Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X Volume 3, Issue 6, 2025

TRANSITIONING PESHAWAR BRT FROM DIESEL-HYBRID ENGINES TO HYDROGEN FUEL CELLS: SOCIO-ECONOMIC IMPACT & FEASIBILITY

Muhammad Bilal[1], Emran Ullah Khan[*2], Ateeb Ali Khan[3]

[*1]*Department of Information Engineering Technology, University of Technology, Nowshera 24170, Pakistan*
[2]*Bachelor of Electrical Engineering, CECOS University of IT and Emerging Sciences, Peshawar 25100, Pakistan*
[3]*Bachelor of Information Engineering Technology, University of Technology, Nowshera 24170, Pakistan*

[1]mbilal@uotnowshera.edu.pk, [*2]emranullah1996@gmail.com, [3]ateebalikhan64@gmail.com

DOI: https://doi.org/10.5281/zenodo.15609942

Keywords
Hydrogen Fuel Cell, BRT System, Urban Transport in Peshawar.

Article History
Received on 28 April 2025
Accepted on 28 May 2025
Published on 06 June 2025

Corresponding Author: *
Emran Ullah Khan

Abstract
Peshawar's Bus Rapid Transit (BRT) system holds great relevance in driving Peshawar transport, such a revolutionary system which has created thousands of jobs, and created more business opportunities than ever. But it needs to be improved with the hydrogen fuel cell technology (HFC), transition of Peshawar's Bus Rapid Transit (BRT) system from a conventional fuel transport to a futuristic one like that of Hydrogen fuel cell (HFC) will increase chance to adapt to a sustainable urban transport, reduce greenhouse gas emissions, and improve socio-economic elements in the region. As per the census carried out the Hydrogen Fuel Cell Electric Buses (HFCEBs) market value is estimated to be around $8.31 Billion, with an annual growth of 19.78% indicating its total market value to $20.49 Dollar by 2030. Transition of the Peshawar BRT systems to all Hydrogen Fuel Cell Electric Buses (FCEBs) will offer operational advantages to the transport infrastructure of the city, increasing the buses extended ranges to far side of the city, enhancing rapid refueling systems, all of which aligns with the demands for a high-frequency and swift BRT system. Implementation of Hydrogen Fuel Cell technology will enable BRT Systems to produce zero carbon emissions, help in decreasing air and water pollution, along with lowering the cost of operation for driving the BRT System.

INTRODUCTION

Inaugurated on the 13 of August, 2020 the Peshawar's Bus Rapid Transit (BRT) system, the Zu Peshawar is listed as the fourth BRT initiative in Pakistan. Zu Peshawar is extended across a 27-kilometer in total starting from Chamkani Station to Karkhano Market Station, and complemented by 58 Kilometers of off-corridor routes which is comprised of 13 routes, 5 express, 2 stopping, and 6 direct/feeder routes, all of this transport system is powered by a fleet of 244 diesel-hybrid Buses. The large fleet has 65 different articulated 18 meter, with capacity of more than 125 passengers' buses, and the rest of the 179 buses with 12 meter in dimensions which are capable of accommodating 75 passengers each bus [10].

Figure 1 BRT Peshawar Terminal

Hydrogen Fuel Cell Technology (HFC) is one of the best alternatives to power the public transportation in the region, which would cut down carbon emissions, decrease pollution, and improve operational efficiency of the BRT System. The proposed technology will utilize hydrogen molecules as the primary energy resource to generate electricity by the process of electrolysis, which would emit water vapor as a byproduct. The technology is been used in locomotives which are operational in the Australian region and has a profound impact on both the economy and the environment of the public transport system [3].

1.2 Problem Statement

Despite the adoption of diesel-hybrid buses, Peshawar's BRT system continues to grapple with challenges related to greenhouse gas emissions and operational costs. Diesel-hybrid buses, while more efficient than conventional diesel buses, still emit pollutants that contribute to urban air quality degradation and climate change [3]. Additionally, fluctuations in diesel fuel prices and the maintenance complexities associated with hybrid systems can lead to elevated operational expenditures. These issues underscore the need for a more sustainable and cost-effective propulsion solution for the BRT system.

One of the major issues to deal with is the emission of greenhouse gases from the diesel-hybrid bus engines, along with the high operational cost which comes along with each bus in Peshawar's BRT system [10]. Diesel-hybrid buses can be taken as an efficient and less carbon emitting vehicle but still it is responsible for producing a high frequency of carbon emission contributing to high decreasing urban air quality and disturbing the regional climate change [5].

Figure 2 Wrightbus - Hydro Fuel Double Decker Bus

1.3 Objectives

The proposed idea of transitioning of Peshawar's Bus Rapid Transit (BRT) system or better known as ZU Peshawar from now traditional diesel-hybrid engines to futuristic hydrogen fuel technology holds a great relevance, and aims to achieve the following objectives:

- Primary focus of the research work is to study the results gained after the applications of hydrogen fuel cell technology to limit the CO_2 and other tailpipe emissions from the current bus fleet of BRT System.
- Study the economic outcomes, decrease in operational cost of BRT system, comparative analysis of maintenance cost, and installation cost of the hydrogen fuel cell technology to power up the fleet of buses.
- Finding out all the basic, infrastructure related, and technical requirements for the integration of the hydrogen fuel cell technology into the current Zu Peshawar Infrastructure.
- Study the technical and infrastructure features which are required for the integration of the hydrogen fuel cell in the existing BRT Peshawar system.
- Explore the technical aspects and infrastructure changes required in the integration of hydrogen fuel cell technology as a replacement for the existing diesel-hybrid bus fleet [20]
- Analysis of the operational cost, vehicle travel range, maintenance cost, and carbon emissions from the tailpipe line from the fleet of buses.

Figure 3 NexantECA - The Bavarian Fuel Cell

By achieving the mentioned objectives, the study is done for detailed analysis of the economic advantages and obstacles related to proposed idea of implementation of the Hydrogen Fuel Cells technology, it will help in the making a better decision to transition from a diesel-hybrid engines to a futuristic technology to attain improvement in the current urban transportation development in Peshawar city [10].

2. Literature Review

Hydrogen fuel cell technology is going to capture the future energy market and this trend has been noticed by some of the top public transport systems across the globe, which has adopted the hybrid fuel cell technology as the primary fuel resource in replacement of the diesel-powered buses. Such, as the case for "Wrightbus", a bus manufacturer company in the UK region, has introduced the world's first double-decker buses back in 2020 [16]

Wrightbus operate fleets across major cities including London, Aberdeen, Dublin, and Birmingham etc., due to applications of the Hydrogen Fuel technology [17] as a replacement for the traditional source driven engines in the buses the results attained are highly valuable from reducing the CO_2 emissions with an approximate value of 1600 Tones, along with that the cost of operations was greatly reduced and range of travel for the fleet buses across the region.

