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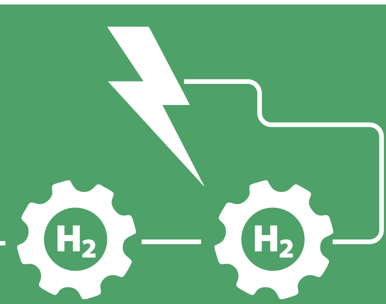
STRATEGY ROAD-MAP FOR DEPLOYMENT OF HYDROGEN FUEL CELL ELECTRIC PUBLIC TRANSPORT BUSES IN KERALA, INDIA



STRATEGY ROAD-MAP FOR DEPLOYMENT OF

HYDROGEN FUEL CELL ELECTRIC PUBLIC TRANSPORT BUSES

IN KERALA, INDIA

IMPRINT

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Registered office:
Bonn and Eschborn, Germany
Integrated Sustainable Urban Transport Systems for Smart Cities (SMART-SUT)
GIZ Office
B-5/2 Safdarjung Enclave,
New Delhi 110029
Phone +91 11 49495353,
Fax +91 11 49495391
www.giz.de/india

Officer Responsible for the Commission:
Juergen Baumann, Project Head, SMART-SUT

Project Advisor:
Laghu Parashar, Deputy Project Head, SMART-SUT

Project Coordinators:
Shirish Mahendru, Technical Expert, SMART-SUT (GIZ)
Krishna Desai, Technical Expert. SMART-SUT (GIZ)

Project Team:
Spotimyze Energy: Anand Vasudevan and team

Honourable Mention:
Mr. K.R Jyothilal IAS, Principal Secretary, Transport Department, Government of Kerala

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Office of the Principal Secretary Transport General Administration Devaswom

FOREWORD

The transport sector in India and world is looking at a transition to clean energy fuels. India is looking at electrification of transport sector, use of bio-fuels, including ethanol, methanol, and hydrogen. While the hydrogen technology is very nascent, it offers advantages in terms of zero tail pipe emission, long range, quick refuelling, and high load application.

The Kerala Transport Department is looking at hydrogen fuel cell-based transportation systems as one of the pathways to achieve carbon neutrality, and looks at its application in public transport, logistics and shipping. This strategy document assesses the applicability of hydrogen fuel cell electric buses in long distance inter-city and intra city routes. It also discusses the opportunities and risks in its implementation. We believe that the right policy framework, subsidization, and technology partnerships can lead to the successful deployment of hydrogen-based transportation systems in Kerala.

The Transport Department, Kerala is thankful to SMART-SUT, GIZ for supporting in developing this strategy document, which will help us in take an informed decision in implementing hydrogen-based transportation systems.

K.R. JYOTHILAL IAS
PEN No. 325167
Principal Secretary
Dept. of Transport, Aviation & Metro
Govt. of Kerala, Thiruvananthapuram
Ph: 0471 2518669

FOREWORD

Under the COP 21 held in Paris in 2015, 196 countries pledged to limit global warming to within 1.5 degrees compared to the pre-industrial levels. To achieve this goal, all countries, including India are looking at a transition to renewable energy sources.

A paradigm shift is also seen in the transport sector, with the adoption of electric vehicles, and a hydrogen-based transportation system. While battery electric vehicles and plug-in hybrid electric vehicle technology is more established, hydrogen-based transportation systems offer advantages in terms of range, continuous use and heavy load application. However, the technology is still nascent, and needs a thorough investigation of the opportunities and risks before its implementation. This report assesses the different paths for green hydrogen production, the infrastructure required, estimates the total cost of ownership and the GHG emissions for various scenarios. As the total amount of green hydrogen is limited for the time being, it will take many years until it would become a game changer also in the Public Transport systems.

It has been a pleasure to support the Transport Department, Government of Kerala in developing this strategy document, and we believe that this document will guide the Transport Department, Government of Kerala and other states in taking an informed decision for achieving the zero carbon emission goals in the future.

Juergen Baumann
Project Head
Integrated Sustainable Urban Transport Systems for Smart Cities (SMART-SUT)
GIZ

SCOPE AND PURPOSE

The objective of this report is to provide an understanding of the opportunities and risks in implementing a Hydrogen Fuel Cell (HFC) powered public transportation bus mobility initiative for the state of Kerala. Kerala is the first state in India to include Hydrogen powered mobility in its zero-emissions mobility policy and a comprehensive roadmap with penetration goals by mobility type (public, freight, private) across land, water and air would be needed to create industry impetus, financial stimulus, indigenous technology development, and cross-country technology partnerships.

Orchestrating a new clean energy transition vector, requires consideration of costs, risks and benefits, in displacing incumbent well entrenched and integrated energy players. While such an assessment is out of scope for this report, it instead focuses on a specific infrastructure project to understand the benefits, costs, risks, and gaps to help in setting policies, subsidies and incentives needed to support adoption.

India is preparing her National Hydrogen Policy and related roadmaps across sectors in line with the recently announced National Hydrogen Mission. Hydrogen's properties as a zero-emissions energy carrier, flexibility in its application across industrial, power and mobility sectors makes it a promising energy transition vector to address India's twin challenges of energy security and emissions reductions targets. India's projected penetration of 450 GW of renewable energy and her abundant biogenic feedstock from agriculture and other wastes are opportunities to generate green hydrogen at scale and competitive prices.

The degree of the transition to green hydrogen adoption from other shades in an important dimension in setting national hydrogen roadmaps. There are two camps. One that prioritizes environmental and climate impacts, such as the EU, with an accelerated timeline towards green hydrogen generation and use. While the other, ensures a transition that doesn't economically disadvantage incumbent industry, such as the UK and Canada, for example, with abundant gas reserves.

Regardless of the color of Hydrogen, it is imperative to start the transition with beach head initiatives that addresses gaps in solutions and products needed at the intersection of the use of Hydrogen and existing infrastructure and end use assets. For example, pipelines readied for blending hydrogen greater than 15%, gas turbines that can burn 100% Hydrogen without NOx emissions, transitioning to a liquid hydrogen refueling infrastructure from a gaseous one, green ammonia production offshore platforms.

On the supply side, an assessment of potential pathways of green, grey and blue Hydrogen generation, capacities and costs from available sources within the state of Kerala to meet the demand from the proposed 50 HFC bus program is evaluated. This exercise will help the government of Kerala to understand the current economics of the color of Hydrogen, and green hydrogen cost curve timelines to set HFC fleet scaling timelines.

The complexities involved in the generation, storage, transportation and dispensing of Hydrogen for refueling requires designing, implementing and provisioning *new* capital infrastructure assets. While the landscape of solutions and vendors is rapidly evolving, we present a model and approach used to forecast, design, and implement an optimal infrastructure. The study designs HRS infrastructures for three demand scenarios of public road transportation modes: I) Long haul inter-city routes provided by KSRTC (Kerala Road Transport Corp), ii) short haul intra-city routes (city of Kochi) and iii) short haul feeder routes (servicing Kochi Metro last mile feeder routes).

On the demand side, understanding the gaps to enable the indigenization and manufacture of Hydrogen Fuel Cell (HFC) mobility assets and related supply chain risks is assessed to arrive at average production costs today. Some of India's leading auto-OEMs who are currently capable of manufacturing battery electric buses were tapped to arrive at the costs, supply chain gaps and engineering skill deficits.

To understand the relative environmental impact of the HFC bus program, conducting an assessment of all possible Zero-Emission-Vehicle (ZEV) and Low-Emission-Vehicle (LEV) options is out of scope for this study. This is in part due to the limited information available on the performance of BEV, CNG, LNG, CNG + Hydrogen blended mobility projects. We therefore limited our scope to a Wells-to-Wheels LCA (Life Cycle Analysis) of HFC vs BEV vs Diesel.

