard to travel a long distance is essential. Hence, hydrogen must be compressed at high pressure before refueling the car at the gas station. Commercially available tanks in FCEVs are Type III and Type IV, which can hold the hydrogen at high pressures of 350 and 700 bar, respectively. The energy required to compress hydrogen from ambient to 700 bar through a five-stage compressor is 21 MJ/kg [47]. In this study, a compression process at the refueling station is assumed to have a group efficiency of 91.38% (from the GREET model) using the 2023 Indian electricity mix.

2.1.3. Well-to-wheel GHG emissions of hydrogen production pathways

The WTW greenhouse gases emitted by eight hydrogen production pathways are estimated using the GREET model in Table 1.

The WTW stage comprises WTT and TTW stages. However, the TTW stage in FCEV doesn't emit any GHG emissions, as hydrogen combustion results in water formation as a product. So, whatever GHG emissions are associated with the WTT stages of the hydrogen production pathway are the same as WTW GHG emissions. As inferred from Table 1, out of eight H_2 production pathways, electrolysis using grid electricity has

Table 1
Well-to-wheel GHG emissions during H_2 production.

H_2 pathway	CO_2 (kg-CO_2/kg H_2)	CH_4 (g-CH_4/kg H_2)	N_2O (mg-N_2O/kg H_2)	Total GHG (kg–CO_2–eq/kg H_2)
SMR	12.333	32.557	0.107	13.248
SMR-CS	6.926	43.219	171.9	8.149
CG	21.215	34.178	85.211	22.257
CG-CS	5.439	34.733	85.714	6.497
EG23	53.889	87.694	1267.9	56.621
EG30	37.076	60.872	881.1	38.972
ES	2.804	5.275	73.971	2.968
EW	0.527	0.746	5.342	0.548

maximum GHG emissions, 4 × higher than SMR technology, whereas electrolysis using wind-powered electricity has the least emissions. On the other hand, SMR and CG routes integrated with CCUS can reduce their emissions by 38% and 71%, respectively. Thus, blue hydrogen production can be a rational solution until green hydrogen technology matures and is implemented commercially.

2.1.4. Well-to-wheel GHG emissions for electricity generation pathway

Presently, India has a total installed capacity of 417 GW for electricity generation [5]. A major fraction (56.8%) of this capacity is based on thermal route, of which 49.1% capacity is based on coal. The coal-thermal route also has a major share of 73.8% of the total electricity generated in India. The Central Electricity Authority (CEA) of the Ministry of Power, Government of India [48,49] predicts the installed capacity to rise approx. 831 GW by 2029-30 will be dominated by the non-fossil-based plants (65% share) with 300 GW of solar-based capacity. Tables S4 and S5 of supplementary material provide greater details of the present (2022-23) and projected (2029-30) installed capacities in India, along with the actual generation mix and the associated GHG emissions. Renewable energy sources (wind, solar, and hydropower) are expected to contribute 44% of the total electricity generation in India by 2030. The GREET model predicts the net specific GHG emission for India's present and projected energy mix as 0.91 and 0.62 kg CO_2-eq per kWh.

2.2. Vehicle cycle analysis

Estimating vehicle cycle GHG emissions begins with evaluating the weight of vehicle system components and replaceable components/parts. The second phase estimates each component's material composition, which differs greatly depending on the vehicle type. In the last phase, the GHG emissions associated with various vehicle components and replaceable parts are estimated using the quantity of the material, energy/process fuel consumed, and emission factor values. The net vehicle cycle emissions $E_{vehicle\ cycle}$ can be estimated using equation (3) [50].

$$E_{vehicle\ cycle} = m_{vehicle\ system} {}^* e_{vehicle\ system} + m_{battery} {}^* e_{battery} + m_{tyre} {}^* e_{tyre} + m_{oil\ and\ fluids} {}^* e_{oil\ and\ fluids} \quad (3)$$

$E_{vehicle\ system}$, $E_{battery}$, E_{tyre}, and $E_{oil\ and\ fluids}$ are the GHG emissions produced while manufacturing different vehicle system components. $m_{vehicle\ system}$, $m_{battery}$, m_{tyre}, and $m_{oil\ and\ fluids}$ are the weights and $e_{vehicle\ system}$, $e_{battery}$, e_{tyre}, and $e_{oil\ and\ fluids}$ are the emission factors (in CO_2-eq. per kg weight) for vehicle systems, batteries, tyres, and oil and fluids, respectively.

The GREET model uses the material composition data for vehicle-fuel systems manufactured in the USA. We have used the same data for passenger vehicles manufactured in India [51,52]. The following sections thoroughly explain each phase involved in vehicle life cycle emissions and provide information on the data needed, utilized, and assumed for this study.

2.2.1. Technical specification of vehicle models

As this study compares FCEV with BEV, analysis requires FCEV and BEV vehicle models under both passenger car and SUV categories. The reason behind analyzing both body type vehicles is that their weight distribution and material composition are different. As a result, their vehicle cycle GHG emissions will be different and may differ in the life cycle GHG emission patterns. With the recent progress in the National Hydrogen Mission (NHM), many automobile manufacturers have shown interest in developing and building sustainable FCEV technology in India. It is speculated that Toyota MIRAI (sedan–passenger car) and Hyundai NEXO (SUV) will be the first two FCEV cars to launch in India by 2025. To benchmark them against BEVs, BEVs with similar specifications have been chosen to keep the comparison fair among vehicle types. The following vehicle makes and models are selected in this analysis:

Passenger Car (Sedan) category: BYD Seal (BEV) and Toyota Mirai (FCEV)

SUV category: Morris Garage ZS EV (BEV) and Hyundai Nexo (FCEV)

The technical specifications of the selected vehicle models are given in Table 2.