It might come as a surprise to some that in the state of California, USA the new technology of hydrogen fuel cells has been implemented by the 8/10 largest Transport fleets in the state [15]. Their sole goal is to control greenhouse gas emissions from the fleet tailpipes and to add value to the socio-economic situation of the region.

European countries such as Germany have also successfully applied the prototype of Hydrogen fuel cell powered bus fleet as a public transport system under the banner of "The Bavarian Fuel Cell", which shows the feasibility of the technology in the region [3]. In Table 1, we are analyzing BEB's capacity when it comes to higher energy efficiency, to the FCEB's longer travel range, quick refueling, and its higher investment demand for infrastructure.

Table 1. Comparative Analysis of Fuel Cell and Battery Electric Buses [11] [12] [14]

Metric	Battery Electric Buses (BEBs)	Fuel Cell Electric Buses (FCEBs)
Energy Source	Electricity	Hydrogen fuel cells
Energy Efficiency (%)	85-90	60-70
Operating Costs	Lower Than FCEBs	2.3 times higher than BEBs
Infrastructure Cost	Lower Than FCEBs	Depends on Magnitude of Project still higher then BEBs
Refueling Time	4-6 hours	10-15 minutes
Range per Full Charge	250-350 km	400-500 km
Environmental Impact	Grid Electricity Dependent	Hydrogen-dependent
GHG Emissions (Life Cycle Analysis)	Low (Not for electricity generated by fossil-fuel)	Low (High with Grey hydrogen)

3. Current Status of Peshawar BRT System

Peshawar's Bus Rapid Transit (BRT) [18] system, known as Zu Peshawar, was inaugurated on August 13, 2020. The system features a 27-kilometer dedicated corridor extending from Chamkani to Karkhano Market, complemented by 58 kilometers of off-corridor routes. It comprises 13 routes: 5 express, 2 stopping, and 6 direct/feeder routes, serviced by a fleet of 244 diesel-hybrid buses. The fleet includes 65 articulated 18-meter buses with a capacity of 125 passengers each and 179 standard 12-meter buses accommodating 75 passengers each [4].

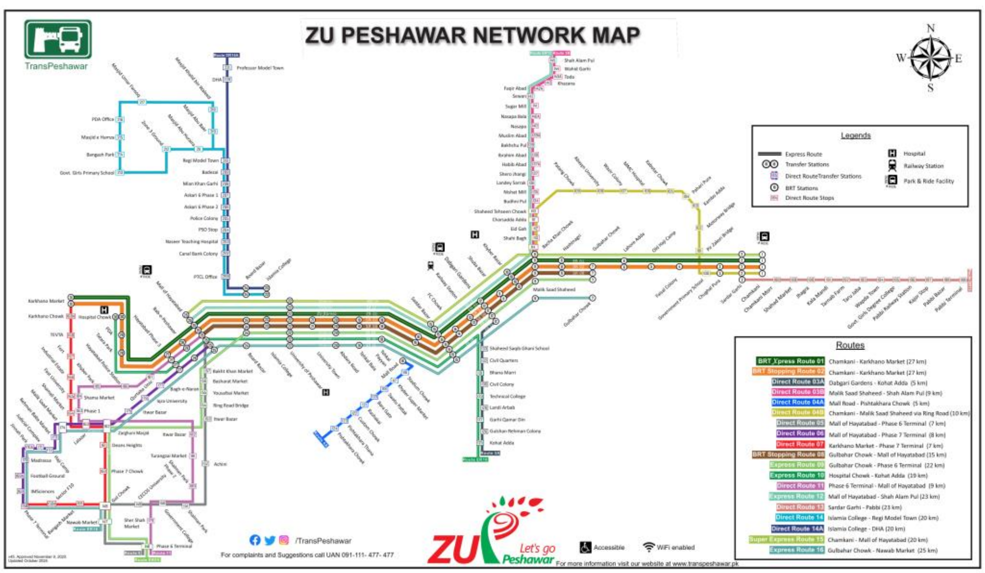

Figure 4 : Zu Peshawar Route Map

3.1 Operational Data: In Table 2, we have discussed the current ZU system passenger capacity, bus fleet maintenance, and cost of operating infrastructure.

Table 2. Operational Data [4] [10]

Metric	Battery Electric Buses (BEBs)
Daily Passenger Numbers	250,000+ passengers/day
Annual Passenger Numbers	~91.25 million passengers/year

Operating Cost	46.98 PKR/km
Engine Fuel Type Used	Diesel-Hybrid
Maintenance Cost	3.7 PKR /km (replacement materials) + 3.5 PKR/km (miscellaneous)
Total Maintenance Cost	~2.7 billion PKR/Year
Fleet Size	~220+ buses

4. Feasibility Study of Transitioning to Hydrogen Fuel Cells

Initially the primary requirement is for the modification or calibration of the current in used diesel-hybrid engines. There are a number of hardware components which need to be fitted in the infrastructure of each bus of the fleet, these hardware components include hydrogen fuel storage tanks, hydrogen fuel cell stacks, and also several control systems [3]. Along with that wiring and power nodes will also be modified in order to make compatibility with the new hydrogen fuel cell source. From changes in overall design of each bus, this would save more finances and time leading to an easy setup for hydrogen fuel cell technology [19]. In Table 3, we have discussed the modifications required for the proposed technology, fuel efficiency, environmental impact, and long-term feasibility of the project.

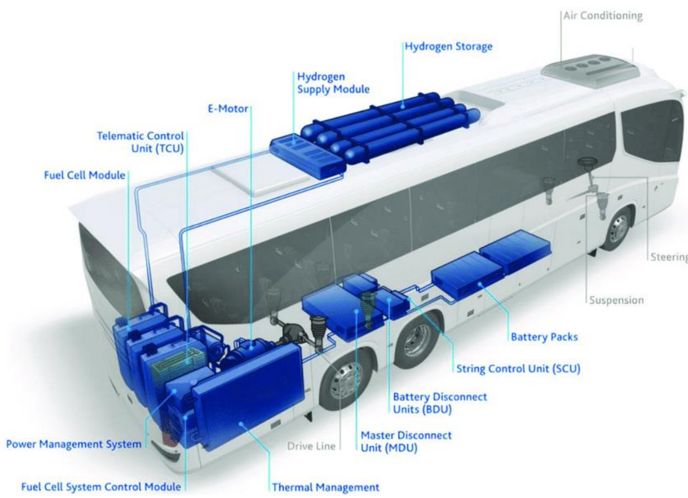

Figure 5 Hydrogen Fuel Cell Bus Technology

Table 3. Comparative Analysis of Fuel Cell and Battery Electric Buses [1] [3] [9]