We conclude the report with a comparative analysis of the TCOs of HFC, BEV and Diesel bus programs, analysis of contributing factors to the Viability Gap Funding (VGF), a key metric to determine the economic viability of a public transit initiative, and recommendations to narrow it.

1

A FRAMEWORK FOR THINKING ABOUT THE HYDROGEN ECONOMY

The world is moving towards carbon neutrality with more countries pledging to reduce their carbon emissions to meet (and exceed) obligations under the Paris Accord and contain the temperature rise within 1.5°C by end of this century. The approach being adopted towards decarbonization is to electrify almost all human activities including transportation and agriculture to the extent possible and decarbonize the power sector through renewable energy, carbon capture and sequestration and other emerging technologies. There are “hard-to-abate or electrify” sectors such as long-haul truck traffic, shipping, aviation and production of steel and cement which contribute about 15% of global CO_2 emissions. Hydrogen as a clean fuel has been in use for long; however, the traditional production process of hydrogen was not carbon neutral and hence it did not attract much attention for above end uses. 95% of today’s hydrogen is produced as a by-product of petrochemical refining operations, by reforming Natural Gas, referred to as Grey Hydrogen, while that’s produced from coal and petroleum coke through gasification is called Brown Hydrogen. Grey and brown hydrogen combined with carbon capture and storage (CCUS) technologies to capture CO2 is known as Blue Hydrogen and electrolytic hydrogen produced by splitting water using electrolysers using renewable energy is called Green Hydrogen.

Countries with good renewable energy resources could produce green hydrogen locally, at its point of consumption, generating economic opportunities, and increasing energy security by reducing exposure to oil price volatility and supply disruptions. Globally, green hydrogen is considered as the sustainable solution to decarbonize the “*hard-to-abate-or electrify”* sectors mentioned above. Green hydrogen could provide energy systems with a longer hours of energy storage solution capable of mitigating the variability of renewable resources, thus increasing the penetration of renewable energy.

1.1 ENERGY TRANSISTION

After the Paris Agreement on Climate Change in 2015, countries around the world have intensified their energy transition goals and declared their NDC targets. Now that the USA has rejoined the Paris Climate Treaty, we will see more committed actions on the energy transition and technology collaborations. At end of 2020, India was the only major economy that exceeded her NDC targets committed under the Paris Agreement. For the third year in a row, India added more renewable energy capacity in 2020 than conventional power plants.

As per the IEA Report, *Net Zero by 2050: A Roadmap for the Global Energy Sector* released in May 2021, annual addition of 630 GW of Solar and 390 GW of Wind energy by 2030 is required to give the planet a chance of achieving the emission reductions needed to limit global temperature rise to 1.5°C by end of this century. These new targets are four times the record highest levels of Solar addition in 2020; and almost five times the Wind capacity additions in 2020. The report also estimated the requirement of about 306 million-tons of green hydrogen per year by 2050 by which time about 90% of the electricity to be produced from renewable resources. In order to achieve these levels, it estimated annual investments to the tune of US$ 5 trillion by 2030 onwards.

1.2 OVERVIEW OF THE INDIAN POWER SYSTEM

India is one of the largest electricity market areas in the world. India has reached "one nation one grid" as it has synchronized its regional grids into one national grid at one frequency. The Government of India (GOI) has made impressive progress in recent years in increasing citizens' access to electricity. It has also successfully implemented a range of energy market reforms and carried out a huge amount of renewable energy deployment, primarily solar energy. Indian power system is the third largest in the world with 381 GW of installed capacity and close to 300 million customers. Coal accounts for largest India's electricity generation, which is consumed mostly in the industrial, commercial and residential sectors. India has successfully completed village electrifying over 6,19,000 villages.

The GOI has ambitious plans to scale up renewable energy (RE) in a cost-effective

Table 1: GOI's Renewable Energy Scale-up plan

175 GW RE Program by (2022)	
Solar	100 GW – (60 GW from ground mount and 40 GW from rooftop)
Wind	60 GW
Small Hydro	5 GW
Bio energy	10 GW

way to integrate with the power system. India's estimated potential for electricity generation from renewables is 900 GW. In India, RE resources totaling about 93 GW accounts for 24% of total installed capacity. At the Copenhagen climate summit in 2009, India made a voluntary commitment of emission reduction by 20-25% by 2025. As a part of the initiatives to achieve this goal, GoI started the Jawaharlal Nehru National Solar Mission (JNNSM) in January 2010 with a target of 20 GW of grid connected solar power by 2020. Towards realizing the objective of carbon free energy, in 2015, India has enhanced the RE target to 175 GW by 2022. The solar and wind energy industry has been a highly competitive market with the solar tariffs which started at Rs 17/kWh in 2011 dropping to as low as Rs 2/kWh in 2021 in the reverse tariff bidding auctions. The present RE installed capacity of wind is 38.78 GW and solar is about 39.08 GW. Ministry of New and Renewable Energy (MNRE) has been vested with the responsibility of developing all the RE projects in the country.

Table 2: State-wise installed capacity of Grid Interactive Renewable Power

Sr. No	State/ UT	Estimated Solar Potential (GW)	State-wise installed capacity of Grid Interactive Renewable Power as on 28.02.2021						
			Small Hydro Power (MW)	Wind Power (MW)	Bio-Power (MW)	Solar Power (MW)			Total (MW)
						Ground Mounted	Roof Top	Total	
1	India's Total	749	4,873	38,789	10,315	34,759	4324	39,084	92,970

[1] https://iea.blob.core.windows.net/assets/4719e321-6d3d-41a2-bd6b-461ad2f850a8/NetZeroby2050-ARoadmapfortheGlobalEnergy-Sector.pdf

To further address the environmental issues, old coal plants are being replaced with more efficient supercritical units. The capital cost of renewable technologies for power generation is becoming competitive day by day with the coal-based generation. Solar deployment has been the flagship green growth story of the last decade and this would be instrumental to stimulate growth and build a climate-resilient world. With this GoI has set an ambitious target of 450 GW of renewable capacity by 2030, comprising 300 GW of solar capacity. With increase in penetration of RE resources, grid reliability become critical in power system operations.

IEA's India Energy Outlook issued in February 2021 estimates Indian power system to grow to 823 GW by 2030 and 1584 GW by 2040; and it would require up to 85% flexibility which will be a huge challenge.

Table 3: Projected Installed Capacity by source in India- 2030 & 2040

Energy Source	2030	2040
Solar	207	622
Wind	119	219
Other RE	19	28
Other Sources	444	597
Battery Storage	34	118
Total	823	1584
Flexibility Requirement	-	±85% (50% ramp-up and 35% backdown

IEA estimated 118 GW of battery energy storage in the power system by 2040. With steep decline in prices and significant improvement in performance, Lithium-Ion batteries (LiON) have become the most attractive option for grid scale energy storage systems. (ISGF estimated battery energy storage of about 210 GWh by 2032 to support the grid.)

Giga-watt scale electrolysers can enhance the reliability of power grid with hydrogen storage and by providing flexibility services to the grid whenever needed.

Electrolysers can help integrate RE into power systems, as their electricity consumption can be adjusted to follow wind and solar PV power generation, where hydrogen becomes a medium of storage for renewable electricity. Electrolysers may be operated as demand response assets to support energy balancing on the grid, making additional revenue from grid balancing or ancillary services.

2

GREEN HYDROGEN – ALIGNMENT WITH INDIA'S NATIONAL MISSION

NATIONAL HYDROGEN MISSION (NHM)

The Ministry of New and Renewable Energy (MNRE) developed a Hydrogen and Fuel Cell Road Map in 2006. Later in 2016, MNRE published another report, which laid out a comprehensive plan for increasing R&D activity across many program areas. Most recently, the Government of India is in the process of preparing a Hydrogen Mission, with support from the MNRE and NITI Aayog, which is expected to be unveiled in 2021.