2.2.2. Weight distribution and material composition

The weight distribution of different vehicle system components is estimated using the data given in Table S6 of supplementary material [51,52]. The amount of materials needed for the selected FCEV and BEV models was calculated using this data. The GHG emissions during the manufacturing of vehicle components were estimated using the GREET model.

The vehicle's kerb weight is the total weight of the vehicle, which also accounts for the replaceable parts, viz. tyre and rim assembly, traction and auxiliary batteries, oil and fluids, and adhesives, in addition to vehicle system components mentioned in Table S6. Thus, to estimate GHG emissions associated with vehicle system components, the system component weight is calculated by deducing the weight of replaceable parts from the kerb weight. Greater discussions on the technical specifications of replaceable parts, replacement schedules, and the related GHG emissions are discussed in section S7 of the supplementary material. Using the data and assumptions discussed in section S7 of the supplementary material, the weight of replaceable parts, the net weight of vehicle system components, individual component weight, and

Table 2
Technical specifications of selected passenger car (sedan) and SUV models#.

Make & Model	BYD Seal (BEV)	Toyota Mirai (FCEV)	MG ZS EV (BEV)	Hyundai Nexo (FCEV)
Fuel type	Electric	Hydrogen	Electric	Hydrogen
Vehicle body type	Passenger car	Passenger car	SUV	SUV
Total system power (kW)	150	136	130	120
Fuel tank capacity	N/A	5.6 kg	N/A	6.33 kg
Auxiliary battery (ah)	60	60	60	60
Traction battery (kWh)	61.6	1.24	50.3	1.56
Kerb weight (kg)	1922	1930	1641	1809
Tyre size (inch)	18"	19"	17"	17"
Fuel efficiency	8.3 km/kWh	115.18 km/kg	9.16 km/kWh	97 km/kg
Oil & fluid requirements in liters				
Brake fluid	1.15	1.15	0.85	0.70
Transmission fluid	1.50	1.00	0.90	1.00
Powertrain coolant	4.80	6.00	10.40	6.50
Windshield wiper	4.00	4.00	4.00	4.00

Source: OEM brochure and owner's manual

overall material composition for all the selected vehicle models are shown in Table 3 and S13 of the supplementary material.

2.2.3. Energy consumption rate and lifetime fuel consumption

This study uses OEM provided fuel economy to keep the analysis simple. The Energy consumption rate per kilometer for all vehicle models is estimated and depicted against the kerb weight of the vehicle in Fig. 2. Also, the lifetime (160,000 km) electricity and hydrogen consumption for BEVs and FCEVs were estimated and listed in Table S14 of the supplementary material. Fig. 2 shows that BEVs have significantly lower ECR than FCEVs, making BEVs more energy efficient. Thus, BEVs consume significantly less energy and have smaller GHG emissions. It is assumed that these vehicles have a 15-year life span and, as per the OEM warranty, a lifetime travel distance of 1,60,000 km.

3. Results and discussion

3.1. Vehicle cycle GHG emissions

Vehicle cycle GHG emissions are estimated for the selected vehicle models, and their results are discussed in this section. It consists of two components: (i) vehicle system components emissions and (ii) emissions from replaceable parts.

3.1.1. Vehicle system component and periodically replaceable parts GHG emission

Table 3 describes the vehicle system component's weight distribution. Table S12 of supplementary material provides the material composition of different components. Using the GREET model, the component's CO_2, CH_4, and N_2O emissions per kg weight are estimated. With these emission values, net GHG emissions by vehicle system components are calculated and listed in Table S15 in the supplementary material for passenger cars and SUVs. The results are compared between BEV and FCEV car models for passenger cars (sedans) and SUVs, as shown in Fig. 3.

The results show that GHG emissions for vehicle system components depend on the net kerb weight. As the engine is replaced by light motors and fuel tanks are absent, BEV's net vehicle system component weight is lower than FCEV. As a result, BEV's GHG emissions are lower than FCEV by approximately 1.6 and 2 times for passenger cars and SUVs, respectively. Meanwhile, fuel cell auxiliary in FCEV is associated with a considerable amount of emissions due to the type of materials, which is around 33 and 35% of the total emissions, even if its actual weight share is 15.8 and 18% of the vehicle system component for passenger cars and SUVs, respectively. However, BEVs require a huge battery to provide energy to the motors. GHG emissions associated with battery manufacturing may increase net vehicle cycle GHG emissions, which will be discussed in the next section.

Table 3
Weight distribution of passenger cars and SUVs.