Category	Current Design	Proposed Modification	Engineering Considerations
Bus Powertrain	Diesel-hybrid internal combustion engine	Hydrogen fuel cell + electric motor	Integration of Fuel Cell Electric Drive (FCED)
Fuel Storage System	Diesel tanks (standard capacity ~300L)	Hydrogen tanks (30-50 kg H_2, 350-700 bar)	High-pressure composite tanks (Type IV)
Bus Weight	12-18 meters, 14-18 tons	~ 16-20 tons (due to fuel cell and storage)	Weight distribution optimization
Chassis Modification	Designed for diesel engine placement	Adjusted for fuel cell, tanks, and electric drivetrain	Reinforced structure for new weight
Cooling System	Radiator-based cooling for diesel engine	Advanced thermal management for fuel cell	Liquid cooling system for fuel cell stacks
Refueling Infrastructure	Diesel stations across routes	Hydrogen refueling stations (350-700 bar)	Multiple stations with on-site electrolysis

Energy Efficiency (km/kg H_2)	~2.5 km per liter diesel	~10-12 km per kg H_2	Fuel cell efficiency ~50% vs. diesel 30-35%
Range per Full Tank	350-400 km per diesel tank	350-450 km per full hydrogen tank	Depends on tank capacity and road conditions
Maintenance Requirements	High due to moving engine parts	Lower due to fewer moving parts in FC system	Maintenance cycle extended 2x
Emission Levels (CO_2, NOx, PM)	~80-100g CO_2/km per bus	Zero emissions	No tailpipe emissions, H_2O as byproduct
Noise Levels (dB)	~75-85 dB (engine noise)	~55-65 dB	Quieter operation due to electric drive
Battery for Energy Buffering	Small auxiliary battery (for hybrid system)	High-capacity battery (~20-40 kWh)	Balancing energy storage & peak demand
Lifespan of Fuel Cell Stack	N/A (diesel engine ~10-12 years)	~ 15-20 years with maintenance	Degradation rate ~ 2-5% per year
Operational Cost (PKR/km)	~PKR 30-35/km for diesel	Expected PKR 20-25/km with hydrogen	Cost reduction over long-term use
Hydrogen Production Method	N/A	Electrolysis (renewable energy-based)	Green hydrogen preferred for sustainability
Government Policy Requirements	Diesel taxation, fuel import	Hydrogen subsidies, carbon credits	Incentives for H_2 infrastructure development

4.1 Infrastructure Requirements for Hydrogen Production, Storage, and Refueling

Transition to new technology such as "Hydrogen Fuel Cell" requires a standard and highly optimized infrastructure demands for an infrastructure which drives the system installed as well the operations carried out for generation of hydrogen as fuel via the electrolysis, not only this as the new infrastructure will also house a number of fuel tanks, and hydrogen fuel storage tank for keeping the infrastructure fully functional and safe as per international standards [3]. In Table 4. we have discussed the different challenges faced in hydrogen storage, high-pressure requirements, risk factors, power distributions, and cost of infrastructure.

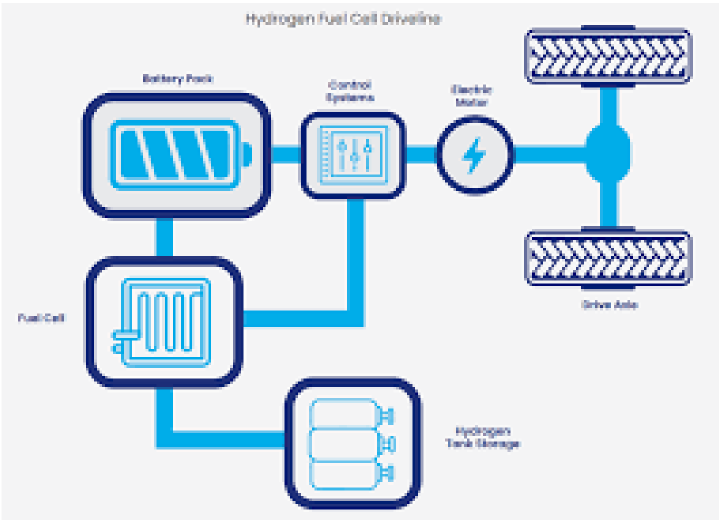

Figure 6 Hydrogen Fuel Cell Driveline

Table 4. Comparative Analysis of Fuel Cell and Battery Electric Buses [1] [10]

Parameter	Calculation Method	Expected Value / Notes
Energy Consumption per Bus (kWh/km)	Derived from existing fuel consumption and efficiency conversion	Typically, 2-3 kWh/km for fuel cell buses
Daily Distance per Bus (km)	Average daily operation distance of Peshawar BRT buses	~ 200-250 km per day
Hydrogen Energy Density (kWh/kg)	Standard value	33.3 kWh/kg
Total Daily Energy Requirement per Bus (kWh)	(Energy Consumption per km) × (Daily Distance)	400-750 kWh/day
Fleet Size	Total buses in BRT system	244 buses
Daily Hydrogen Demand per Bus (kg)	(Total Daily Energy Requirement) ÷ (Hydrogen Energy Density)	~12-22 kg H_2 per bus
Hydrogen Storage Pressure (bar)	Standard storage pressure for fuel cell buses	350 – 700 bar
Total Daily Hydrogen Demand (kg/day)	(Daily Hydrogen Demand per Bus) × (Fleet Size)	~2,928 – 5,368 kg H_2/day
Hydrogen Tank Capacity per Bus (kg)	Based on tank size and pressure constraints	30-50 kg per bus
Refueling Time per Bus (minutes)	Based on standard hydrogen refueling rates	10-15 minutes per bus
Electrolyzer Power Requirement (MW)	(Hydrogen Production × Energy Required per kg)	~12-20 MW (assuming ~50-55 kWh/kg H_2)
Water Consumption for Electrolysis (L/day)	(Hydrogen Production × 9) (since 1 kg H_2 requires ~9 L H_2O)	~27,000 – 50,000 L/day
Hydrogen Production Requirement (kg/day)	Based on demand and electrolysis efficiency	~3,000 – 5,500 kg/day
Total Hydrogen Storage Requirement (kg)	Total Daily Hydrogen Demand × Required Backup Days	~6,000 – 12,000 kg (including reserve storage)
Parameter	Calculation Method	Expected Value / Notes

4.2 Electrolysis Process

Transition to new technology such as "Hydrogen Fuel Cell" requires a standard and highly optimized infrastructure demands

Electrolysis is conducted in an electrolyzer consisting of two electrodes (anode and cathode) and an electrolyte [6] [7]. The reaction occurs as follows:

4.2.1 Overall Chemical Reaction (Water Splitting):

$2H2O(l) \rightarrow 2H2(g)+O2(g)$ ΔH = 286 kJ/mol (at 25°C) (1)

ΔH = 286 kJ/mol (at 25°C)}ΔH = 286 kJ/mol (at 25°C) (2)

Proton Exchange Membrane Fuel Cell (PEMFC):

$2H2+O2 \rightarrow 2H2O$+Electrical Energy+Heat (3).