MNRE has been supporting various hydrogen projects in academic institutions, research organizations and the establishment of two hydrogen refueling stations at the Indian Oil R&D center in Faridabad, and National Institute of Solar Energy, Gurugram. Indian Railways is also working on the development of a hydrogen-powered suburban train and has invited expressions of interest for industry participation. Indian Oil Corporation Limited (IOCL) set up the 1st high pressure hydrogen storage and dispensing terminal in India, with the refueling station located in Delhi. This refueling station uses a PEM electrolyser generating hydrogen at 30 Nm3/hour at a purity of 99.999%, which is required for fuel cell vehicles. They have also recently put out a tender for 15 fuel cell buses, as part of a Rs 300 crore ($40mn) demonstration project for hydrogen fuel cell vehicles.

In India, several groups are working on hydrogen domain in silos with different mandates and targets. As a country it is imperative that we have a national roadmap for hydrogen. In 2005, MNRE had setup a Hydrogen Advisory Board and prepared a 15-year Hydrogen Roadmap. That is no longer relevant in the advent of green and the present technology trajectory.

The Union Budget for 2021-22 has announced a National Hydrogen Energy Mission (NHM) that will draw up a road map for using hydrogen as an energy source. The details of this National Mission are yet to be announced.

3

HYDROGEN SUPPLY CHAINS

The supply chain for hydrogen comprises the processes necessary to produce, distribute, and dispense the hydrogen. Currently, 95% of the global hydrogen is produced from natural gas through stream methane reforming close to where it is needed for industrial purposes.

The major factors that will affect the cost of delivered hydrogen are:

- The feedstock and/or the major energy source from which the hydrogen is produced,
- Size of the facility at which hydrogen is produced and the transportation requirements to deliver
- The state of the technology used—whether current or to be improved by future developments
- Whether carbon dioxide by-product is sequestered when hydrogen is produced from fossil fuel.

Globally 120 million Tonnes (mt) of hydrogen is produced every year. About 95% of this is from natural gas through steam-methane reforming (SMR) or from coal through coal gasification technologies About 5% hydrogen is produced from electrolysis as a byproduct of chlorine production. Though electrolyser technology dates back to late 19th century (1888), only in the recent past that production of green hydrogen through electrolyser run on renewable energy has gained momentum.

Hydrogen is already widely used in India, primarily as an industrial feedstock in the manufacture of fertilizers based on ammonia. In India, most hydrogen is made through steam methane reforming, resulting in significant emissions of CO_2. There is the potential for carbon capture and storage technologies to capture the CO_2 emissions, but this is still expensive. India has been operating one of the world's first large-scale alkaline electrolyser plants to generate hydrogen from electricity at the Nangal fertilizer plant in Punjab since 1962.

3.1 HYDROGEN FROM ELECTROLYTIC GENERATION

India's solar installed capacity is about 39.08 GW as of March 2021. National Institute of Solar Energy has assessed the country's solar potential of about 748 GW assuming 3% of the waste land area to be covered by Solar PV modules. Solar energy has taken a central place in India's National Action Plan on Climate Change with National Solar Mission targets to install 100 GW grid-connected solar power plants by the year 2022. In order to achieve this target, the Government of India has launched various schemes to encourage generation of solar power in the country like Solar Park Scheme, CPSU Scheme, Defense Scheme, Canal bank and Canal top Scheme, Bundling Scheme, Grid Connected Solar Rooftop Scheme and Viability Gap Funding (VGF) Scheme. The region-wise breakup of the 100 GW solar energy target by 2022 as allotted by MNRE as follows: Northern Region – 31 GW, Western Region – 28 GW, Southern Region – 27 GW (Kerala – 1.8 GW), Eastern Region – 12 GW and North Eastern Region – 2 GW.

As of this writing, it appears unlikely to obtain forecasts of the cost of solar power *in India for the next 10 – 15 years. This makes it difficult to predict how the cost of hydrogen produced from solar energy will be in the near term*

3.1.1 Hydrogen From Electrolysis of Water

The average price of green hydrogen is presently US$ 7.0-8.0/ Kg whereas grey hydrogen is about US$ 1.0 /kg. The key factors influencing the cost of green hydrogen are given in the table below:

Table 4: Key factors influencing the cost of Hydrogen (source: IRENA Report)

Key Factors	Status in 2020	Required levels to reduce the cost of Green Hydrogen to US $1.0/kg
Cost of Electrolyser	US$ 650 to 1000/kW	80% cost reduction
Cost of Electricity	5-6 cents (US$)/kWh	2 cents/kWh
Plant Life of Electrolyser	10 years	20 years
Electrolyser Efficiency	65%	76%
Electrolyser PLF	3200 hours/year	4200 hours/year
Cost of Capital (WACC)	10%	6%

Electrolyser cost reduction up to 80% may be feasible if the learning rate of electrolyser production reaches the 30% levels[2]. Also, the plant sizes need to be increased from the present 1MW scale to GW scales. The estimated investment in electrolyser manufacturing capacity is US$ 60-75 million/GW. Other key challenges in upscaling electrolyser production are availability of rare materials such as platinum and iridium; and availability of land and water. Global production of platinum is only 200 tonnes/year (besides a small quantity generated from recycling). Global production of iridium is only 77.5 tonnes/year.

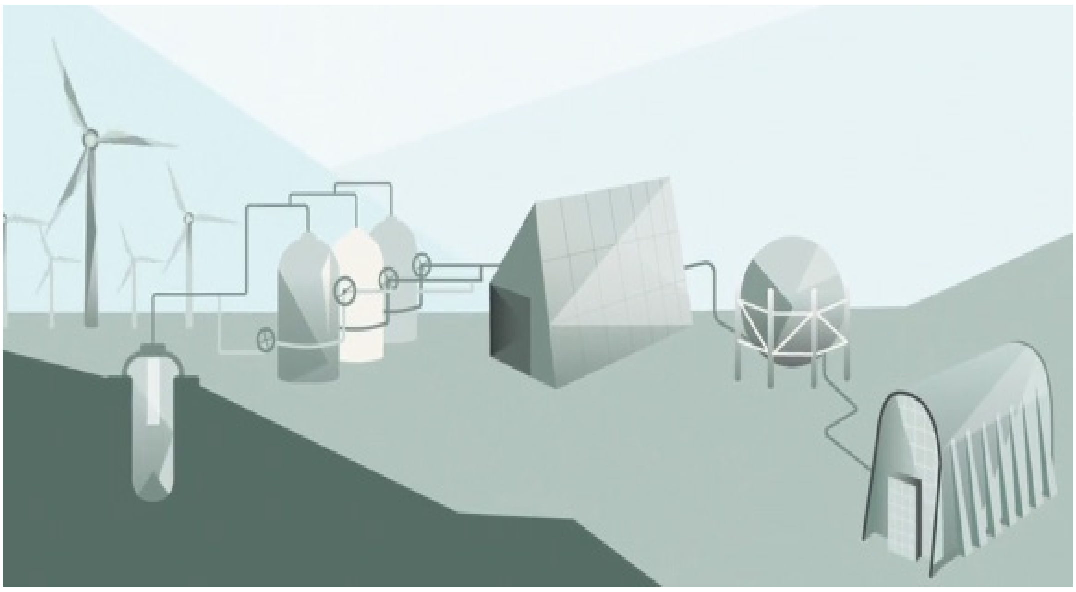


Figure 1- Electrolytic generation of Hydrogen from Renewable Energy

[2] Learning rate is the rate at which the price of an item decreases when the capacity/production is doubled. During the last decade, solar PV prices achieved learning rates above 30%.