Vehicle Components	Passenger Cars (Sedan)		SUVs	
	BYD Seal (BEV)	Toyota Mirai (FCEV)	MG ZS EV (BEV)	Hyundai Nexo (FCEV)
Kerb weight	1922	1930	1641	1809
Tyre & rim weight	68	77	59	59
Battery weight	530	28	437	31
Oil & fluid weight	26	27	31	27
Net vehicle system weight	1298	1798	1114	1692
Vehicle body	637	768	547	674
Power train	26	128	18	116
Transmission	48	47	36	44
Chassis	404	415	365	451
Traction motor	97	69	79	67
Controller	86	61	69	59
Fuel cell auxiliary		310		281

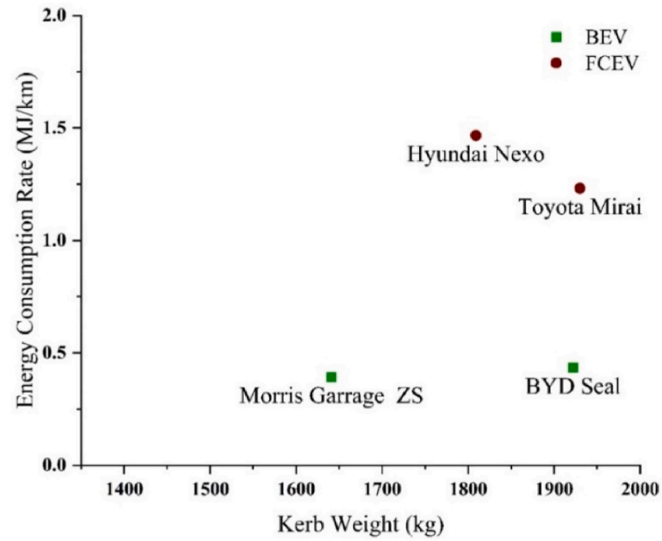

Fig. 2. Energy consumption rate (MJ/km) of vehicle models vs kerb weight (kg)

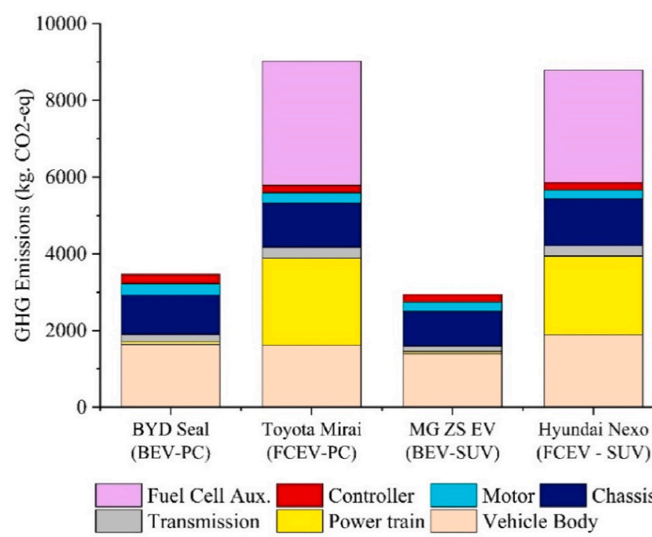

Fig. 3. Vehicle system components GHG emission of BEV and FCEV for Passenger car (PC) and SUV body types

The lifetime GHG emissions of the replaceable components in kg CO_2-eq are determined based on the replacement schedule and other related data discussed in earlier sections. The estimated GHG emissions of periodically replaceable parts (160,000 km) are listed in Table S16 of the supplementary material.

3.1.2. Total vehicle cycle GHG emission

The net vehicle cycle GHG emission is estimated by adding vehicle system components' emissions, lifetime replaceable parts emissions, and emissions due to assembly, disposal, and recycling (ADR) of vehicle components, which are listed in Table S17 of supplementary material. The estimated results are also plotted, as shown in Fig. 4.

The results reveal that vehicle cycle GHG emission of FCEV is higher than BEV by 45 and 63% for passenger cars and SUVs, respectively. This is due to the high emissions produced from vehicle system components, which are highly contributed by fuel cell auxiliary manufacturing, and the bigger drive train in FCEVs compared to BEVs. Even if emissions due to battery manufacturing in BEVs are 16 and 12 times higher than in FCEVs for passenger cars and SUVs, respectively, their total vehicle cycle

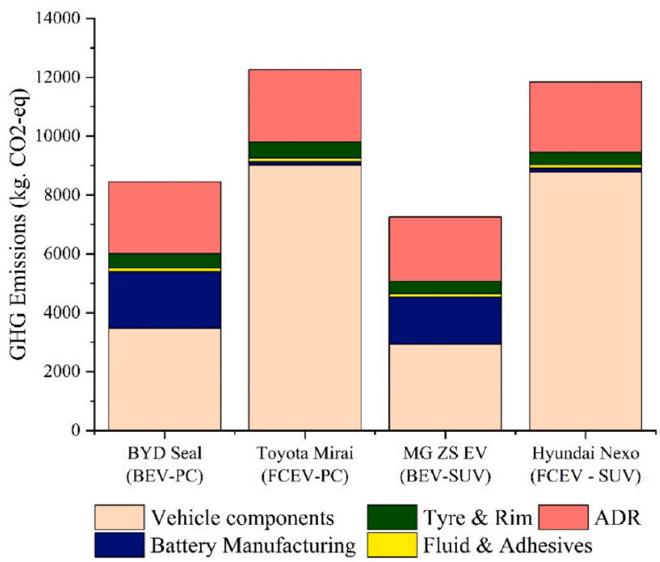

Fig. 4. Vehicle cycle GHG emissions (in kg CO_2-eq) of Passenger cars and SUVs

emissions are lower than in FCEVs.

