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Review

FCEV vs. BEV — A short overview on identifying the key contributors to affordable & clean energy (SDG-7)

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ABSTRACT

Battery electric vehicles (BEVs) are surging worldwide due to technology improvements in lithium-based batteries and rising petroleum prices. India's EV30@30 campaign aggressively penetrate the Electric vehicle and target share by 30% in 2030. Sarcastically, from the Indian context, the availability of Li-source is limited and subsequently, there has been an impetus to find out a promising electric vehicle (EV). Fuel cell-based EVs are one such potential option. The present review critically assesses the scope and perspective of battery electric vehicles (BEVs)with fuel cell electric vehicles (FCEVs) in line with the Indian context. The assessment validates that fuel cell-based EVs can be a likely option for the Indian sub-continent. As a whole, FCEV technology will advance, and over time, smaller and mid-segment commercial vehicles will eventually be more affordable in addition to being sustainable, especially when using green hydrogen as a fuel. The total cost of ownership (TOC) of FCEV is better than BEV for the period of twelve years and also supports the future of FCEV in the Indian context (Sontakke et al. 2024).

1. Introduction

Energy has become a fundamental component that is very much essentially a part of our life, from charging your mobile to automobiles. The automobile sector in India predominantly relies on petroleum-based fossil resource that emits greenhouse gases (GHGs). Thus, Climate change is largely caused by increasing greenhouse gas emissions [1–6]. Continued emission of GHGs can potentially cause severe, pervasive, and irreversible impacts on the climate which include higher heat waves, rise in sea level, and intensification in the storm surges. The use of petroleum and related hydrocarbon fuels is very much inevitable in the recent context. Ironically, the upsurge in the use of Petroleum-based Internal Combustion Engine (ICE) vehicles is causing prevalent environmental tribulations in our atmosphere due to the emission of noxious greenhouse gases, such as COx, SOx, NOx, and particulate matter. Transport-related emissions contribute to over 30 % of global emissions, with close to 70 % of these emissions coming from on-road cars, according to a report by the International Energy Agency (IEA) [7]. Table 1 provides the detailed outline of emission level and its health issues. In addition, from the economic perspective due to low supply and high demand, the cost of petroleum-based products is significantly causing (3%) negative impact on nations GDP. Although Battery-based EVs are emerging as a potential option, they still lack the range anxiety and again from the Indian context, we have limited Lithium resources. Fuel cell-based energy systems are potential and reliable energy systems, which convert clean hydrogen fuel into power with water and heat as by-products. In this situation, FCEVs will become significantly more ecologically beneficial and achieve a "true" zero emission because of the usage of renewable energy sources for power generation (solar, wind, ocean, etc.). Assessments of FCEV's life cycle, environment, and toxicology are provided in the report [8–11]

1.1. *Why proton exchange membrane (PEM) fuel cells for EV application*?

Their distinguishing features include:

- High electrical efficiency (at least double that of the most efficient ICE vehicle [12,13])
- Lower temperature/pressure ranges (20 to 120 °C/1 barg) [14,15]
- Due to this high-power density and energy density [10,16,17], they have potential applications in transportation.

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Table 1
Type of air pollutant, major sources of emission and its health impact [22].

Air Pollutant	Major source of Emission	Averaging Time	Standard Level	Health Impact and Target Organs
Particulate Matter, $PM_{2.5}$	Motor engines, industrial, smokes	24 Hr	35 μg/m3	Respiratory and Cardiovascular diseases, Central Nervous System and reproductive dysfunctions, Cancer
Particulate Matter, PM_{10}		24 Hr	150 μg/m3	
Ground level Ozone	Vehicular exhaust, industrial activities	1 Hr	0.12 mg/m3	Respiratory and Cardiovascular dysfunctions, eye irritation
Carbon monoxide	Motor engines, burning coal, oil and wood, industrial activities, smokes	1 Hr	35 mg/m3	Central Nervous System and Cardiovascular diseases
Sulphur dioxide	Fuel combustion, burning coal	1 Hr	75 μg/m3	Respiratory and Central Nervous System involvement, eye irritation
Nitrogen dioxide	Fuel burning, Vehicular exhaust	1 Hr	100 μg/m3	Damage to liver, lung, spleen, and blood
Lead	Lead smelting, industrial activities, leaded petrol	3 months average	0.15 μg/m3	CNS and hematologic dysfunctions, eye irritation
Polycyclic Aromatic hydrocarbons	Fuel combustion, wood fires, motor engines	1 Hr	1 ng/m3	Respiratory and Central Nervous System involvement, cancer

- Petrol, hydrogen, and batteries have mass-based energy densities of 13 kWh/kg, 39.6 kWh/kg at 700 bar pressure, and 0.1 to 0.27 kWh/kg, respectively [18].
- Apart from low emissions PEM fuel cells produce low noise levels (< 25 dB) compared to that of ICE that generates 96 dB [19].