Different types of electrolysers are:

i. *PEM (Proton Exchange Membrane)* Electrolyser: these are in commercial operation but require platinum (1 gram/kW) and iridium (12.5 gram/kW) and hence expensive

ii. *Alkaline* Electrolyser: In commercial operation but require platinum and cobalt

iii. *Anion Exchange Membrane* (AEM) Electrolyser does not require rare materials but this technology is still at lab scale

iv. *Solid Oxide Electrolyser* is also at lab scale presently; but the main concern is that 95% critical materials for this technology are in China only

Land and water requirement are other constraints affecting green hydrogen production. While PEM Electrolysers require 8-13 hectares for 1.0 GW, Alkaline Electrolyser require 10-17 hectares for 1.0 GW. *The production of 1.0 kg of hydrogen through electrolysis requires 960 liters of water*. The limitations posed by availability of rare materials is the most serious as maximum 6.2 GW of PEM electrolyser can be produced in a year even if entire 77.5 tonnes of iridium production are allotted for electrolysers (@12.5 gram/kW).

4

SOURCES AND CAPACITY OF HYDROGEN AVAILABILITY ROADMAP IN KERALA

This section addresses the concept of hydrogen valleys and corridors to go hand in hand with a geographical region's hydrogen transition roadmaps. As we saw in the section on Hydrogen supply chains, the physical nature of the hydrogen molecule, demands very specific infrastructure to handle its storage, transport and supply. To support the transition, detailed assessment of infrastructure capacity, which in turn will need a detailed study of all available sources of generating hydrogen and forecasted demand from specific geographical regions, will be needed. We will cover in the section on hydrogen production cost modeling, the levelized cost of delivered hydrogen's highest contributing factor comes from its packaging and transportation.

Pipelines and surface transport via tube trailers of compressed gaseous hydrogen of varying pressures calls for expensive carbon nano-composite material coatings and high energy needed for packaging (compression). Existing gas pipelines will need to be upgraded or new ones installed. Without sufficient demand investing in such expensive upgrades is not anticipated for another decade or more. This leaves surface transport via tube trailers of either gaseous or liquid hydrogen that can be serviced within a 24-hour round-trip travel time between the generation and consumption points, as the interim strategy.

While a detailed assessment for the state of Kerala is warranted as next steps, specifically for demand forecasts from mobility, this study limits its scope to identifying sources to meet the demand from Hydrogen Refueling Infrastructure (HRI) network designs for several scenarios of public HFCEV fleets.

Priority to source from as close to the HRI or locate the HRI close to the source or better yet, generate hydrogen at the location of the HRI.

4.1 Grey Hydrogen

The only currently available source of grey hydrogen is at the BPCL (Bharat Petroleum Corporation Limited) facility near Kochi. The Hydrogen is generated by steam methane reformers, installed and operated by Air Products, and used captively by BPCL for its downstream refining operations. It is not known if additional Hydrogen can be generated using existing SMRs or if new ones will be needed. The Grey Hydrogen will need to cleaned of its impurities using PSAs (Pressure Swing Absorbers) to supply fuel cell grade Hydrogen of 99.9999% purity.

Natural gas pipelines and supply exist in Kerala. This allows for the design of:

i. Hub-and-Spoke HRI design with a large central Grey Hydrogen generation site using SMRs and supplied via tube trailers to Hydrogen Dispensing stations,
ii. Central large HRI that combines generation (grey H2) and dispensing for overnight refueling HFCEV bus depots.
iii. Decentralized HRI design of a network of on-site modular Hydrogen generation using SMRs and Hydrogen dispensing systems to which Natural gas get supplied via tube trailers or pipelines installed.

4.2 Hydrogen From Biogenic Sources

This report calls for a detailed techno-economic feasibility assessment (and gaps) to understand the potential to develop *Waste-to-H2* circular loops using Biogenic sources of wastes in Kerala. Currently, wastes of various commodities are being used for upcycling or repurposing or conversion to a different end use. Does a "Higher-and-Best" use case resulting in generating greater economic returns benefitting all stakeholders exist from conversion to Hydrogen of these commodities?

It calls for stakeholders from the following state agencies and ministries to facilitate the creation of digital libraries and platforms to track the daily quantity, quality (composition, calorific value) of waste generation and end-use-cases across the following commodities. This facilitates the creation of a real time "Material Market Platform" for innovators and entrepreneurs to develop processes and products, with Hydrogen being one such outcome.

4.2.1 Municipal Solid Waste (ANERT)

The biogenic waste stream from this commodity presents a sizable opportunity not just in Kerala but all over India for conversion to Hydrogen. Existing supply chains to collect, segregate and aggregate needs to be de risked with newer robust physical and digital assets.

A de-centralized MSW collection, aggregation, segregation and supply to sites where modular 5-10 TPD anaerobic digestors (that generate bio-gas) to feed to modular SMRs (to generate H2) reduces feedstock sourcing risk by creating smaller circular waste-2-H2 loops. And such decentralized models help to support a network of distributed smaller HRI for HFCEVs.

ANERT should study the implications of developing such distributed strategies instead of large centralized 300 – 500 TPD waste to energy systems.

4.2.2 Agriculture Waste (Ministry of Agriculture)

This report identified substantial gaps in sourcing and aggregating agriculture waste in Kerala. While there are some models of agriculture waste feedstock collection and aggregation in other parts of India, the feasibility of setting a similar process is still unknown for Kerala. A detailed study on available sources of agriculture wastes, monthly generation capacities, their calorific values, and current uses, is needed as a starting step.

4.2.3 Fisheries Waste (Ministries of fisheries)

The fishing industry in Kerala combined with its vast coastline dotted with ports presents an infrastructure design opportunity to set up decentralized bio-gas generators from fish waste digestors that can be fed into a pipeline. Fish waste however contends it's higher and best use in the cosmetics and Nutricite (Omega 3 fatty acids) industry. Nevertheless, a detailed study of the capacity of the waste combined with its sustainability impact assessment, if one doesn't exist already.

4.2.4 Plastic waste (ANERT)

While there are policies being implemented to disincentivize the use of single use plastics in Kerala, completely eliminating all plastics is a few decades away. This means, effective, innovative and economically viable circular plastics-to-plastics or other non-landfill or incinerator disposal loops needs to be implemented. Quite a few laboratory scale *plastics-to-hydrogen* conversion processes exist today and one or two scaled up versions being piloted globally, one such pilot in Japan.

4.2.5 Paper waste (ANERT)

China stopped accepting wastes from around the world a few years back. This has translated in US and EU being backed up with several single source waste streams of high value in global markets but not domestically, which has resulted in a few economically viable *paper-to-hydrogen* projects, where the municipality pays for the paper to be taken away. ANERT should conduct a techno-economic feasibility study of using commercial *Paper-to-H2* conversion technologies from current global projects in Kerala.

Other waste, such as Cow Manure, Fisheries Waste and Animal Slaughter waste are not viable economically based on discussions with various Waste to Energy SME's and vendors.

4.3 Green Hydrogen From Water Electrolysis

To understand the generation capacity of green electrolytic hydrogen in Kerala requires an understanding of the Kerala Power System, it's current and future renewable energy capacity, infrastructure gaps and energy pricing policies. This section summarizes with all available strategies to source green electricity in Kerala along with their landed costs.