Referring to the warranty provided by OEMs for traction batteries, this study assumed the battery lifespan to be 160,000 km. Hence, there is no traction battery replacement in BEV as it is the same as the lifetime travel distance. However, studies by Refs. [53,54] suggested that the traction batteries of BEVs may need to be replaced once or twice during their lifetime. This may impact the lifecycle emissions, the effect of which is discussed in the sensitivity analysis section.

3.2. GHG emissions during fuel cycle

The fuel cycle comprises WTT and TTW pathways, and total GHG emissions in the fuel life cycle are the sum total of emissions in these pathways. GHG emission value associated with WTT and TTW pathway was discussed in section 2.1. The fuel cycle GHG emission per unit quantity obtained from the GREET model for electricity and various H_2 production pathways is used to estimate TTW emissions for all vehicle types. The estimated fuel cycle emissions are tabulated in Tables S18 and S19 in supplementary material. As there are no tailpipe emissions in BEVs and FCEVs, the TTW emissions for both vehicles are zero. Therefore, total WTW GHG emissions associated with BEV and FCEV are essentially the WTT emissions.

Results depicted in Fig. 5 clearly show that H_2 produced by electrolysis using grid electricity cannot achieve emission reduction targets. The fuel cycle emissions of FCEV using SMR are almost equal to those of BEV using 2023 grid electricity, but the integration of CCUS with SMR reduces the FCEV emissions to half. The results of green hydrogen are very attractive, showing that around 90–99 % of fuel cycle emissions can be reduced. However, till the green hydrogen technology matures, blue hydrogen showed a promising reduction in fuel cycle emissions. A comparison with the emissions of BEV would reveal that FCEV with H_2 produced from SMR and CG technology has no environmental benefits, but the blue hydrogen reduces the WTW emissions by 40 and 51%, respectively, compared to BEVs.

3.3. Life cycle GHG emissions

The total life cycle (vehicle life cycle + fuel life cycle) GHG emissions for different combinations of vehicle-fuel systems are given in Tables S20 and S21 of supplementary material. The specific life cycle GHG emission (g CO_2-eq/km) is also listed in these tables. The results obtained are plotted in Fig. 6.

The results reveal that green and blue hydrogen-powered FCEVs in

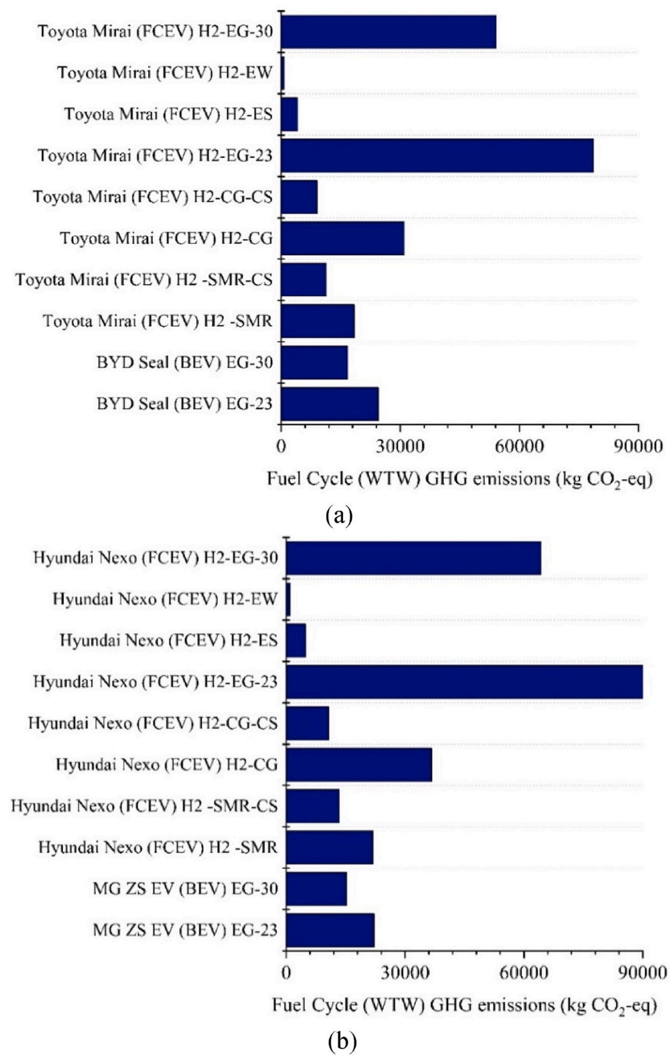

Fig. 5. Fuel Cycle GHG emissions (kg CO_2-eq) of (a) passenger cars (b) SUV

passenger cars and SUVs have great potential for reducing the life cycle GHG emissions. The best solution is FCEV with H_2 produced by electrolysis using wind and solar energy. Comparing BEVs with the 2023 energy mix against FCEVs using blue hydrogen, it is observed that FCEVs emit around 17 (passenger car) and 31% (SUV) lesser life cycle GHG emissions, making it a more suitable choice. However, BEVs with a projected 2030 energy mix produce 13% fewer emissions than FCEVs with blue hydrogen from SMR-CS and at par with blue hydrogen from CG-CS. The above analysis shows that, as the green hydrogen technology is still maturing in India, blue hydrogen will be a viable and effective solution for the FCEVs during the transition phase of the next few years.