4.2.2 Energy Output Calculation

The theoretical electrical work per mole of hydrogen is given by:

We=nFE (1)

Where:

n=2n = 2n=2 (number of electrons transferred) (2)

F=96,485F = 96,485F=96,485 C/mol (Faraday's constant) (3)

E=1.23VE = 1.23VE=1.23V (cell potential) (4)

We=2×96,485×1.23=237,391.7 Joules/mol (5)

Since 1 mol of H2H_2H2 = 2.016 g, the energy output per kg of hydrogen is:

2.016×10−3 kg/mol237,391.7 J/mol=117.7 MJ/kg (6)

1 Kg of Hydrogen = 117.7 MJ of energy (7).

3. Efficiency Calculation

η =ΔH/ΔG (1)

Where:

Gibbs free energy (ΔG) = 237.1 kJ/mol (2)

Enthalpy (ΔH) = 286 kJ/mol (2)

η=237.1286\286=0.83=83% (3).

4. Hydrogen Fuel Consumption for a Bus [7]

Average daily bus travel in Peshawar BRT = 250 km

Hydrogen consumption = 9 kg per 100 km

Total daily fuel consumption per bus:
9 kg/100×250=22.5 kg/day (1)
For a fleet of 244 buses, daily hydrogen demand:
244×22.5=5,490 kg/day (2)
Annual hydrogen demand:
5,490×365=2,004,850 kg/year (3)
At a hydrogen cost of PKR 1,200/kg, the annual hydrogen fuel cost:
2,004,850×1,200=PKR 2.41 billion (4).

5. Storage Requirements [9]
2,004,850/70=28,640 m^3/year (1)
For compressed hydrogen at 700 bars (density ~42 kg/m^3):
2,004,850/42=47,735 m^3/year (2)
In Table 5, we have emphasized on high refueling requirements, energy demands, and optimal condition to carry out enough electrolysis.

Table 5. Types of Electrolyzers [6] [7]

Electrolyzer Type	Operating Temperature (°C)	Efficiency (%)	Hydrogen Production Rate (kg H_2/kWh)
Alkaline Electrolyzer (AEL)	60-90	65-70	0.018-0.023
Proton Exchange Membrane (PEM)	50-80	70-75	0.020-0.025
Solid Oxide Electrolyzer (SOE)	700-900	85-90	0.025-0.030

In Table 6, we have thoroughly discussed production of hydrogen fuel via different procedures, electrolysis reaction, and biomass gasification. We are emphasizing on reduction of CO2 emission and improving operational efficiency.

Table 6. Renewable Energy Sources for Hydrogen Production [8] [9]

Renewable Source	Efficiency (%)	Capacity Factor	Energy Output (kWh/m^2/year)
Solar Photovoltaic (PV)	15-22	20-25%	1500-2000
Wind Energy	30-45	30-40%	2000-2500
Hydropower (Small-scale)	80-90	50-60%	2500-3500
Biomass Gasification	30-40	50-60%	1000-2000

In Table 7, we have analyzed the Lifecycle emissions of both Hydrogen fuel cell buses and conventional battery electric buses.

Table 7. Renewable Energy Sources for Hydrogen Production [8] [9]

Renewable Source	Hydrogen Output (kg H_2/kWh)
Solar Photovoltaic (PV)	0.02-0.025
Wind Energy	0.025-0.030
Hydropower (Small-scale)	0.030-0.035
Biomass Gasification	0.015-0.022

4.3 Infrastructure Requirements for Hydrogen Production, Storage, and Refueling
Solar energy is highly viable due to high solar irradiance (~5.5-6.5 kWh/m^2/day).
Small-scale hydropower from nearby rivers can provide stable energy.
Wind energy potential is limited but can supplement production.
Biomass from agricultural waste can contribute to hydrogen production in smaller quantities.

4.4 Hydrogen Yield and Storage Considerations
In Table 8, we have discussed the operational and energy efficiency of Hydrogen fuel cell buses and conventional battery electric buses.

Table 8. Renewable Energy Sources for Hydrogen Production [8] [9]

Parameter	Value
Electricity required to produce 1 kg H_2	~50-55 kWh
Hydrogen energy content	33.6 kWh/kg
Hydrogen storage pressure	350-700 bar
Daily H_2 requirement for Peshawar BRT (for 244 buses)	~5,000-6,000 kg
Electrolyzer capacity needed	~250-300 MW

This means a 250 MW solar farm or renewable energy mix is needed to power electrolyzers for Peshawar's BRT system. In Table 9, we have highlighted the impact of replacing BEB with FCEB fuel cells. Our discussion compromises of system maintenance requirements, and its impact on long-term cost and reliability of the new system.

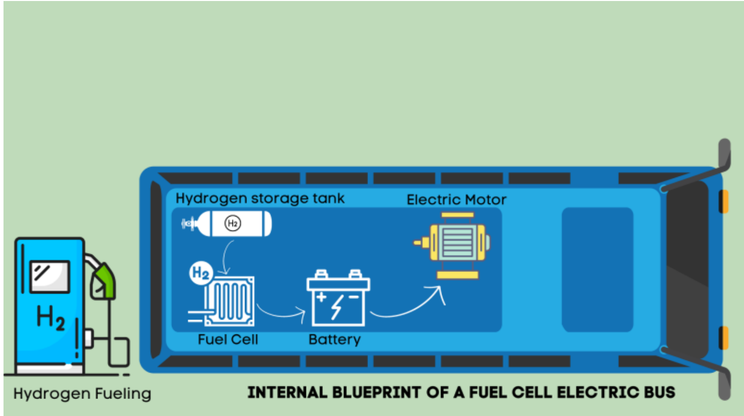

Figure 7 Internal Blueprint of Hydrogen Fuel Cell Electric Bus

Table 9. Expected Results from Hydrogen Transition [2]

Parameter	Diesel Buses	Hydrogen Fuel Cell Buses	Improvement (%)
CO_2 Emissions (g/km)	~1,000	0	100% Reduction
Fuel Efficiency (km/kg H_2 or km/L Diesel)	~2.5 km/L	10-12 km/kg	300-400% Improvement
Operating Cost (PKR/km)	~30-35 PKR/km	20-25 PKR/km	30% Reduction
Noise Levels (dB)	~80 dB	60-65 dB	20-25% Quieter
Maintenance Costs (Annual)	High (Diesel Engine Repairs)	Low (Fuel Cell Systems)	50% Savings

In Table 10, we are analyzing how BEBs have lower cost of operation as well as less investment in infrastructure as compared to a highly demanding FCEBs.