4.3.1 Kerala Power System

The Kerala power system is owned and managed by Kerala State Electricity Board Ltd (KSEBL) which is wholly owned by the state government; and few licensees operating in small geography within the state like Cochin Export Processing Zone (CEPZ), Cochin Port, Info Parks/Techno-Parks etc. Private participation in power generation is very limited. On RE potential and generation, Kerala has solar power potential of 6.1 GW followed by 1.7 GW of wind and 1 GW of biomass out of which 4.7% of solar and

Table 5: Installed Generation Capacity in Kerala as on March 2021

Source	Installed Capacity (MW)
Thermal + Gas	539.54
Hydro (Including 215.56 MW of small hydro)	2125.5
Nuclear	0
Solar	288
Wind	70.27
Total	3023
Generation Source: KSEB	

Table 6: Renewable Energy Potential in Kerala

S. No	Technology	Estimated Potential (MW)
1	Solar	6,110
2	Wind	1,700
3	Biomass	1,044
4	Small Hydro	647
5	Waste to Energy	36
6	Total	9,537

Source: ttp://karenvis.nic.in/Content/SourcewiseandStatewiseEstimatedPotentialofRenewablePowerinIndia_15906.aspx

4.1% of wind power has been developed so far.

The state of Kerala has also started exploring development of RE sources with programs such as SOURA scheme under URJA Kerala Mission, which aims at developing rooftop PV (RTPV) and ground mounted solar plants aggregating to 1 GW by 2022. The planned capacity under various other schemes /projects/purchases is estimated to be 1.97 GW by 2025.

Moreover, with Government of India defining the new RPO trajectory till 2022 which is 10.5% for solar and non-solar RPO in 2022, state of Kerala has to meet target of 1482 MW of solar and 850 MW of non- solar considering energy requirement of 27960 MU (million units) in 2022. To cater to this requirement, KSEB is set to purchase 300 MW with Solar Energy Corporation of India (SECI) at a pooled tariff of INR 2.44 per kWh to meet its RPO requirement. KSEB has also signed a contract with Tata Power to develop 110 MW solar power plant in the state which will enhance its RE portfolio and meet its RPO target.

Production of Hydrogen from renewable energy will help Kerala to increase its RE capacity (if generated within the state) and meet its RPO requirement. Power-to-Hydrogen generation and storage vectors will help integrate VRE (Variable Renewable Energy) into power systems, by synchronizing electricity consumption by electrolysers with excess wind and solar PV power generation. Hydrogen as a medium of long duration storage for renewable electricity offers flexible load and grid balancing services.

If connected to the grid, Hydrogen can be produced subject to short-time variations in the power market or under flat rates through long term power purchase agreements (PPA). In the first stage, production will happen especially at moments of low and medium power prices. There will be a certain number of operating hours at higher prices, causing hydrogen production cost to increase.

4.3.1.1 Electricity Requirement: Green H2 for the combined HFC bus fleets

This section calculates the total capacity of captive renewable energy required to supply green Hydrogen for the combined fleet of 50 HFC inter-city buses (KSRTC), 10 intra-city HFC buses (Kochi city) and 10 Kochi Metro Feeder HFC buses (KMRL). SECTION 5 covers in depth the methodology, assumptions and parameters used to calculate the Hydrogen demand from several scenarios of HFC deployments for Kerala.

The combined Hydrogen demand from Table 26, Table 29 and Table 30 is 4,100 Kgs/ Day. *The total annual electricity demand is 88 GWh and if all the electricity were to be supplied from solar, it will require 60.5 MW of a captive solar installation.*

Table 7: Inputs to calculate average electricity for supplying Green H2 for the combined HFC fleet.

Total Number of HFC Buses across all three fleets	[50 + 10 + 10]
Combined Hydrogen Requirement (inter-city, intra-city, metro feeder HFC buses)	4,100 kg
Electricity required for 1.0 kg of Electrolytic Hydrogen using PEM or Alkaline electrolysers (conservative estimate of the two)	59 kWh
Electricity required per day at Kochi (assuming a central generation hub)	2,41,900 kWh
Annual electricity requirement for hydrogen generation at Kochi	88 GWh

Table 8: Required Solar Capacity at Kochifor Green H2 to fuel the combined 70 HFC Fleets

Capacity utilization factor of Solar PV in Kerala	4 kWh per Day per kW of solar PV
Solar installed capacity required in Kochi	2,41,900 KWh/Day / 4 = 60.5 MW

4.3.2 Power Procurement Options in Kerala State (Green H2 generation)

Renewable energy requirement for generating green hydrogen can be either generated onsite to supply power to electrolysers or can be procured from KSEB under industrial category or through various market-based instruments like Green Term Ahead Market, long term or medium-term contracts with renewable energy developers.

All the proposed hydrogen Refueling Stations (HRS) may be located inside or on the periphery of large cities where land availability will be limited in terms of development of MW-scale RE plants., Hence, considering the installed capacity requirement and land availability limitations, it will be difficult to construct a 60 MW solar power plant within the city which will require 350 acres of land. Therefore, a combination of onsite generation and power purchase from open access sources or KSEB directly will be a better option. If each location is connected to the KSEB grid, and the power requirement at each of the electrolyser locations is above 1.0 MW, it qualifies under the open access regulations.

KSRTC may apply to KSEB for availing open access and KSEB will estimate the demand charges as applicable under relevant tariff of KSEB at HT/EHT category will be applicable. Per existing tariff norms, we have estimated the probable charges in the following sections.

4.3.2.1 Onsite Generation of Renewable Energy for H2 generation

Onsite generation of renewable energy using solar typically is from roof top, ground mounted or a combination of them both. These plants can be developed under several government schemes or as per provisions of RE regulations 2020, applicable to captive or grid interactive consumers.

Development of large solar capacity will need to factor contiguous land area availability *(minimum 5 acre for 1 MW)* and proximity to usage location. It will require availability of a 220 kV sub-station for 60 MW to evacuate power from the generation plant. The added cost of the sub- station or an additional bay in the existing sub-station and transmission line up to the sub-station at the generation site needs to be taken into account.

An alternative will be to develop a limited capacity roof top or ground mounted solar at the project site based on land and roof area availability and procure rest of the power through open access. Additional charges for open access, as applicable, under relevant Kerala State Electricity Regulatory Commission (KSERC) regulations of open access 2013 and KSERC RE 2020 regulations, such as grid support charges, transmission charges, wheeling charges, system losses, and cross subsidy charges depending on whether the power is purchased from IPPs within the state, and other charges for IPPs outside the state for open access consumers using ISTS (Inter-State Transmission System) under Central Electricity Regulatory Commission (CERC) regulations.

Cost of per unit electricity from onsite roof top solar is INR 4.5. Inclusion of battery storage increases the cost to INR [8 -18] depending on battery capacity and duration.

4.3.2.2 Captive RE Plant in Kasaragod, Kerala development scenario

Another option is to build a dedicated solar or wind power plant in a location away from the Hydrogen generation site, in Kerala based on land availability. Kasaragod appears to be a good location with plenty of land availability and high utilization factor for solar power. The cost of land in Kasaragod is around INR [7 – 8] lakhs per acre as compared to INR [15 – 25] crores per acre closer to Kochi.

A 50 MW solar project at Paivalike, part of the Solar Park in Kasaragod district which has been developed by The Renewable Power Corporation of Kerala Limited (RPCKL), joint venture of KSEB and SECI, has been commissioned. Another 50 MW project had been commissioned at Ambalathara.

If a dedicated solar power plant of 60.5 MW is built at Kasaragod (for use at the Kochi H2 Hub), it could leverage the existing 220 kV sub-station from the Paivalike and Ambalathara solar plants for evacuating power to the grid or an additional bay can be developed in the existing sub-station, reducing the total electrical infrastructure CAPEX. Other charges for transmission, wheeling and distribution of electricity to the hydrogen onsite generation plant.