3.4. Sensitivity analysis

It is also essential to assess the variations in life cycle GHG emissions of the BEVs and FCEVs concerning the base-case factors considered in the analysis presented in the preceding sections [55]. Based on the conclusions of the previous section, sensitivity analysis is done only for the following vehicle-fuel systems: (1) BEV for energy mix of 2023, (2) BEV for energy mix of 2030, (3) FCEV for hydrogen through SMR-CS route, (4) FCEV for hydrogen through CG-CS route. The sensitivity analysis was performed for three base-case factors, as described below.

(1) The first base-case factor was the lifetime distance traveled by any vehicle, which was assumed to be 160,000 km. The

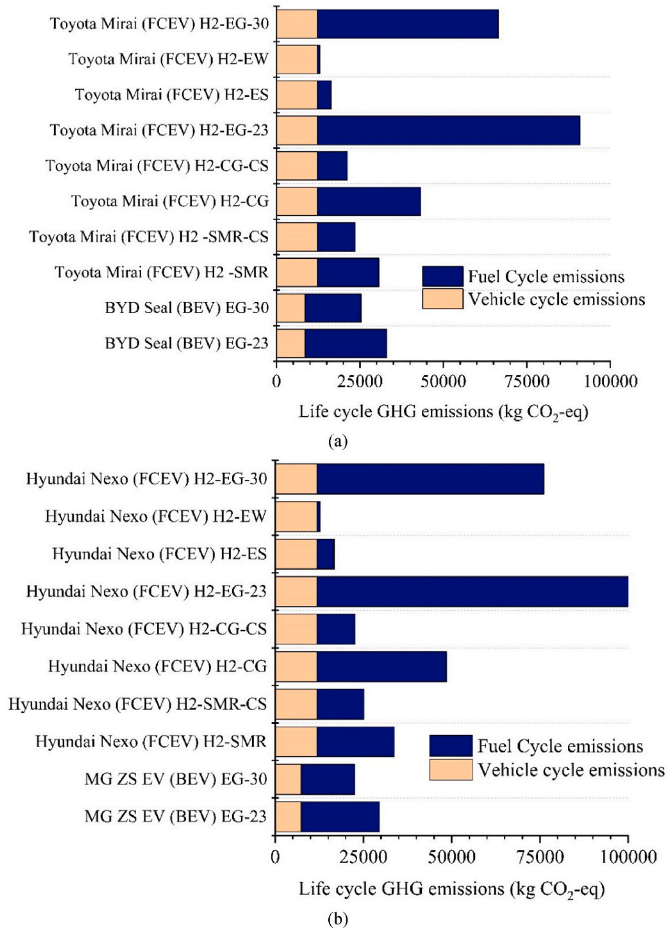

Fig. 6. Life Cycle GHG emissions of (a) passenger car (b) SUV

sensitivity analysis for this base-case factor is done by varying the lifetime travel distance of the vehicle in the range of 40,000 to 240,000 km with increments of 40,000 km.

(2) The second factor to be considered is the degradation of fuel cells used in FCEV. After 6000 h of operation, fuel cell degradation will likely increase hydrogen consumption by ~15% [25].

(3) The third factor to be considered is the battery's lifespan, which is assumed to be 160,000 km. However, as noted earlier, previous studies [53,54] have shown that batteries need to be replaced once or twice during the vehicle's lifespan. Hence, a sensitivity study is performed for one- and two-time replacement of the batteries in FCEV and BEV during the vehicle lifetime.

3.4.1. Sensitivity analysis – lifetime travel distance

The change in the life cycle GHG emissions per kilometer due to the variations in lifetime distance traveled for passenger cars and SUVs are shown in Fig. 7.

Passenger car results reveal that for small travel distances of 40,000 km, BEV(EG23) emissions are almost on par with FCEVs (2% lesser than FCEV(SMR-CS) and 1% higher than FCEV(CG-CS)). At this point, BEV (EG30) has 18 and 14% lesser emissions than FCEV(SMR-CS) and FCEV (CG-CS), respectively, making it a better choice among the options. However, the result trend changes for lifetime travel distances over 80,000 km as FCEVs have smaller emissions than BEVs. Compared to BEV(EG23), FCEV(SMR-CS) and FCEV(CG-CS) have approximately 14, 23, 29, 36, 38%, and 20, 29, 36, 42, 45% lesser lifecycle GHG emissions for travel distances of 80000, 120000, 160000, 200000, 240000 km respectively. Compared with BEV(EG30), the emission pattern remains the same, but the difference in emission margin is reduced by 18–20%, making FCEVs with blue hydrogen a favorable solution.