Due to the complexity and expense of fuel cell technology, FCEVs have a high upfront cost from an economic perspective. However, because hydrogen fuel is less expensive, their operational expenses are lower than those of an EV or ICE car. The Total Cost of Ownership (TCO) of an FCEV in the midsize and large car sectors is equivalent to that of a gasoline-powered vehicle, according to research by the National Renewable Energy Laboratory. Joshi et al. [20], Sontakke et al. [21] presented the comprehensive life cycle assessment with ICE, BEV & FCEV in Nepal conditions. They have concluded that the use of renewable energy sources, advancements in battery and fuel cell technology, and tightened regulations and laws around e-mobility position BEV and FCEV as desirable alternatives to conventional transportation.

In relation to supply and demand, India does not yet import or export hydrogen from other countries. By 2050, according to The Energy and Resources Institute (TERI), India's consumption might be 23 million tonnes annually [17,23–25]. To balance this demand and supply gap a special scheme or incentives are expected from Government's end to create the supplier attraction towards localization.

The comprehensive comparison of both the technical as well as socio-economic aspects of BEV vs FCEV in the Indian scenario is not addressed to the knowledge of the authors. The current effort, therefore, tries to address such comparison holistically by giving a comprehensive understanding from both technical and socio-economic perspectives. The flow of information as follows in Section 2 the comparison of energy density with FCEVs and BEVs and in Section 3 consist of detailed discussion on an available infrastructure, refueling time with respect to FCEV and BEV technologies. Followed by, critical material resource and its environmental, safety aspects are reviewed with available literature in Section 4. In Section 5 discussion on socio-economic aspect, where the cost aspect is estimated based on Indian context, followed by Section 7 deals with outlook and Section 8 concluded by emphasizing the various integral factors.

1.2. Methodology

In this study, thematic analysis has been used for knowledge gap analysis. For keywords 'electric vehicle in India', 'Fuel cell electric vehicles in India', 'Internal combustion engine emissions' and 'electric vehicle transition', literature was extracted from ScienceDirect. After reviewing the article and considering duplication, 60 research and review papers were selected for literature review. Additionally the reliable News articles are also taken with reference to understand the recent developments.

2. Energy density and range

Although, the average battery-electric vehicle only has 200 miles of range. There are some exceptions when considering high-end BEVs like Teslas, which have an EPA-estimated 400 miles of range. The prime reason is that the storage mechanisms of fuel cells and batteries are different, despite being "electrochemical similarities". Batteries and fuel cells rely on the conversion of chemical energy into electrical energy. The criteria for ion and electron conduction in the electrolyte and electrodes apply to both systems [26]. Fig. 1 composes the specific energy (energy per unit weight) of existing deep-discharge lead acid (PbA) batteries, nickel metal hydride (NiMH), Lithium ion batteries (LIB), and the US ABC (Advanced Battery Consortium) target in comparison to the specific energy of a PEM fuel cell + compressed hydrogen storage tanks. With fiber-wrapped composite tanks, two hydrogen pressures of 5000 psi and 10000 psi are being examined. Due to the necessity for more fiber wrap to provide the necessary strength, the 10000-psi tanks weigh more than the 5000-psi tanks. Compared to the weight of fuel cells, batteries are at least 10 times heavier. The mass-based energy density of batteries is in the range of 0.1 to 0.27 kWh/kg. In comparison, gasoline is 13 kWh/kg, and hydrogen gas at 700 bars pressure has an energy density of 39.6 kWh/kg. Batteries consume 0.24 kWh to 0.87 kWh of electricity per mile (an average of about 0.33 kWh per mile) [18]. Toyota Mirai on the contrary is able to deliver a 100 km (80 miles) range for 1 kg of H2 [27,28]. Additionally, some difficulties are with battery thermal management systems with prismatic and cylindrical shapes [29].

3. Charging/refueling infrastructure and time

FCEVs are still in their early adoption stages compared to the BEVs both in the international and Indian context. In America, only states such as California have hydrogen refueling stations, with just 69 hydrogen refueling stations [31]. In India, the count is still worse there is one hydrogen refueling station at Faridabad. Though, Indian Government has initiated a concrete road map to be less dependent and more reliable on hydrogen-powered vehicles. Since home EV charging is ineffective in high-density areas, the quantity of public charging infrastructure is a priority. Government of India's (GOI) National Hydrogen Energy Mission (NHM) initiative will capitalize on Hydrogen one of the most abundant elements on earth for a cleaner alternate fuel option [32]. Power major NTPC Ltd is considering setting up a green hydrogen production facility in Andhra Pradesh [33]. The Ministry of Power bids for 4000 MW of electrolyzer capacity funded with INR 8 billion, to deliver sustainability gap support, production-associated enticements, and the obligation of green hydrogen consumption agreements [34]. Two hydrogen refueling stations have been established (one each at Indian Oil R&D Centre, Faridabad and National Institute

Table 2
Status of ongoing hydrogen projects for automotive applications in India [30].