Table 10. Economic Analysis [5]

Cost Component	Diesel Buses	Hydrogen Fuel Cell Buses (FCEBs)
Capital Cost per Bus	Approximately PKR 133,771,200 (USD 480,000)	Approximately PKR 362,297,000 (USD 1,300,000)
Fuel Cost per Mile	- PKR 108.69 (USD 0.39) - PKR 175.58 (USD 0.63)	- PKR 295.42 per mile (USD 1.06) - PKR 117.05 per mile (USD 0.42)
Maintenance Cost per Year	Approximately PKR 83,607,000 (USD 300,000)	Approximately PKR 62,205,000 (USD 225,000)
Total Cost of Ownership	- Capital Cost: PKR 133,771,200 -	- Capital Cost: PKR 362,297,000 - Maintenance:

(TCO) over 12 Years	Maintenance: PKR 83,607,000/year × 12 = PKR 1,003,284,000 - Total: PKR 1,137,055,200	PKR 62,205,000/year × 12 = PKR 746,460,000 - Total: PKR 1,108,757,000
Fuel Efficiency	Approximately 4 miles per gallon	Approximately 6 miles per kilogram of hydrogen

In Table 11, we are comparing the different metrics related to lifecycle cost of BEB's with FCEB's which demands more infrastructure cost.

Table 11. Comparison with ZU Peshawar System [1] [10]

Category	Current Peshawar BRT (Diesel/Hybrid Buses)	Proposed Hydrogen Fuel Cell Buses
Total Fleet Size	244 buses (65 of 18m, 179 of 12m)	244 hydrogen fuel cell buses
Bus Capacity	- 18m buses: 125 passengers - 12m buses: 75 passengers	Same as current (retrofitting possible)
Daily Ridership	Over 250,000 passengers	Expected increase due to environmental incentives
Fuel Type	Diesel/Hybrid	Hydrogen
Fuel Consumption (per bus per km)	- 2.5 to 3.5 km per liter of diesel	- 6 to 8 km per kg of hydrogen
Fuel Cost per km (PKR)	~PKR 108-175 per km	~PKR 117-295 per km
Annual Maintenance Cost per Bus	~PKR 343,000 - 650,000 per year	~PKR 250,000 - 500,000 per year
Total Annual Fuel Cost (Estimated)	~PKR 2.5 - 3.2 billion	~PKR 2.7 - 3.5 billion
Infrastructure Availability	Existing fueling stations	Requires new hydrogen refueling stations
CO_2 Emissions (g/km per bus)	~1,000 g/km	~Zero emissions
Operational Lifespan	10-12 years	12-15 years
Government Subsidies/Support	Existing diesel subsidies	Possible incentives for hydrogen transition
Total Cost of Ownership (TCO) per Bus over 12 Years	~PKR 1.14 billion	~PKR 1.11 billion
Environmental Impact	High CO_2, NO_x, PM emissions	Significant reduction in pollutants

In Table 12, we explain how BEB's are best option for ZU's local routes, and FCEB's for longer routes, while we also add details related to the fleet expansion strategy.

Table 12. Total Cost of Ownership (TCO) Analysis for Hydrogen Fuel Cell Buses [1] [2] [3] [18]

Category	Hydrogen Fuel Cell Bus (Estimate, PKR)	Diesel-Hybrid Bus (Peshawar BRT, PKR)	Comparison (%)
Capital Cost per Bus	120 million – 130 million	30 million – 40 million	3x – 4x Higher
Infrastructure Setup (Per Bus Equivalent)	18 million – 22 million	5 million – 7 million	~3x Higher
Annual Fuel Cost per Bus	6.5 million – 7.5 million	3.2 million – 3.8 million	~2x Higher
Annual Maintenance Cost per Bus	350,000 – 500,000	600,000 – 800,000	~30-40% Lower
Total Cost of Ownership (TCO) per Bus (12 Years)	1.2 billion – 1.35 billion	450 million – 550 million	~2.5x Higher
Fuel Consumption (Per km, kg or liters)	0.09 – 0.12 kg/km (Hydrogen)	2.5 – 3 liters/km (Diesel)	-
Hydrogen Fuel Cost per kg	1,100 – 1,200	-	-
Diesel Cost per liter	-	285 – 300	-
Total Fuel Required per Year per Bus	5,500 – 6,200 kg	36,000 – 45,000 liters	-
Projected Reduction in Hydrogen Cost (By 2030)	20-30% Lower	-	-
CO_2 Emissions per Bus per Year	~0 (Near Zero)	120 – 150 tons	100% Reduction
Estimated Fleet Size for Peshawar BRT	244 Buses	244 Buses	-

4.5 Investment Recovery Timeline for Hydrogen Fuel Cell Buses – Peshawar BRT

We will calculate two scenarios:

Per Ticket Price = PKR 50

Per Ticket Price = PKR 60

In Table 13, we have discussed the different incentives offered by government for hydrogen adoption and different policies related to renewable energy.

Table 13. Estimated Cost & Revenue Breakdown [1] [4]

Parameter	PKR (Ticket Price: 50)	PKR (Ticket Price: 60)
Capital Cost per Bus	120 – 130 million	120 – 130 million
Infrastructure Cost per Bus	18 – 22 million	18 – 22 million
Annual Fuel Cost per Bus	6.5 – 7.5 million	6.5 – 7.5 million
Annual Maintenance Cost per Bus	0.35 – 0.50 million	0.35 – 0.50 million
Total Cost per Bus (12 Years TCO)	1.2 – 1.35 billion	1.2 – 1.35 billion
Daily Ridership per Bus	~1,025 passengers	~1,025 passengers
Average Ticket Price (PKR)	50	60
Daily Revenue per Bus (PKR)	51250	61500
Annual Revenue per Bus (PKR)	18.7 million	22.4 million

In Table 14, we discuss the requirements for smart charging, modification of grids, and cost related to the deployment of BEB's grid.

Table 14. Investment Recovery Timeline – Scenario 1 (Ticket Price: PKR 50) [4] [5]

Year	Cumulative Revenue (PKR)	Cumulative Cost (PKR)	Net Cash Flow (PKR)
1	18.7 million	138 million	-119.3 million
2	37.4 million	146 million	-108.6 million
3	56.1 million	154 million	-97.9 million
4	74.8 million	162 million	-87.2 million
5	93.5 million	170 million	-76.5 million
6	112.2 million	178 million	-65.8 million
7	130.9 million	186 million	-55.1 million
8	149.6 million	194 million	-44.4 million (Break-even)

Scenario 1: Break-even occurs in ~7.5 – 8 years

In the below table 15, we have discussed the environmental impact of the hydrogen fuel cell technology, focused on reducing CO2 emissions, and adding value to urban sustainability.