EHT tariff will be applicable and the total cost of electricity considering the solar generation cost of INR 3.78 per unit (weighted average cost of solar) is mentioned below:

Table 9: Total cost for generation, transmission, distribution and wheeling of electricity to the H2 generation hubs in Kochi from the solar plant in Kasaragod

Tariff for solar po wer plant	INR 3.78
Tariff for consumer (EHT 110kV)	INR 5.4
Grid support charges (5%)	INR 0.28 (approx.)
Wheeling Charges	INR 0.55
Transmission Losses (3.95%)	INR 0.22 (approx.)
Total Cost	INR 4.73
*No cross-subsidy charges will be applied for captive plants * Above 33kV, distribution losses are not applicable (assuming consumer connection at 33 kV)	

If power is procured through a long-term arrangement from an IPP in Kerala, a cross subsidy charge of INR 1.20 will be applicable, increasing the total cost to INR 5.93. For sources of RE other than solar, the costs will differ, as respective tariffs will be different. Table 10.

Table 10: Weighted Average cost of RE generation

Renewable energy sources	Weighted Average cost of generation of different plants
Wind Power	INR 3.86 (approx.)
Small Hydro	INR 3.70 (approx.)
Source: KSEB	

4.3.2.3 Captive Power Plants in Other States

Developing dedicated captive power plants in other states, such as Karnataka, Tamil Nadu, Rajasthan, the cost of interstate transmission charges and losses will need to be considered. However, if the power can be procured from SECI owned plants, whose tariffs have been determined through reverse auctions, the interstate transmission charges and losses will not be applicable and only cross subsidy surcharge will apply. The charges that will be applicable for procuring power from dedicated RE plants from other states is estimated in Table 11 below.

Table 11: Procuring power purchase cost from RE plants

Point of Connection Charge	INR 0.43
State Transmission Charge	INR 0.39
Wheeling charges	INR 0.55
Interstate transmission Loss	3.32%
State transmission loss	3.95%
Cross Subsidy Surcharge	INR 1.20
Source: KSEB	

With these charges being applied, the landed cost for the consumer will be INR 7.40 (INR 4.5 is the levelized cost of solar generation in Karnataka) as compared to power procurement from captive plants within the state. If power is procured from IPPs on the basis of reverse auction, inter-state transmission charges and losses will be waived, but cross subsidy charges will be applicable, bringing the landed cost down to INR 6.82.

4.3.2.4 Procurement from Cochin International Airport Limited (CIAL)

CIAL launched one of Kerala's largest floating solar power plants in 2021 at 452 KWh. The airports total installed capacity increased to 40 MW at 1.60 lakh kWh per day. With the current total power consumption at 1.50 lakh kWh/ day, 10,000 kWh is free to be sold externally. The excess solar energy is traded with KSEB on a banking arrangement. During the day time, CIAL exports the excess solar energy to KSEB and at night, the same amount of energy is procured back from KSEB, without additional charges being incurred by KSEB and CIAL for the power injection and withdrawal.

CIAL is planning to extend its solar power capacity to a total of 52 MW. With its the future power consumption expected to be around 1.90 lakh units/ day, a surplus of 18,000 kWh/day is anticipated.

If the excess power from CIAL is procured for the hydrogen generation, then CIAL has to forgo the banking arrangement with KSEB and will have to buy power from KSEB under HT-IV (A) commercial consumer tariff, which is INR 7.30 for consumers with

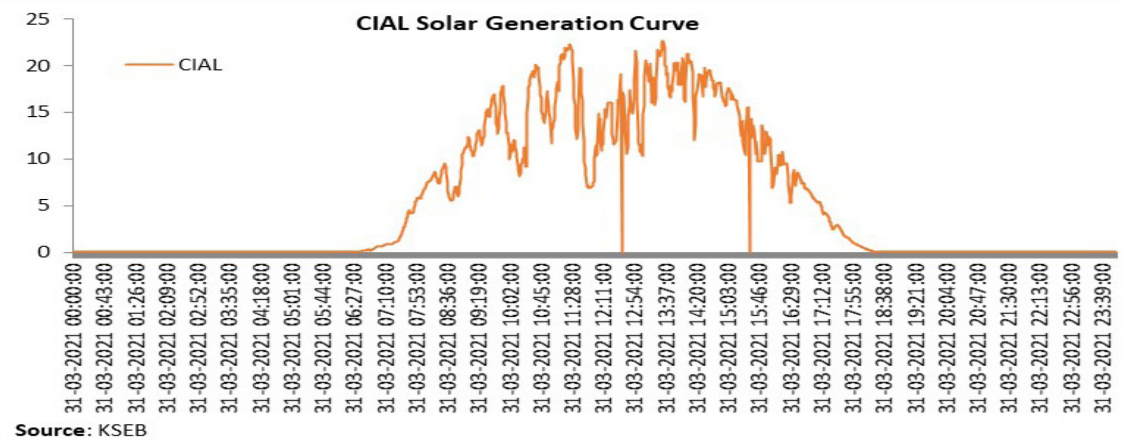


Figure 2- CIAL Solar Generation Curve

consumption above 30,000 units per month. To compensate for these charges which CIAL will need to pay KSEB, it will need to recover by pricing the excess power sold for H2 generation at INR 7.30+/ KWh. The maximum surplus power availability from CIAL is far lower, and along with the high landed costs, makes this procurement route infeasible.

Greening Power Procurement from Kerala State Electricity Board (KSEB)

The procurement of Renewable Energy Certificates (RECs) to cover KSEB's green deficit, based upon the energy mix, would make its power 100% green. The Kerala State Electricity Regulatory Commission (KSERC) should consider the option of selling Green Power at a premium similar to the Maharashtra Electricity Regulatory Commission (MERC). MERC charges a premium of INR 0.66 / kWh for procuring green power.

Generation of hydrogen from RE will benefit KSEB to fulfill its RPO obligations, where KSEB is currently falling short as depicted in Figure 4.3.2c. Kerala state's Hydrogen Mobility initiative should prioritize Kerala State Road Transport Corporation (KSRTC) to request KSEB to arrange for additional green power generation from its intra-state