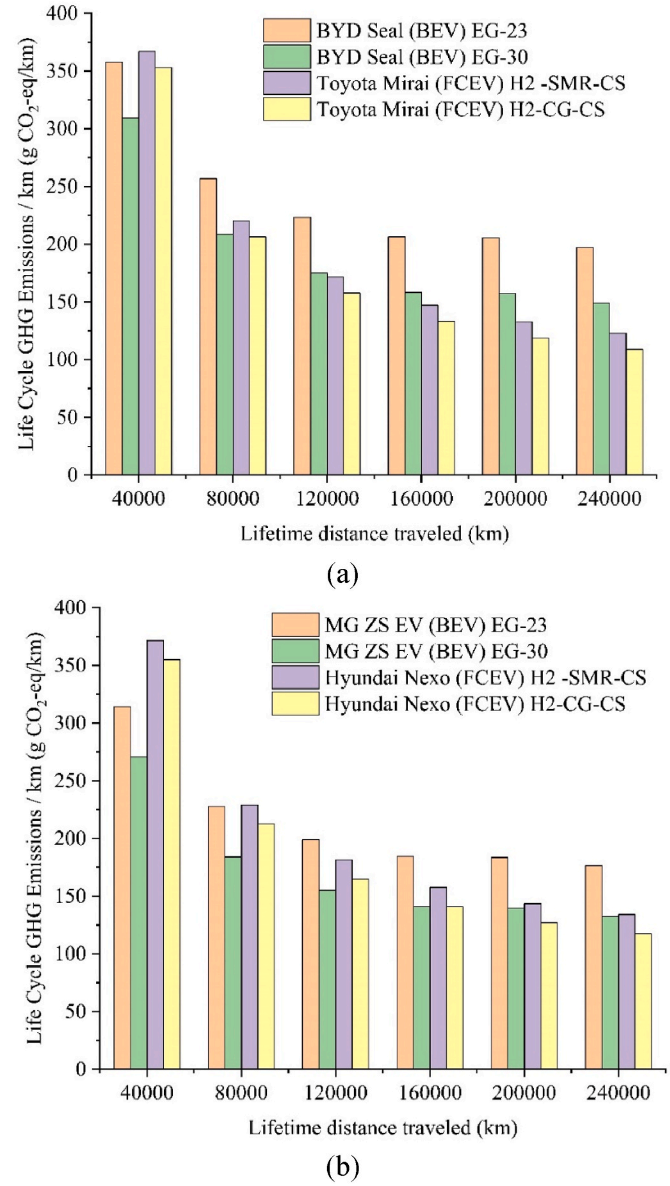

Fig. 7. Life cycle GHG emissions due to variations in lifetime distance traveled for (a) Passenger cars, (b) SUVs

For SUVs, compared to BEV(EG23), FCEVs have a similar trend as passenger cars. At 40,000 km, BEV(EG23) has lesser emissions than FCEVs (18 and 13%, respectively, for FCEV(SMR-CS) and FCEV(CG-CS)). From 80,000 km onwards, FCEV(SMR-CS) and FCEV(CG-CS) have 1, 9, 15, 22, 24% and 7, 17, 24, 31, and 33% lesser emissions than BEV (EG23), respectively. But interestingly, for low-to-moderate travel distances of 40,000 to 160,000 km, BEV(EG30) has lesser emissions by 37, 24, 17, 12%, and 31, 15, 6, 1% compared to FCEV(SMR-CS) and FCEV(CG-CS), respectively. The trend shows that the emission difference gradually reduces as the travel distance increases. For travel distances higher than 200,000 km, FCEV(CG-CS) emitted 9 and 12% less emissions than BEV(EG30).

3.4.2. Fuel cell degradation in FCEV

A study by Ahmadi and Khoshnevisan [25] revealed that after 6000 h of operation, the fuel cell voltage would reduce by 11.1% and thus increase fuel consumption by ~15%. As per the Indian Drive Cycle (IDC), the vehicle's average speed is ~21.9 km/h. Thus, for 6000 h of fuel cell operation, the vehicle would have traveled 131,400 km. Hence, sensitivity analysis has been done for additional fuel (hydrogen) consumption for lifetime travel distances of 160000, 200000, and 240000 km to estimate the change in lifecycle GHG emissions per kilometer. The results of this analysis are depicted in Fig. 8.

In the passenger cars category, the lifecycle GHG emissions with fuel cell degradation for both FCEV(SMR-CS) and FCEV(CG-CS) are smaller than BEV(EG23) and BEV(EG30). However, in the SUV category, only FCEV(CG-CS) has fewer emissions than both BEV(EG23) and BEV (EG30). Although emissions of FCEV(SMR-CS) are lesser than BEV (EG23), they are higher than BEV(EG30) by 13, 6, and 5 % for travel distances of 160000, 200000, and 240000 km, respectively.

3.4.3. BEV battery replacement

The results of variations in lifecycle GHG emissions per kilometer due to one-time and two-time replacement of traction batteries in BEVs and FCEVs are depicted in Fig. 9.

The results reveal that the FCEVs emit fewer emissions for battery replacement cases in the passenger car segment than BEVs. However, in the SUV category, BEV(EG23) has higher lifecycle GHG emissions than both FCEVs. BEV(EG30) has lesser emissions than FCEV(SMR-CS) for no battery and one-time replacement cases. However, with two-time battery replacement, the lifecycle GHG emissions of FCEV(SMR-CS) are almost similar to that of BEV(EG30).