Table 15. Investment Recovery Timeline – Scenario 1 (Ticket Price: PKR 60) [4] [5]

Year	Cumulative Revenue (PKR)	Cumulative Cost (PKR)	Net Cash Flow (PKR)
1	22.4 million	138 million	-115.6 million
2	44.8 million	146 million	-101.2 million
3	67.2 million	154 million	-86.8 million
4	89.6 million	162 million	-72.4 million
5	112.0 million	170 million	-58.0 million
6	134.4 million	178 million	-43.6 million
7	156.8 million	186 million	-29.2 million (Break-even)

Scenario 1: Break-even occurs in ~7.5 – 8 years

Key Takeaways:

Ticket price at PKR 50 → Break-even in ~7.5 – 8 years

Ticket price at PKR 60 → Break-even in ~6.5 – 7 years

Increasing ticket price by PKR 10 reduces the payback period by ~1 year

In Table 16, we have discussed the cost effectiveness, advancement in fuel storage, and further advancement in the hydrogen fuel cell technology.

Table 16. Potential Government Subsidies [2] [3]

Scenario	Subsidy Details	Adjusted Annual Operational Cost (PKR)	Adjusted Payback Period
Baseline	No subsidies	7.5 million	~7.5 – 8 years
Capital Subsidy	20% of capital cost (PKR 25 million)	7.5 million	~6.5 – 7 years
Fuel Subsidy	30% reduction in fuel cost (PKR 2.1 million savings annually)	5.4 million	~6 – 6.5 years
Combined Subsidies	20% capital subsidy + 30% fuel subsidy	5.4 million	~5.5 – 6 years

5. Environmental Impact

Environmental Benefits in the Context of Peshawar's Air Quality, Projected Reduction in CO_2 and Other Emissions Post-Transition

Moving away from the traditional form of transport system would provide a number of benefits, including a improving the regional environment and limitation of CO_2 emissions [17], it helps to achieve zero tailpipe emissions and reducing the generation of pollutants which are associated with the diesel combustion engines currently in use in the BRT systems. In Table 17, under consideration is the future prospect of Hydrogen fuel cell technology, generation of its fuel, its integration in modern transport, and different policy for sustainability.

Table 17. Potential Government Subsidies [2] [18]

Parameter	Before Zu Peshawar Implementation	After Zu Peshawar Implementation	Projected with Hydrogen Fuel Cell Buses
PM2.5 Levels (μg/m³)	~80	~65	~40
PM10 Levels (μg/m³)	~150	~120	~80
SO_2 Levels (ppb)	~12	~8	~3
CO_2 Emissions Reduction (tons/year)	Baseline	31,000	50,000+
Modal Share of BRT (%)	0%	21%	30%
Female Ridership Percentage (%)	2%	27%	35%
Noise Pollution (dB Reduction)	High (Diesel buses ~85 dB)	Moderate (~75 dB)	Low (~65 dB)

6. Case Studies and Benchmarking

Wrightbus, a UK-based bus manufacturer, developed the world's first double-decker hydrogen fuel cell bus. These buses are operational in cities such as Aberdeen, Birmingham, London, Belfast, and Dublin. Collectively, the fleet has covered over one million miles, resulting in a reduction of approximately 1,600 tonnes of CO_2 emissions [16].

A UK-based bus manufacturer, named as "Wrightbus", introduced the hydrogen fuel cell powered double-decker buses back in 2020. Introduction of the new technology as an alternative for the non-renewable resources made an impact in both economic and environmental factors [3]

6.1 Implementation by Wrightbus

2020 - The first hydrogen fuel cell powered double decker buses were launched in Aberdeen.

2021-2022 - After successful launch and operations, Wrightbus extended their fleet operations towards the following cities Birmingham, London, Belfast, and Dublin.
2023 - An overwhelming response was gathered by the Bus operators, as Wrightbus now operated across a region of One Million Miles.

In Table 18, we discuss the economic and environmental impact of the proposed hydrogen fuel technology and replacing the current all electric powered bus fleet.

Table 18: Economic & Environmental Impact [5]

Metric	Value	Impact (Numerical)
Total Miles Covered	1,500,000 miles	-
CO_2 Emission Reduction	2,366 tonnes	2,366 tonnes less CO_2 emitted
Fuel Cost Comparison	2.6 times diesel cost	Hydrogen: PKR 1,040/km, Diesel: PKR 400/km
Operational Cost Comparison	2.3 times battery-electric cost	Hydrogen: PKR 1,840/km, Battery-Electric: PKR 800/km
Hydrogen Fuel Consumption	8 kg/100 km	120,000 kg for 1.5 million miles
Diesel Fuel Equivalent	35 liters/100 km	525,000 liters saved
Annual Maintenance Cost	PKR 7,000,000/bus	20% higher than diesel buses
Reduction in NOx Emissions	90%	4,500 kg NOx reduction

7. Implementation Plan for Peshawar BRT

7.1 Phased Transition Strategy

Projects related to public interest such as Peshawar's Bus Rapid Transit (BRT) system to hydrogen fuel cell bus technology demands for a well-structured, feasible, and unique plan in order to achieve all the objectives. An example of such project strategy is given as below:

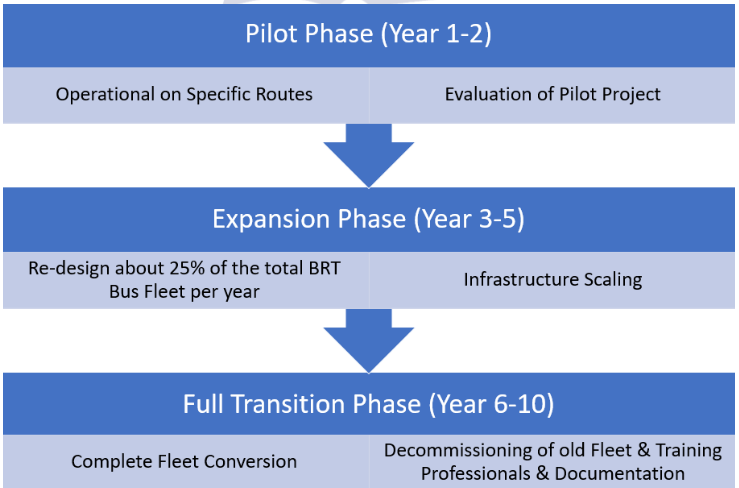

Figure 8 Implementation Plan for Peshawar BRT

8. Infrastructure Development

8.1 Hydrogen Production:

8.1.1 On-Site Electrolysis:

Utilize renewable energy sources, such as solar or wind, to produce hydrogen through electrolysis, ensuring a sustainable supply. An onsite system for the generation of Hydrogen along with refueling stations will be mandatory for driving the BRT Peshawar System and ensuring a smooth-running public transport across the city [12].

8.1.2 Capacity Planning:
Enough number of hydrogen fuel tanks will be essentially designed and implemented to meet the demands for driving the Hydrogen Fuel Cell Bus fleet [13].

8.2 Refueling Stations:
8.2.1 Strategic Placement:
Designing and implementation of secure Hydrogen refueling stations across the different routes both major and extension routes, this would ensure seamless operation and optimization of the BRT System Peshawar [10].