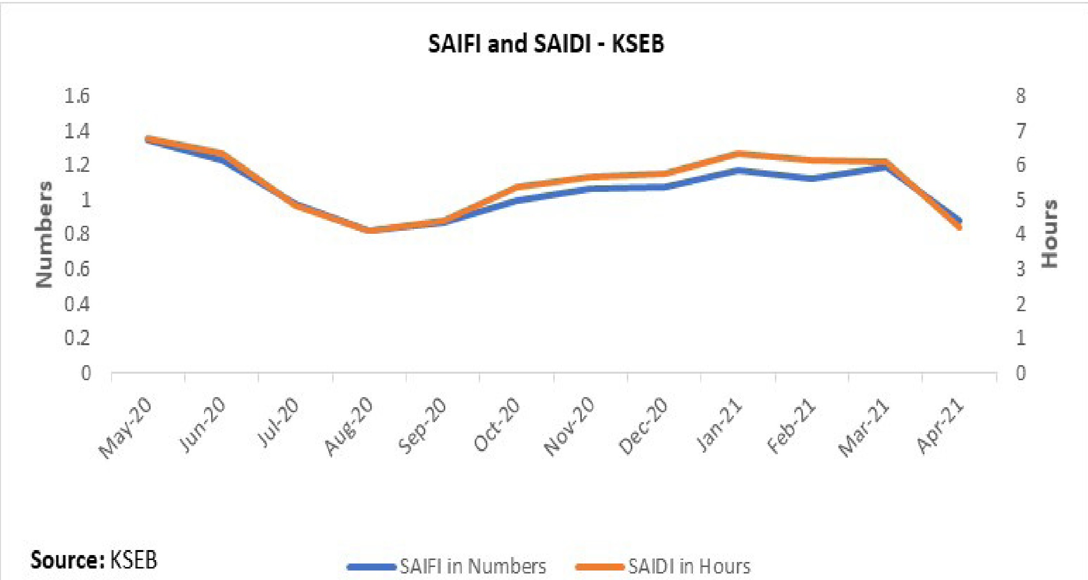


Figure 3- KERALA SAIFI and SAIDI – KSEB

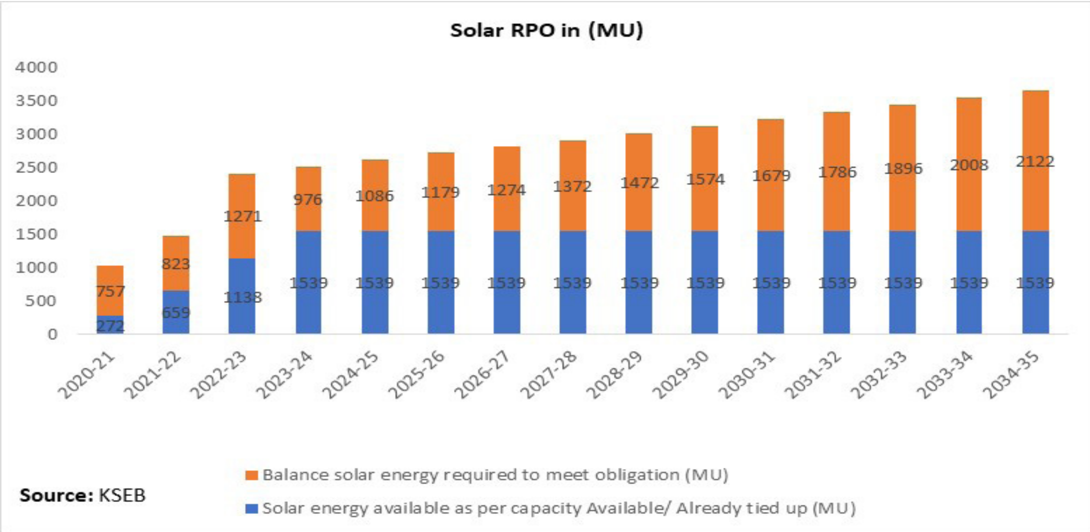


Figure 4.- Solar RPO in MU

and inter-state resources.

Kerala faces severe flooding during monsoons and related power outages and shown in Figure 4, which will result in disruption of ZEV public transit services, if adequate provision for the resiliency of the Hydrogen refueling isn't made.

A critical consideration to factor in designing and provisioning a public Hydrogen Refueling infrastructure is the **resiliency** of the system to provide uninterrupted year-round supply of Hydrogen to avoid HFC fleet service interruptions. The resiliency should factor in risks from power outages, Hydrogen generation and refueling infrastructure equipment failures. The reliability of the grid year-round, especially during periods of extreme weather should be factored in: i) provision Hydrogen buffer capacity at the refueling site, ii) contractual Hydrogen supply agreements with suppliers, iii) provision battery capacity for back-up power to be supplied to electrolysers.

4.3.2.5 Power Procurement from Green Term-Ahead Market

The Green-Term Ahead Market (G-TAM) is a new market segment for trading in renewable energy following CERC approval. The new market segment features contracts such as Green-Intraday, Green-Day-ahead Contingency (DAC), Green-Daily and Green-Weekly. It is the only exchange based RE market which provides flexibility to procure power from 15-minute block intervals to an entire week. Price

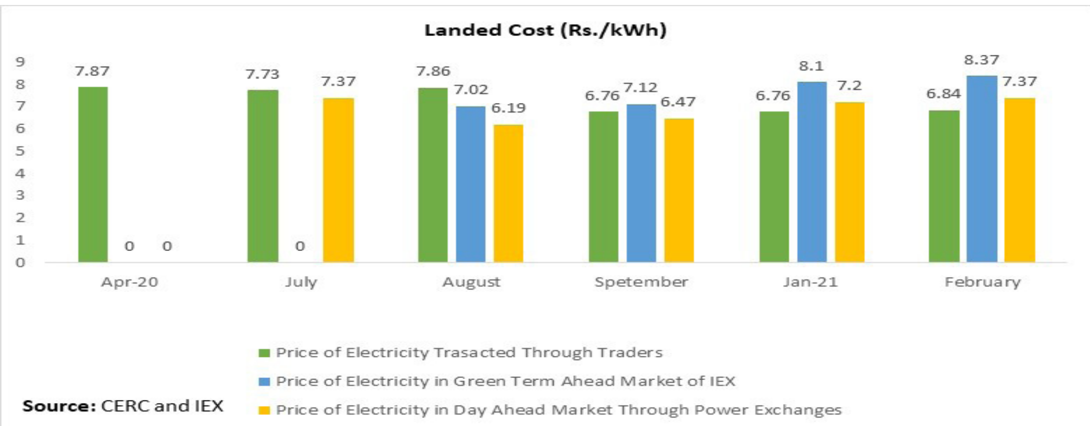


Figure 5- Landed Cost of Electricity variation by month (Rs. /kWh)

comparison of green term ahead market with day ahead market and short-term bilateral market is given below:

4.3.2.6 Roof Top Solar via a Renewable Energy Service Co (RESCO) Model

RESCO market is maturing in India and large aggregators have successfully executed several MW-scale RTPV (Rooftop Photo Voltaic) projects. Under the RESCO model, a third-party aggregator leases and installs solar on rooftops and land from multiple locations, and executes long-term PPA's with prospective buyers. Since KSRTC owns several bus depots and bus stands across the state, they could explore the feasibility of contracting with an aggregator who will install solar PV on these properties and enter in to a long-term PPA with KSRTC for the sale of power.

4.3.2.7 Floating Solar

Kerala has an abundant area of water bodies across the state in its back waters, lagoons, hydroelectric dams and lakes. These water bodies present an attractive opportunity to install floating solar plants. Several RESCO operators have quoted a rate of INR 4.50/kWh to be supplied to the KSEB Grid. With T&D costs added, the landed cost at each of the electrolyser sites would be INR 5.45/kWh. For a captive floating solar power plant, the cross-subsidy charges will not be applied. If it's not under the captive model or if 50% is owned by the IPP, then with cross subsidy charges of INR 1.20 applied, the landed cost will be INR 6.65/kWh.

4.3.2.8 Landed Cost of Power Procurement Options in Kerala

The summary of all the power procurement options available in Kerala along with their landed costs is shown in Table 12.

Of all the options, a single large captive solar plant with 220 kV systems for evacuation, while ensuring landed cost will not change much from charges at point of injection, and availing existing exemptions for open access charges/wheeling/T&D losses, appears to be the most economically viable power procurement strategy.

Table 12: Landed cost of various power procurement options

Power Procurement Option	Landed Cost (INR)	Remarks
Onsite generation	4.50	Direct consumption from roof top solar
Captive power plant in Kerala	4.73	Cross subsidy charges waived off
IPP in Kerala	5.93	Cross subsidy charges levied
Captive Power Plant in Other States	7.40	Inter-state transmission charges and losses are applied
Power from plants bided through reverse auction	6.82	Inter-state transmission charges and losses waived off but cross subsidy will be levied
CIAL generation	7.30	Commercial tariff as CIAL has to forgo banking arrangement with KSEB
KSEB	5.75	HT-I (A) category tariff. With REC, the landed cost will be INR 6.75
Green Term Ahead Market	7.65 (4 months average)	Market determined price
RESCO Model	5.45	State distribution charges applied and if it is not captive power plant then cross subsidy charge of INR 1.20 will be applied which will make the landed cost INR 6.65

During non-solar hours, power can be procured from KSEB at the regulated tariff (section 4.3.5), along with structuring a banking arrangement with KSEB, if surplus solar energy is available during solar hours from the captive solar plant and injected to the KSEB grid.