S.No.	Projects	Organization
1	Support for the existing energy center for hydrogen vehicles	BHU, Varanasi
2	Design and production of hydrogen-powered three wheelers	BHU, Varanasi
3	New hydrogen production process from liquid and gas phase HC via non-thermal plasma refurbishment techniques based on green and renewable power source for vehicles	CIMFR, Dhanbad
4	Biomass Gasification of hydrogen liquid fuels for cars	IISC, Bangalore
5	Design and development of Hydrogen-diesel dual fuel SUV	Mahindra & Mahindra,Chennai
6	Mission on hydrogen production through Biological Routes	IIT Kharagpur
7	Mission on Hydrogen Storage with Carbon Materials for enhanced safety storage in vehicles	IIT Madras
8	Mission project on hydrogen Storage Materials (Hydrides)	BHU, Varanasi
9	Design and development of hydrogen fueled ICEs for vehicles	IIT Delhi
10	Improved efficiency, assessment and analysis of Indirect Fuel Injection (IDI) diesel engines fueled by straight vegetable oils (SVO) with the supplementation of hydrogen	UPES, Dehradun
11	Development of hydrogen refueling system for the fuel cell vehicle demonstration	IOCL, Faridabad
12	Experimental research on combustion properties and emission control of laser ignited hydrogen engine	IIT Kanpur
13	Design and development of Hydrogen-fueled multi-cylinder gasoline engines built for stationary power production	IIT Delhi
14	Demonstration and ground experimentation of three-wheeler powered by hydrogen	IIT Delhi
15	Development and demonstration fuel cell stack and fuel cell-battery hybrid vehicle in a 10 kW power plant	SPCI foundation, Chennai

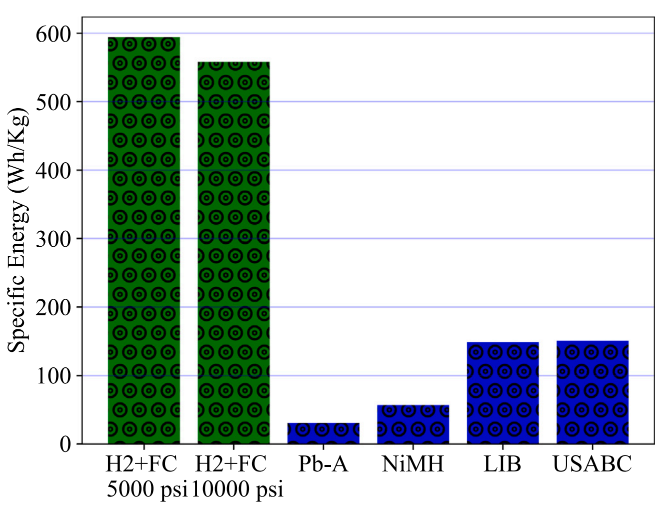

Fig. 1. Comparing the specific energy of various battery systems with that of hydrogen and fuel cell systems.

of Solar Energy, Gurugram) [35]. The finance minister in the Union budget for 2020–21 officially announced the National Health Mission (NHM) which aims to generate hydrogen from green power resources. It is speculated that NHM will emphasize generating green hydrogen and enabling its commercial use as a transportation fuel [36]. The current status of major ongoing hydrogen projects for automotive applications in India among various academic research institutions and leading industrial projects are listed in Table 2. The initiatives supports the progress in Hydrogen energy development in India and also indirectly supports for Fuel cell based energy conversions. Rather than related to automotive, research and development for various projects on implementing hydrogen as an energy carrier is extensive in India, that is under the eye of Ministry of New and Renewable Energy (MNRE), especially with the scope that it can fuel IC engine as well especially as a hybrid fuel such as Hythane. Thus, the infrastructure for hydrogen is minuscule compared to BEV charging stations. The primary reason is the chicken or egg problem. The investors are afraid that if the hydrogen fueling stations could become futile if there is no sale of FCEVs. Using an existing refueling station to generate hydrogen through the reformer technique is a potential option to generate hydrogen with minimal investment. Ironically, resilience in infrastructure will be a challenging aspect of BEV implementation. Grid issues in India lead to hesitant EV owners to establish their investments in India [37]. Tata Motors and the Indian oil corporation initiated the Solar energy-based EV charging station to improve the resilience of charging stations. Standardization in batteries plays a vital role in implementing charging facilities. The infrastructure to dispose of batteries after the end of life is also a critical thing in India, as everyone thinking of the sustainability of batteries [38–40]. About the charging/refueling time, Table 3 lists the estimated battery charging time and hydrogen refueling time. Although the Charging infrastructure is well established with respect to BEVs, the charging time is still a challenge for BEVs. Even the best-in-class BEV, Tesla model has a minimal charging time of around 30 mins for supercharging [41,42]. But, it must be noted that continuous supercharging leads to battery degradation and deterioration [43–45]. In a fuel cell system, the energy is stored in a storage tank, similar to the gasoline systems, so subsequently, the refueling time is in the range of a few minutes.However, the conversion efficiency supports Battery electric vehicles since there is no electrolysis loss involved in the process compared to FCEV. The detailed sets involved in the calculation are listed in Table 4. The comparison between BEV, FCEV and ICE starts from 100% renewable electricity and clearly shows the overall efficiency is supporting the BEV.

4. Materials availability, environmental & safety concerns

Irrespective of performance the availability of the material resource is an essential criterion for EV penetration. Specifically, materials such as lithium, nickel, and cobalt, are used to make lithium-ion batteries. Although production of these materials is increasing every year, there

Table 3
Comparison of refueling time (hours) between BEV and FCEV [16].