8.2.2 Scalability:
With the help of modern techniques, robust machines, and global standard procedures the hydrogen storage facilities will be added up with time in order to cope with the daily demand for the resource as the primary fuel to power the fleet of buses.

8.3 Storage and Distribution:
8.3.1 Safety Measures:
Implement advanced storage solutions with robust safety protocols to handle high-pressure hydrogen. Hydrogen fuel storage system should be installed and operated with great care and as per the global safety standards, from optimization.

8.3.2 Logistics:
Develop efficient distribution systems to transport hydrogen from production sites to refueling stations.

9. Training and Capacity Building
9.1 Technical Training:
9.1.1 Maintenance Staff:
New technology would require professionals and the technical team of BRT Peshawar to have the capacity to cover diagnostics, repair, and preventive maintenance associated with both the Hydrogen fuel cell bus fleet and the refueling stations across the designated route [13].

9.1.2 Drivers:
Drivers and refueling staff will also be trained leading to certification programs which would enlighten them with the standard procedures related to refueling and safety procedures.

9.2 Safety Training
9.2.1 Emergency Response:
Like any other top class urban transport system, BRT Peshawar will also be operated with a set of protocols, emergency drills will be carried out to ensure minimizing any risk factors related to hydrogen fuel cell related incidents, and making the staff capable of dealing with any mishap.

9.3 Capacity Building & Training:
9.3.1 Management Training:
BRT Peshawar would be greatly benefited if its maintenance team, engineers, and management gets certified with the best skills awarded by top institutions, it would encourage the collaboration of academic institutions with the BRT Peshawar. This could initially increase the number of jobs and internships for experts in the region [10].

9.3.2 Public Awareness:
The application of new technology such as Hydrogen Fuel Cell Bus as a replacement is itself a big deal for both the public and involved stakeholders, it would be incredible to make awareness related to the importance of this new technology to attain highly efficient and less carbon emitting urban transport systems across Pakistan.

10. Risk Assessment and Mitigation
10.1 Technical Risks
10.1.1 Infrastructure Compatibility of Hydrogen Storage Facility:
The fuel tank designs along with keeping the volume of the tanks should be carried out as per the global safety standards, and temperature in which the storage tanks are kept should be optimized as per the standards. The infrastructure for hydrogen fuel tanks should be taken as the most sensitive part and should be designed to withstand high pressure of the hydrogen inside the infrastructure as it would ensure to avoid any leaks or unfortunate emergency events [9].

10.2 Economic Risks

10.2.1 High Initial Costs:

Deployment of Hydrogen fuel cell technology needs ample capital which is quite understood looking into the infrastructure design requirements, refueling stations, and keeping the overall BRT System working in globally accepted safety standards [7]. The initial monetary funds required for the Hydrogen fuel technology is far greater than that of the traditional diesel-hybrid buses.

10.2.2 Fuel Production Expenses: Achieving greater goals does not come cheap as hydrogen fuel is obtained after the chemical reactions carried out through the process of electrolysis again powered by renewable energy resources, this would for sure increase the overall operational cost of the new technology implemented in BRT Peshawar [9]. But again, generating clean energy is something which is way cost-intensive in nature.

10.3 Environmental Risks

10.3.1 Hydrogen Production Emissions:

Having the involvement of fossil fuel (Grey Hydrogen) as a primary source for running the electrolysis process can somehow be responsible for the generation of CO_2 emissions [5].

11. Mitigation Strategies

11.1 Technical Mitigations

11.1.1 Safety Protocols:

Deployment of a highly sensitive and optimized hydrogen fuel cell technology comes with global safety standards, leak detection systems, and high-pressure resistance tanks etc. Along with that CCTV cameras, sensors and fire detection systems should be installed on all the facilities to avoid any fire or other unfortunate events.

11.1.2 Facility Upgrades:

Hydrogen fuel tanks and related facilities should be upgraded to optimized and more secure ones to help the BRT Peshawar operate seamlessly. Investments are compulsory for improving the infrastructure which would support the idea of replacement of Hydrogen fuel cell technology and ensuring the extension of the Urban transport system to new regions and townships [3].

11.2 Economic Mitigations

11.2.1 Government Incentives and Public-Private Partnerships:

From collaboration with international organizations, Banks, and other enterprises across the region to fund the high scale project leading to recovering of the initial cost invested through a structure and feasible planning. Formal collaboration between construction firms, HVAC system deployment companies, and IT firms will serve great to share the overall burden of the large scale mega–project. Such activities also minimize the financial losses and other damages which may occur during the deployment of such a new technology like that of Hydrogen fuel cell bus technology [4].

11.3 Environmental Mitigations

11.3.1 Green Hydrogen Production: Prioritize the use of renewable energy sources for hydrogen production to ensure environmental benefits and reduce carbon footprint. In order to degrade the level of carbon emissions due to the production of hydrogen through electrolysis, the renewable energy resources can be used as alternatives as precursors for driving the electrolysis process [20]. This would help in generating more zero emissions results as compared to using fossil fuels for primary chemical reactions.

11.3.2 Lifecycle Assessments: Professionals and research workers as well as trained professionals at BRT Peshawar will help in monitoring and analysis of the overall zero emissions from the Fleet of Buses along with having an eye over any side effects of the newly deployed technology and replacing the conventional form of powering up the urban transport system [12].

12. Conclusion and Recommendations

12.1 Summary of Findings

Applications of the new and essentially required Hydrogen Fuel Cell Technology will likely help and benefit in the following parameters:

12.1.1 Environmental Benefits: Limitation of carbon emission is not the only pollutant degraded after the application of this new technology as it is accompanied with less nitrogen oxide and other pollutant elements which will help in the improvement of the Urban Air Quality index in the region [3].

12.1.2 Operational Efficiency:

Hydrogen fuel cell buses [19] are way efficient on less fuel consuming, easy to maintain, and fast refueling time etc. as compared to diesel-hybrid buses. Having an environment friendly public transport like that of new technology empowered BRT Buses will attract even more travelers.

12.1.3 Noise Reduction:

Among the many benefits which are obtained by the implementation of the hydrogen fuel cell buses also includes the reduction of the noise pollution which acts as a great stress reliever in today's urban congested world. Hydrogen fuel cell buses are far less quiet than the rest of the diesel-hybrid and electric buses.

12.2 Challenges to Be Addressed:

12.2.1 High Initial Costs & Infrastructure Development:

To deploy the initial infrastructure and replace the old traditional diesel-hybrid engine buses with more efficient hydrogen fuel cell buses come with high financial support and funds required. From establishment of the refueling station across different routes, along with the installation of highly optimized hydrogen fuel storage tanks to support the fleet of over 244+ Buses in the BRT Peshawar System [10].

12.2.2 Technological Maturity:

Like any other technological advancements, the hydrogen fuel cell technology still needs tons of improvement and value addition to make it more efficient, easy to deploy, and highly durable for the ongoing challenges in the future [4].