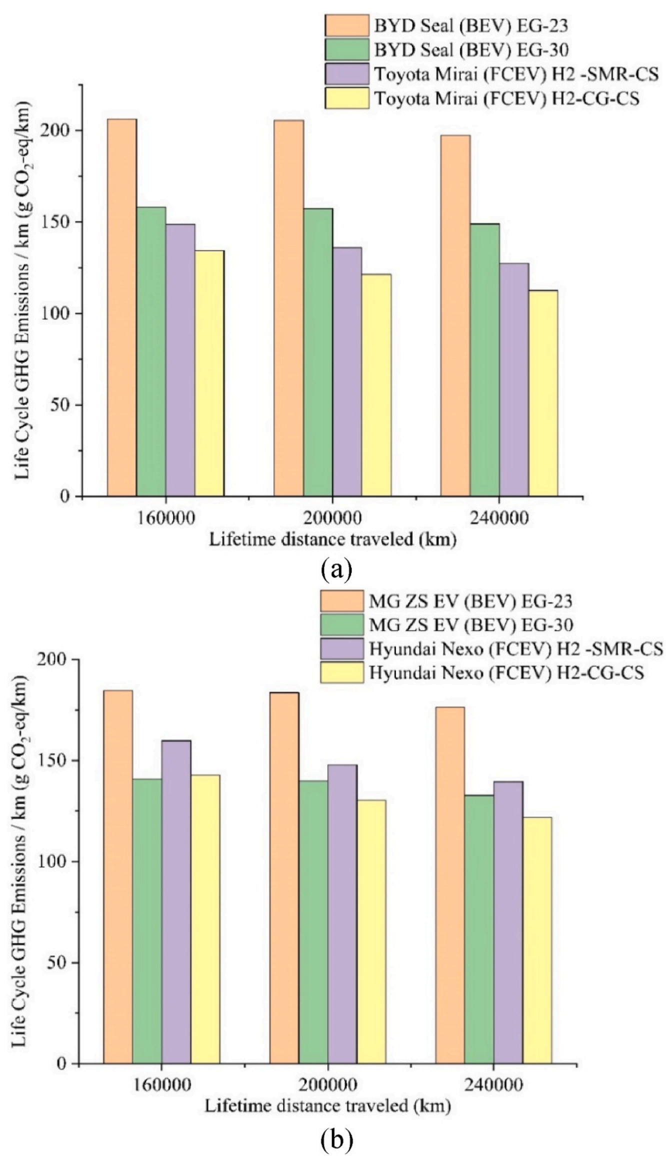

Fig. 8. Life cycle GHG emissions due to fuel cell degradation in FCEV for (a) Passenger cars, (b) SUVs

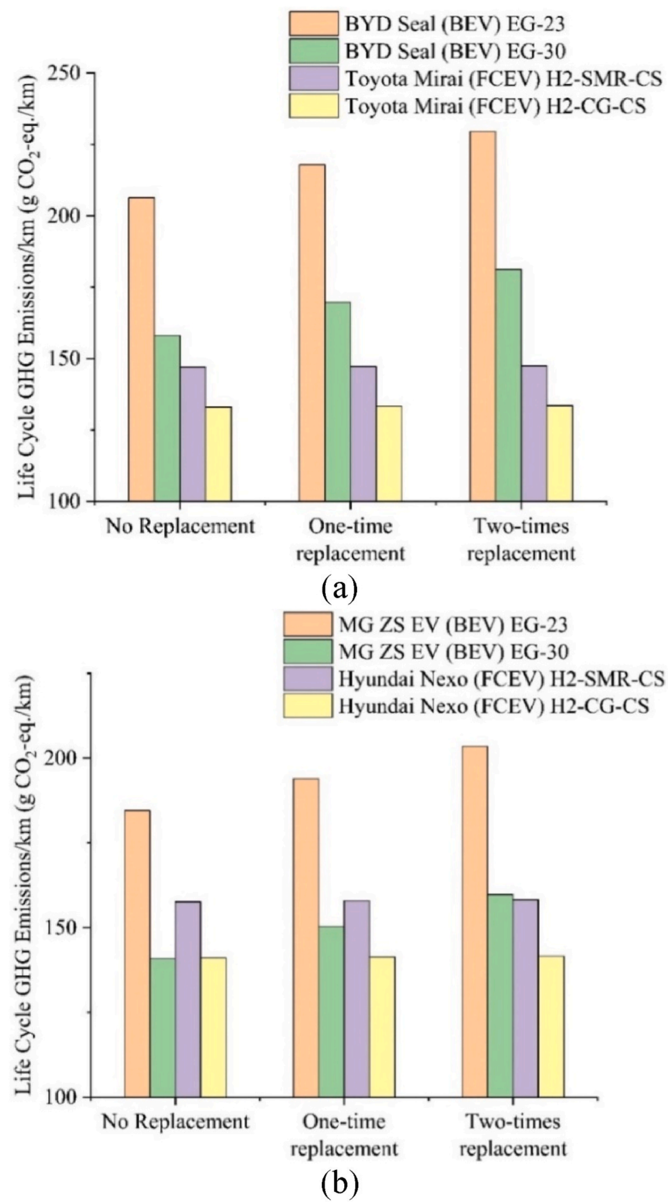

Fig. 9. Life cycle GHG emissions due to traction battery replacement for (a) Passenger cars, (b) SUVs