Vehicle Range (km)	Energy required from grid (kWh)	BEV - Charging time				FCEV
		120 V, 20 A (1.9 kW)	240 V,40 A (7.7 kW)	480 V,3 ϕ (60 kW)	480 V,3 ϕ (150 kW)	Filling time
241	56	29.2	7.3	0.9	0.4	0.08
322	82	42.7	10.68	1.4	0.55	0.1
483	149	77.6	19.40	2.5	0.99	0.15

Table 4
Comparison of conversion energy loss for BEV,FCEV and ICE vehicles [46].

		BEV	FCEV	ICE
100% Renewable electricity				
Well to tank	Electrolysis	–	30%	30%
	Co_2 air capture	–	–	37%
	Transport, storage& distribution	5%	26%	–
Fuel Production Efficiency		95%	52%	44%
Tank to Wheel	Inversion AC/ DC	5%	–	–
	Battery charge efficiency	5%	–	–
	H2 to electricity conversion	–	50%	–
	Inversion DC/AC	5%	5%	–
	Engine efficiency	10%	10%	70%
Overall efficiency		73%	22%	13%

simply are not enough minerals available, especially in line with the Indian sub-continent demand [47]. The role of cathode materials is an essential criterion for the battery system design, specifically Each cathode material combination used in LIBs has unique advantages and disadvantages in terms of price, safety, performance, and other factors. The performance with different cathode materials is illustrated in Fig. 2. Lithium cobalt oxide (LCO), also known as mature cathode chemistry, is the most used battery technology for consumer electronics at the moment. However, this chemistry is not appropriate for EV applications because of its structural instability in terms of overdelithiation [48,49]. Due to their plentiful resources, stable crystal structures, and affordable price, other cathode chemistries, such as lithium nickel cobalt aluminum oxide (NCA), spinal lithium manganese oxide (LMO), lithium nickel manganese cobalt oxide (NMC), and lithium iron phosphate (LFP), replaced LCO as the preferred battery material for automotive applications. In Fig. 2 the cathodes are summarized with important features concerning implementation in the Automotive sector.

In addition, there are also issues pertaining to safety and environmental mining concerns. A $2.4 billion lithium project planned for Serbia ended up ceasing operation in 2022, which some analysts believe would likely cause the scarcity to continue for years. Because of this, several nations (and company executives) have been competing for control of the materials needed to make batteries. Others will inevitably be denied the chance to construct them. Prices also increase as a result of shortages. These import-dependent nations have little influence over the production or pricing of these rare metals. India is attempting to switch from lithium-ion battery technology to fuel cells in large part because of this. Other countries are attempting to create battery technology that uses less resources. Lithium, for instance, is used in LiFePO4 batteries (Lithium Iron Phosphate), which do not need nickel or cobalt. From a safety perspective, Lithium Iron Phosphate is also becoming a potential option. Additionally, scientists are working to develop new battery types, such as sodium-ion batteries [51,52] and zinc-air [53] with more commonly available materials. However, the acceptable performance, reliability, safety, and durability aspects are still a concern. Beyond Li-ion chemistries, the majority of battery technologies are currently in the prototype or research stages and might not hit the market until 2025 [50]. Fuel cells are less complicated in terms of resource availability, specifically the fuel, hydrogen, is the most abundant chemical element in the universe [54]. They use common materials like carbon, graphite, and stainless steel in their construction. The catalyst electrode materials, specifically the cathode materials are one of the expensive components. From the sustainability perspective, the fuel cell material is safer for the environment compared to the lithium counterpart. The hybrid architecture in FCEV could operate with small traction batteries since the conversion system is independent from energy storage.

5. Socio-economic aspect

For a successful market penetration, socioeconomic factors, such as consumer approval of the items, must be addressed. The capital cost of the fuel cell power system is a limiting factor at present for its wide application, particularly in line with the transportation sector [55]. The development of cheap and sustainable catalyst and membrane components will accelerate the marketing which appears to be critical for commercialization success. The recent projection validates that the rate of cost reduction of FCEV is higher compared to that of BEV. Another crucial problem for the car industry is being ready for unstable markets in the context of ongoing globalization and economic volatility during the financial crisis. This should not result in a lack of knowledge about emerging trends to create sustainable goods and alternative transportation ideas employing green technologies [56]. With the help of new business models, it is possible to define some aspects of the new mobility as well as build new business models like mobility stores, or e-mobility provider services [57,58].