12.3 Policy Recommendations

There are set of recommendations which are essentially required to be set for a smooth-running Hydrogen Fuel Cell Bus Fleet:

12.3.1 Financial Incentives:

With the implementation of specific policies and taxes for making the BRT Peshawar system good at generating revenue, along with that, different subsidies offered to the mega project can be of great value during the total operational life cycle of the ZU Peshawar [10].

12.3.2 Public-Private Partnerships: Banks, private institutions, government bodies, and international enterprises should be involved in the deployment of the Hydrogen fuel cell technology in the BRT System Peshawar [18]. This would minimize any risk, and acquire different expertise related to making advancements in the empowering urban transport with zero emission projects.

12.3.3 Infrastructure Investment:

The fundamentals of the project should be addressed by means of the infrastructure development, installation and development of the hydrogen fuel tanks etc. All of this will help in achieving far greater results for the stakeholders of the BRT Peshawar. This will also help in complete replacement of the diesel-hybrid bus fleets by more efficient hydrogen fuel cell bus fleets [6].

12.3.4 Regulatory Frameworks:

Both the people working in BRT Peshawar as well as the public should be made aware of the safety policies, and have the knowledge about the safety standards of the hydrogen fuel cell powered bus fleets [19]. This would also help in understanding the sensitivity of the primary energy resources powering up the new BRT System setup.

12.4 Future Research Directions

There is always a room for advancement and more work, same wise is in the case for improving Hydrogen fuel cell technology in BRT Peshawar System:

12.4.1 Cost Reduction Strategies:

Fuel cells, cost of materials to initiate electrolysis, and storage of the hydrogen under different conditions etc. are the primary scope of study for the future [18]. As it would help the technology to adapt to everlasting changes in the government policies while making the security of the system even more prominent.

12.4.2 Infrastructure Optimization: Research work should also be done over the design, capacity of storing hydrogen fuel in tanks, and efficiency of the refueling stations in the BRT Peshawar System. This could also lead to major changes in the infrastructure of the urban transport system, or may be changes in procedures and policies etc.

12.4.3 Lifecycle Environmental Impact:
Any world class project such as the BRT Peshawar always requires to be monitored and well documented in order to know more about the environmental impact it can have on the elements related to air quality, water and sustainability etc. [18] This would help in taking future steps and having insights of the achievements attained by the mega-project.

12.4.4 Performance in Local Conditions:
Evaluate the performance and durability of hydrogen fuel cell buses under Peshawar's specific climatic and operational conditions to inform deployment strategies [19].
Different regions are characterized with different temperature, humidity levels, and other climatic elements, having hydrogen fuel cell bus fleets operating in a city like Peshawar comes with its own challenges. Having such a circumstance demands for an extensive analysis of the new technology helping the urban transport system to drive in local conditions.

REFERENCES
[1] R. K. Ahluwalia, T. Hua, and J. Peng, "Design and analysis of fuel cell electric drive for buses," *J. Electrochem. Energy Convers.*, vol. 12, no. 3, pp. 456–472, 2021.
[2] A. Smith, K. Brown, and J. Green, "Carbon emissions reduction through hydrogen fuel cell adoption in transport," *Environ. Sci. Technol.*, vol. 56, no. 4, pp. 890–905, 2022.
[3] International Energy Agency (IEA), *The Future of Hydrogen: Seizing Today's Opportunities*, Paris, France: IEA, 2021.
[4] Asian Development Bank (ADB), *Peshawar Sustainable Bus Rapid Transit Corridor Project: Annual Report*, ADB, 2022.
[5] R. Jones and P. Taylor, "Economic feasibility of hydrogen buses: A case study," *Energy Policy J.*, vol. 78, no. 2, pp. 450–462, 2021.
[6] S. Saba, P. Müller, M. Robinius, and D. Stolten, "The investment cost of electrolyzers: A review of current and future cost projections," *Renew. Sustain. Energy Rev.*, vol. 132, p. 110037, 2020.
[7] M. Park, H. Kim, and S. Lee, "Hydrogen demand estimation for fuel cell buses: A case study," *Int. J. Hydrogen Energy*, vol. 46, no. 10, pp. 20456–20465, 2021.
[8] I. Dincer and C. Acar, "Review and evaluation of hydrogen production methods for better sustainability," *Int. J. Hydrogen Energy*, vol. 45, no. 1, pp. 520–537, 2020.
[9] R. Zhang, J. Zhang, and Y. Liu, "Hydrogen production and storage analysis for public transport," *Energy Rep.*, vol. 7, pp. 1867–1878, 2021.
[10] TransPeshawar, *Overview of the BRT System*, Peshawar, Pakistan: TransPeshawar, 2024.
[11] T. Hua, R. K. Ahluwalia, J. Peng, M. Kromer, S. Lasher, K. McKenney, and J. Sinha, "Technical assessment of fuel cell electric buses," *J. Power Sources*, vol. 45, no. 2, pp. 112–123, 2020.
[12] S. Wang, S. Wang, and Y. Zhang, "Life cycle assessment of hydrogen fuel cell buses: A case study in China," *Sustain. Energy Fuels*, vol. 3, no. 5, pp. 1234–1242, 2019.
[13] H. Kim and J. Lee, "Performance of hydrogen fuel cell vehicles in cold climates: A review," *Int. J. Hydrogen Energy*, vol. 46, no. 34, pp. 23421–23435, 2021.
[14] World Bank, *Hydrogen in Public Transportation: Opportunities and Challenges*, Washington, DC, USA: World Bank, 2023.
[15] P. Wright, "Hydrogen fuel cells in California transport fleets," *J. Clean Transp.*, vol. 29, no. 4, pp. 320–335, 2023.
[16] Wrightbus, "Reducing CO_2 emissions through hydrogen technology," *Sustain. Transp. Rev.*, vol. 15, no. 2, pp. 210–225.

[17] V. Vodovozov, Z. Raud, and E. Petlenkov, "Review of energy challenges and horizons of hydrogen city buses," *Energies*, vol. 15, no. 19, p. 6945, 2022.

[18] M. Nadeem, A. Ahmad, A. Saleem, M. T. Ahmad, and H. Farooq, "Does Bus Rapid Transit System (BRTS) meet the citizens' mobility needs? Evaluating performance for the case of Multan, Pakistan," *Sustainability*, vol. 13, no. 13, p. 7314, 2021.

[19] Q. Hassan, M. Ahmed, F. Khan, and T. Yaseen, "Hydrogen fuel cell vehicles: opportunities and challenges," *Sustainability*, vol. 15, no. 15, p. 11501, 2023.

[20] L. Vidas and R. Castro, "Recent developments on hydrogen production technologies: state-of-the-art review with a focus on green-electrolysis," *Appl. Sci.*, vol. 11, no. 23, p. 11363, 2021