3.5. Policy implications and recommendations

This study clearly shows that FCEV using blue hydrogen can reduce GHG emissions from BEVs using the 2030 electricity mix. These results suggest that the Government of India should incentivize existing hydrogen manufacturing plants (based on SMR) to implement CCUS units. The Indian government has also initiated a concrete road map for hydrogen-powered vehicles. The NHM initiative was started to make India a hub for producing and exporting green hydrogen. The initial outlay of NHM is INR 194.44 billion, focusing on four sub-components: (i) Strategic Interventions for Green Hydrogen Transition Programme (SIGHT) targeting domestic manufacturing of electrolyzers and production of Green Hydrogen, (ii) Pilot scale projects, (iii) R&D projects, and (iv) Skill development. India's green hydrogen production capacity is likely to reach at least 5 MMT per annum by 2030 [56], with an associated renewable energy capacity addition of about 125 GW. Two hydrogen refueling stations have been established at Faridabad and Gurugram. Ministry of New and Renewable Energy has carried out various projects in 15 academic research institutes for in-house development of hydrogen technology. Indian Government is already offering a financial incentive in the form of a subsidy (INR 10,000/kWh) for faster adoption of BEVs. A similar incentive is also expected for faster adoption of FCEVs. The government should also incentivize the stakeholders to set up hydrogen refueling stations.

3.6. Limitations

As the green hydrogen and FCEV technologies progress and mature, more technical features and data will be available, which will help conduct a more realistic analysis in the future. This study recommends using blue hydrogen in the immediate future to achieve GHG reduction targets. However, implementing CCUS technology by the SMR plants would require a substantial additional capital investment in the range of \$ 65 – \$ 136 per ton of CO_2 [57]. Hence, a techno-economic analysis is required for further insights into the feasibility of blue hydrogen.

4. Conclusion

Fuel cell electric vehicles (FCEVs) are considered an alternative to battery electric vehicles (BEVs). This study has attempted to give a comparative account of the lifecycle GHG emissions of these electric vehicles for different scenarios of hydrogen production and electricity generation. The major conclusions of this study are summarized below.

1. The relative contributions of the fuel cycle emissions to the total lifetime GHG emissions of FCEV and BEV are found to be significantly different. For the BEVs, the fuel cycle emissions contribute significantly to the lifetime GHG emissions of the vehicles. On the contrary, in FCEVs, the contributions of the fuel cycle emission to the total emission are relatively less.
2. FCEVs fueled with grey hydrogen do not have environmental advantages (or reduced GHG emissions) over the BEVs, even for the present energy mix, which is dominated by electricity generation through the thermal route.
3. FCEVs fueled with hydrogen produced by electrolysis using grid electricity also do not have any advantage over the BEVs in terms of emission reduction.
4. FCEVs fueled with green hydrogen have the smallest lifecycle GHG emissions. However, since the technology for commercial-scale green hydrogen production is still maturing, penetration of green hydrogen-fueled FCEVs in the Indian transport sector is unlikely to be achieved in the near future.
5. Blue hydrogen is a solution for the immediate prospects of FCEVs as an alternative to BEVs. Interestingly, FCEVs fueled with blue hydrogen have emission levels smaller than BEVs, even for the 2030 energy mix of India dominated by renewable energy routes.
6. Sensitivity analysis of GHG emissions has also given interesting results. The emission reduction advantage of FCEVs (fueled by blue hydrogen) over BEVs is not realizable for small to moderate lifetime travel distances. A distinct merit of FCEVs is that fuel cell degradation shows negligible impact on lifecycle emissions.
7. The traction battery lifespan has been revealed to be a significant factor influencing the emission advantage of BEVs. Replacement of the battery (either once or twice) during the lifespan of the BEVs (in both passenger car and SUV categories) results in a rise in lifetime GHG emissions. However, battery replacement has a negligible impact on the lifetime GHG emissions of the FCEVs.

This study introduced the significant role of blue hydrogen as a near-term solution for FCEVs. Compared to existing literature, this research offers a more nuanced analysis of blue hydrogen's viability, highlighting its potential for immediate emissions reductions. It also provides a detailed sensitivity analysis of how factors like lifetime travel distances and fuel cell degradation affect emissions.

Future outlook: Although our analysis has revealed that blue hydrogen could be a viable solution for sustainable transport in the near future, BEVs still have the opportunity to reduce lifecycle emissions with greater penetration of renewable energy in the energy mix and improved battery technology. Further developments in FCEV and green hydrogen technology may reveal pros and cons, enabling a more realistic life cycle analysis of FCEVs. Research into the factors influencing consumer adoption of FCEVs versus BEVs—such as cost, refueling infrastructure, and range anxiety will help determine the actual market impact of these technologies on reducing emissions. As BEVs and FCEVs rely on infrastructure development (such as charging stations and hydrogen refueling stations), future research should examine policy frameworks and investment strategies needed to support the transition to these low-emission vehicle technologies, particularly in emerging economies.

CRediT authorship contribution statement

Harshendra N. Shet K: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Vijayanand S. Moholkar:** CEng FIChemE FRSC, Writing – review & editing, Supervision.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijhydene.2025.01.254.

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