However, it is unclear how much customers are prepared to spend on these services. In addition to the technological hurdles, managing the economic issues is also necessary for successful market penetration. Critical elements include viewpoints on the vehicle's high cost, which is mostly brought on by the high cost of the fuel cell and battery power systems, as well as viewpoints on the range. Research into enhanced materials and design features for fuel cell and battery power systems as well as the processes for optimizing their operation, through artificial intelligence and advanced manufacturing techniques. In order to effectively make up for the drawbacks of electric mobility, new mobility models that incorporate electric cars with other services must be considered for the future. In order for individuals to reconsider their mobility choices, it also appears vital to look at how prior mobility behaviors result in physiological obstacles that might dissolve. Significant elements that must be included in the cost study are the FC system for the car, hydrogen refueling stations, battery/traction motor, and life cycle assessment. FCEV prices today range from $ 55,000 to $ 65,000 depending on the company. As a specialty [8], to include a thorough case study and cost analysis of FCEV in a technical report for Germany. Alavi et al. [59] believed the investments in their analyses from the point of view of infrastructure as not require exceptionally high prices. In addition [60], reported that, in 2050 automotive fuel cell systems will fall to $ 22/kW. The Society of Motor Manufacturers and Traders study, however [60], In 2017 there were 280 percent more fuel cell automobiles than there were in the previous four years. Thompson et al. [9] As stated in the cost studies of FCEV estimation for 2020, and with the car industry's and OEMs' adaptation, prices will drop by about 24 %, and new costs will be in the vicinity of $ 32000-34000. To support this work, the IEA report [7], stated that by 2050 the FCEVs will be in the $ 33400 band. The cost is estimated to be close to $ 33600 in 2030, which is less expensive than BEV, according to the

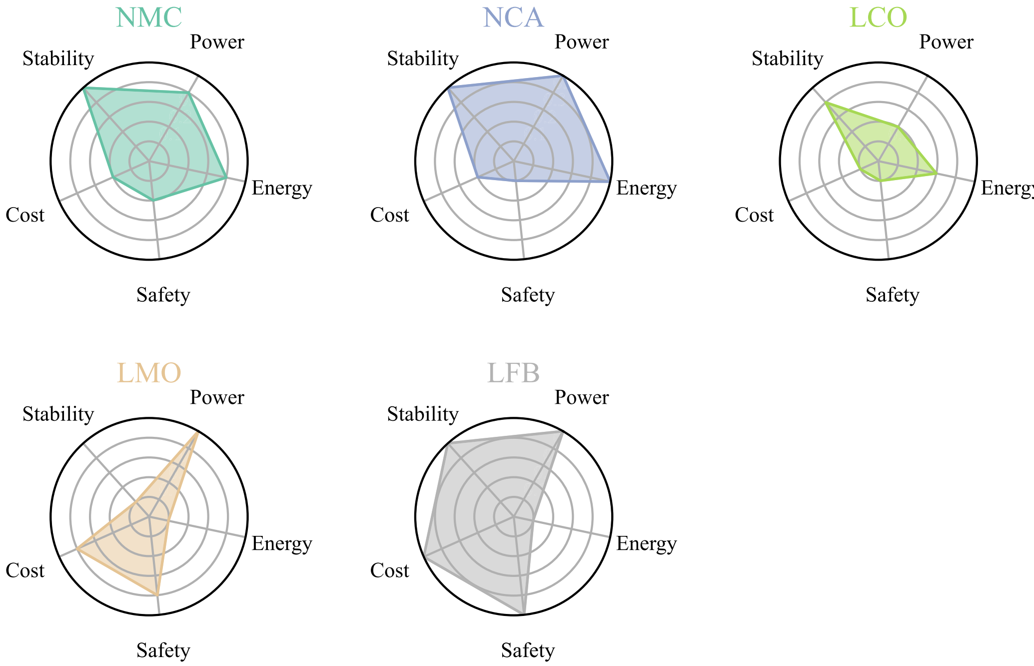

Fig. 2. Radar summary of the features for the most common cathodes [50].

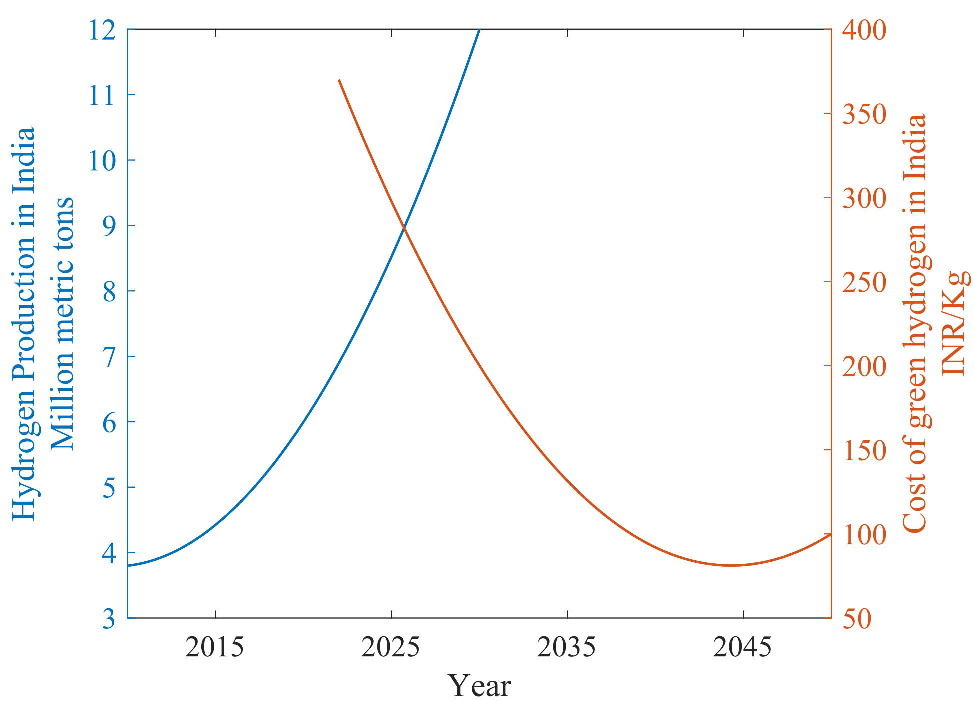

Fig. 3. Expected demand and Cost of hydrogen in India [23].

same analysis. In terms of sales data, a market research analysis from Ref. [61], 6.475 FCEVs have been sold in the last of 2017. In support of this data, the future view is conveyed as [62]; In 2050, there will be at least under 400 million hydrogen-powered automobiles on the road. By 2050, hydrogen will be improved and used on a larger scale in all types of transportation, including cars, trains, and 5% of aeroplanes. The demand and cost analysis is also estimated for the Indian context as in Fig. 3.

Compared to other options, FCEVs have substantially lower carbon emission costs as listed in Table 5. In order to make the green hydrogen sector competitive with other energy sources, the Indian government must work to reduce the cost of production of green hydrogen to as little as one-third of the existing expenses. According to a statement released by Crisil, it is crucial that the government take action to reduce the cost of manufacturing from the present range of $ 3 to $ 6 per

Table 5
Cost of carbon emissions [63] by FCEVs, BEVs, PHEVs, and ICEVs ($/km)

Vehicle	FCEVs	BEVs	PHEVs	ICEs
Car	0.0005	0.0011	0.002	0.002
Bus	0.0044	0.0093	0.012	0.021
Truck	0.0059	0.0091	0.012	0.016

kilogram to less than $ 2 per kg. India will also require a combination of technology breakthroughs and regulatory assistance in order to compete with other energy sources and promote the government's National Green Hydrogen Mission, according to the report, which also noted that the sector has the potential to eventually change the country from being a net energy importer to a net exporter [64].

6. Barriers in transition to electric mobility in India

The Indian government has a two-pronged approach to incentivize electric vehicles (EVs) to both the manufacturers as well as consumers.

Production Linked Incentive (PLI) Scheme: This offers financial incentives to companies that invest in setting up manufacturing units for EVs and key components like batteries in India [65]. The aim is to create a strong domestic EV industry and reduce reliance on imports.

Phased Manufacturing Programme (PMP): This program mandates increasing the local sourcing of EV parts over time, ultimately aiming for self-sufficiency in EV production by 2030 [65].

FAME India Scheme (Phase II): This scheme provides subsidies directly to consumers to bring down the upfront purchase price of electric two-wheelers and three wheelers [66].

New EV Policy (March 2023): This recently announced policy specifically targets attracting large investments from global EV manufacturers to set up production facilities in India. Here are some key features:

Reduced Import Duty: For companies committing to a minimum investment and achieving domestic value addition targets, import duty on EVs under $35,000 is significantly reduced (from 70%–100% to 15%) [67].

Limited Import Allowance: These manufacturers can import a capped number of EVs (up to 8000 annually) while they establish domestic production. Overall, the Indian government is offering a combination of financial assistance, import relaxations, and a push for building a domestic EV supply chain to make EVs more affordable and encourage their adoption in the country.

Energy Security & Environmental Benefits: India relies heavily on imported fossil fuels. E-mobility can lessen dependence on oil and promote renewable energy sources for electricity generation. Reduced tailpipe emissions can significantly improve air quality, especially in urban areas. E-mobility can contribute to meeting India's climate change goals as well to sustainability (SDG-7)

Economic Growth: The EV industry can create new jobs in manufacturing, battery and fuel cell technology, charging infrastructure, and renewable energy.

Manufacturing Hub: India has the potential to become a global hub for EV manufacturing, attracting investments and boosting exports. Despite the promising scope, there are challenges to overcome: Recently, we have observed that the cost of Electric vehicles in India tends to be more cost competitive due to the government's initiatives and subsidies. These incentives have helped to reduce the upfront cost of electric vehicles, making them more competitive with traditional IC-vehicles [68]. However, certain critical challenges still need to be addressed; Charging Infrastructure: The current network of charging stations is limited, especially for long-distance travel. This creates "range anxiety" among potential EV buyers.

Battery Technology: Battery range, charging times, and battery degradation need further improvement to make EVs more competitive.

Raw Material Dependence: India relies on imports for key battery materials like lithium and cobalt. Building a domestic supply chain is crucial for long-term success.

Skilled Workforce: The shift to e-mobility requires a workforce trained to service and repair EVs, which is a nascent area in India.

Grid Capacity: Large-scale EV adoption will put additional strain on the electricity grid. Upgrading and integrating renewable energy sources is essential. Thus, the transition to e-mobility in India has a bright future but requires a multi-pronged approach. Government policies, technological advancements, and private sector investment are all necessary to overcome the challenges and unlock the full potential of e-mobility for a cleaner, more secure, and economically robust India.

7. Outlook and future direction

On, the weight of an average BEV, the weight of the battery packs equals the weight of at least five passengers, and the volume of the batteries also limits the remaining free space. The low energy density of BEV batteries is also the reason for their relatively frequent recharging requirement. Their charging time is a function of the "Level" of the charger used. In an hour, Level 1 chargers will supply enough electricity for 3-5 miles of driving; Level 2 chargers will provide 20-80 miles [69]; Level 3 chargers will provide up to 200 miles; while "DC Fast charging" will load enough electricity for 300 miles of driving in 20 minutes [70]. From the assessment, it is evident, that one of the greatest limiting factors for the penetration of FCEVs is the hydrogen infrastructure, which needs to be well-developed for fuel cell vehicles to lead the race against Battery EVs. The Table 6-provides the compartmental assessment of the most recent BEV (Tesla model 3 - 2023) with FCEV (Toyota Mirai XLE - 2023) [27,28]

In the present context, BEVs are marginally superior to FCEVs in terms of costs and infrastructure availability, but the projection of cost reduction of FCEVs is very promising, especially from the Indian context. The world will need both the BEV and FCEV technologies to disrupt fossil fuels-based technology. It is just a matter of increasing the adoption rate for hydrogen and battery and applying it properly to situations where it is appropriately suited. Some of the initiatives taken by the service provider and supplier in India have been listed in Table 7, Which will also create a positive impact on the FCEV market. Fig. 4 provides a comprehensive explanation of hydrogen usage from initial commercialization to mass market acceptability in the transportation sector [71]. The time line shows the market acceptability of the fuel cell power train and its technology.

The study by the DoE, US, concludes that the fuel cell EV is superior to the Li-ion battery on major counts such as less space and weight on the vehicle, generating fewer greenhouse gases, less time to refuel, less well-to-wheel energy and cost can be competitive [72]. Sarcastically, neither FCEVs nor BEVs are sustainable options unless the energy carrier (hydrogen or electricity) is produced through a renewable source. Also, the energy systems must not environmental impact after their end of life (EOL). The IEA analysis finds that the cost of producing hydrogen from renewable electricity could fall 30 % by 2030 as a result of declining costs of renewable and that is promising good news for hydrogen fuel cell manufacturers. The critical comparison of the advantages of BEV and FCEV is listed in Table 8, where it is also supporting the sustainability in terms of recycling of FCEV products. Battery vehicles can be competitive in the mobility race of low carbon emission, although hydrogen-powered vehicles that include Hydrogen IC engines [73] vehicles and FCEVs could reach the triumph, however, certain parameters limiting the large-scale commercialization of hydrogen vehicles must be addressed rapidly. Both government and commercial measures are expected to speed up the use of hydrogen-powered vehicle technology in India. This will help India transition from a 'technology-taker' status to a position as a global 'technology-maker' successful.

Further to analysis more critical way of the SWOT analysis is added as in Fig. 5.

8. Conclusions

The risks of GHG emission severely impact the degree of climate change shortly and also depending on how well various social and environmental systems can adapt or mitigate the consequences of change, the magnitude of climate change effects on certain regions will alter over time. Eco mobility transition and comparison gains pace around the world and India is not an exception. This study is based on the developments happened in India for last three years and the focus is to give the glimpses of current and expected FCEV development.Despite supply chain disruptions, macroeconomic and geopolitical instability, and high commodity and energy prices, electric car sales got another

Table 6
Comparison of the state of the art BEV with FCEV [27,28].

Parameters	BEVs (Tesla model 3 - 2023)	FCEVs (Toyota Mirai XLE - 2023)
Power conversion	Grid-Battery- Motor (Grid Dependent)	refueling-FC Stack-Motor
Curb Weight	2069 kg	1900 kg
Recharging/Refueling time	Normal charging (22 kW) – 5 h ; Supercharging (150 kW) – 25 min	3 min
Range	270/350 miles	>400 miles
Energy capacity	80 kWh	120 kWh (5.6 kg of H2)
Cost	42 k/53.2 k	$50 k
GHG emission	62 g CO2 MJ-1	41 g CO2 MJ-1
Performance (0–60 mph)	5.1 s	8.5 s
Efficiency	4.375 km/kWh	3.33 km/kWh

Fig. 4. The summary of acceptability timeline with variant segment.

Table 7
Some initiatives by private sectors to support FCEVs development in India.

S.No.	Initiatives
1	The first fuel cell bus in India has been created by the Council of Scientific and Industrial Research and KPIT (Sentient Labs). The bus's operating costs are said to be lower than those of a diesel bus [74].
2	The first hydrogen-powered three-wheeler in India is being created by h2e Power. It is said to utilize an affordable low-pressure hydrogen storage system. H2M, a hydrogen storage company based in Canada, created the technique [75].
3	Toyota and Ministry of Road Transport and Highway (MoRTH) started a study to figure out whether fuel cell cars are sustainable in India. Toyota implemented this by bringing a Mirai FCEV to India [76]. Toyota provided Ashok Leyland with one hydrogen fuel cell module so they were able to build a commercial fuel cell vehicle for a feasibility study [77]. At the 2023 Auto Expo, the maker of commercial vehicles displayed an electric fuel cell truck with a 33.6 kg hydrogen carrying capacity. At the Delhi 2023 Auto Expo, It also displayed prototypes of the Mirai and the Corolla Cross Hydrogen Concept [78].
4	Tata Motors unveiled the Starbus FCEV [79], their first FCEV bus, at the 2023 Auto Expo. In FY2023–24, Indian Oil plans to fulfill its requirements. The Prima E.55S, a hydrogen FCEV truck concept, was also displayed by them [80].
5	Hyundai used the Nexo FCEV in India to carry out a feasibility study. The vehicle was displayed at the 2020 [81] and 2023 Auto Expos [82].
6	Reliance Industries and Ashok Leyland are in discussions on retrofitting the company's current fleet of trucks with hydrogen fuel cells [83].

record year in 2022. From 9% in 2021 to 14% in 2022 – more than ten times their share in 2017 – the proportion of electric vehicles in all auto sales increased [84,85]. The transition to battery EV although seen as a potential solution there lies a series of challenges and especially from the Indian context there exist severe techno, and socio-economic concerns which are listed as follows

Table 8
Comparison of advantages of Battery electric vehicle and Fuel cell electric vehicle.

Why Battery electric vehicle	Why Fuel Cell Electric Vehicle
Has momentum: world market 2019 approaching 2MN	Quick to refuel and Range comparableto ICE
Basic for charging infrastructure is widely available	Technology is proven and available,though immature
Model pipeline and segment coverage are growing	Specific energy capacity of H2 fargreater than battery
Affordability is increasing steadily	Lower environmental impact inproduction process
Better on-board efficiency, fewer stepsto produce fuel	Rare/exotic material requirementis lower
All OEMs will offer a BEV portfolio in the medium term	FC stacks are refurbished andup to 95 % recyclable

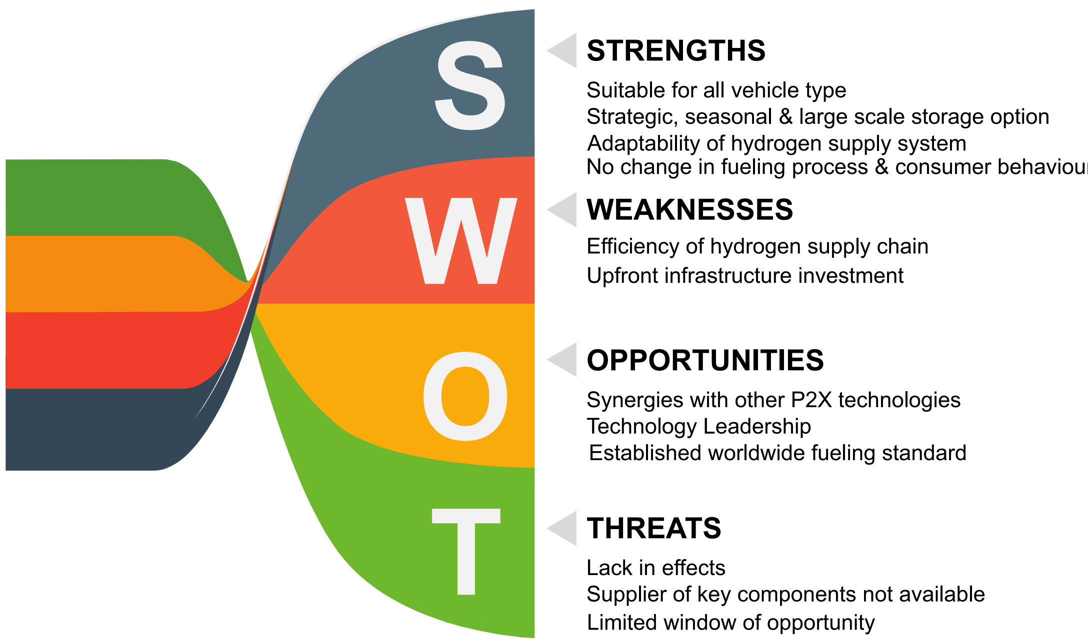

Fig. 5. SWOT assessment of FCEV.

- The charging time of the battery is a serious concern, fast charging is not a potential option as it comes with the cost of battery degradation as well as related safety concerns
- Lithium source is not abundant. Dependent on Li-source in China is worse than the dependency on oil from Middle East countries [86].
- The dynamic cost of reduction for fuel cell components is lower than that of its Battery counterpart
- Limited charging stations for electric vehicles in India and an unstable power grid. Hydrogen infrastructure can be extended with the existing gasoline infrastructure
- Government framework and road map play an important role in improving the technical standard of EVs, ensuring product acceptance, and encouraging the purchase of FCEVs by providing subsidies.
- Neither batteries nor fuel cells are sustainable technologies unless the energy carrier (electricity and hydrogen) is synthesized through a renewable route
- Providing incentives for FCEV purchases, promoting investment in infrastructure, and disseminating information to raise public awareness are integral factors that can accelerate commercialization.
- The vision of government, industries, and the public must converge towards sustainability.
- From the comprehensive assessment it is evident that both battery-electric vehicles and fuel-cell electric vehicles will likely play key, complementary roles in the SDG-7
- In the long run, it will be critical to both continue developing a full range of enabling technologies and to take a holistic approach to the intelligent deployment of EVs and FCEVs in niche applications where they can have the most impact sustainably.

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.

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