4.4 Hydrogen as a by-product from Chlor-Alkali Electrolysis

Hydrogen gas is a valuable by-product from the manufacture of Chlorine through the electrolysis of brine, a concentrated solution of salt (NaCl), which results in the production of Hydrogen, Chlorine and Sodium Hydroxide (NaOH). In the US, approximately 0.4 M Tonnes of Hydrogen is produced every year from chlorine production through the Chlor-Alkali electrolysis process [11]. Some of the Hydrogen is combusted for captive heating, some vented and the rest sold for industrial uses.

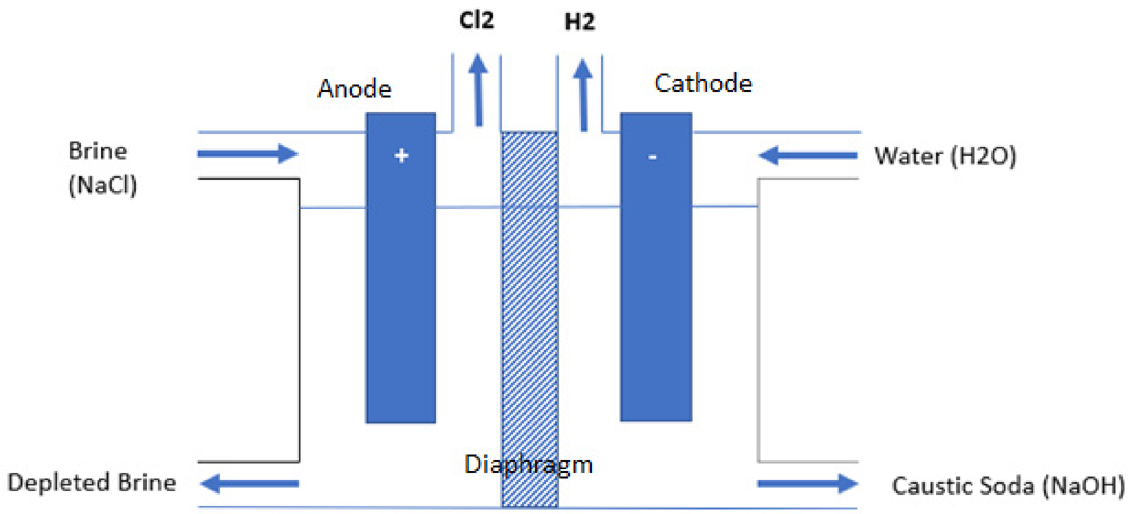


Figure 6- Chlor-Alkali electrolysis process

The impurities and moisture from the by-product Hydrogen are removed using a Pressure Swing Adsorption Process (PSA), and further drying to obtain fuel cell grade Hydrogen.

Currently there is no color associated to the Hydrogen produced through this process, as it's a by-product. The Chlor-Alkali industry has been advocating the consideration to be as green as the electricity mix in the grid. From a Life Cycle Assessment (LCA) of Green House Gases (GHG) of the Chlor-Alkali electrolysis process using data gathered from plants across the US, it was estimated that by-product hydrogen production creates [1.3 to 9.8] kg CO2e/kg H2 of life-cycle GHG emissions on average, which is [20 to 90] % less than the conventional central SMR pathway [11].

The Travancore Cochin Chemicals (TCC) Chlor-Alkali plant in Kochi currently produces 1.5 TPD of Hydrogen as a by-product. It is to be determined how much of that can be made available for the Kerala HFCEV Mobility program. From the following section, which covers the production costs of Hydrogen from different pathways, the Chlor-Alkali by-product route presents the cheapest levelized cost of Hydrogen.

5

HYDROGEN GENERATION AND REFUELING INFRASTRUCTURE DESIGN

5.1 Transportation, Distribution and Storage of Hydrogen

A key metric when comparing fuels is their volumetric and gravimetric densities. Hydrogen's duality of possessing the highest gravimetric density of 120 MJ/Kg (compared to 44MJ/Kg for Diesel) while the poorest in volumetric density of 2 MJ/L @350 bar gaseous and 8 MJ/L of liquid (compared to 32 MJ/L of Diesel) presents challenges to the high-volume storage of gaseous Hydrogen on-board fuel cell vehicles to achieve comparable range, space, (cargo + passenger), refueling time to gasoline vehicles. While the transition to a liquid hydrogen refueling infrastructure is inevitable, due to its higher volumetric density and simpler liquid H2 HRS (lesser number of moving parts), the transition will be dictated by demand to rationalize costs.

Today 95% of the world's hydrogen produced from petrochemical refining is used captively at co-located sites incurring negligible Hydrogen transportation costs. However, the transition to a Hydrogen powered mobility future will require building networks of interconnected refueling infrastructures. The cost of transporting and dispensing Hydrogen surpasses the cost of its generation today. Hydrogen cost at the pump is the sum of the levelized cost of the Hydrogen Refueling Station (HRS) and the levelized cost of hydrogen production and delivery to the point of refueling. Comparing the costs of hydrogen production from steam methane reformation of natural gas at $2/kg-H2 and the cost at the pump in California at (8 – 10) $/kg-H2, the cost of delivery and dispensing is a whopping (6-8) $/Kg. The US DOE projects a cost of $4.0/Kg-H2 at the pump, apportioned 50:50, with production levelized cost at $2.0/Kg-H2 and $2.0/Kg-H2 for delivery and dispensing. These price targets highlight the improvements, scale and learning that still needs to be achieved in storage, compression, transportation and dispenser capital equipment.

Market forces are driving the need for modular, scalable building blocks of onsite Hydrogen generation (electrolysers/ steam methane reformers) integrated with storage and dispensing systems obviating the need for transportation. This helps in several ways. I) Allows HRS operators to create infrastructure capacity to meet current demand and to scale with demand growth. ii) This improves the HRS utilization resulting in lower LCOH, passed on to consumers. iii) allows for Best Available Technology (BAT) to be deployed as the industry is rapidly innovating. As the demand from increasing penetration of HFCEVs grows, large centralized Hydrogen generation hubs with delivery to refueling hubs by tube trailers initially, and pipelines eventually, will become economical.

The development of an integrated wells-to-pump Hydrogen refueling infrastructure (HRI) project that can deliver Hydrogen at a competitive cost requires assessment of all possible design options of generating, packaging, transporting and dispensing hydrogen. A key objective of hydrogen roadmaps is the convergence to a cost of Hydrogen/ Kg, such as $2.0 / Kg in Australia and the Hydrogen moonshot initiative by the US government to achieve $1.0/Kg.

However, during the transition period, especially in public infrastructure initiatives, the cost of Hydrogen (at the pump) should be governed by the overall program's economics. Which will dictate the timeline to deploy HRS infrastructure capacity (supply side economics) for the overall *blended* levelized cost of hydrogen to be competitive with incumbent fleet (Diesel/ CNG/ Electric) fuel costs.

On demand side economics, the capital cost of HFCEV buses is dictated by the high cost of the Fuel Cell Engine at current costs of $1200/kW - $1700/kW. Designing the optimal hybridization of the Fuel Cell engine and battery size in the bus, to match the power requirement for specific load profiles (routes), will help in optimizing demand side capital costs of HFCEV buses.

5.2 Project Specific Integrated HRI Design and Planning Approach

Every Zero Emission Vehicle (ZEV) or Low Emission Vehicle (LEV) fleet deployment initiative requires planning and design of infrastructure to support the delivery of physical fuel (Hydrogen, Bio-CNG, Green Methanol, Etc.) delivery or Electricity. This report presents a whole system design thinking approach towards achieving an optimal Hydrogen Refueling Infrastructure (HRI) for a specific project or overall Hydrogen mobility program. The integrated model forecasts daily hydrogen demand from the HFC fleet; simulates HRI design options using fundamental building blocks of Hydrogen generation, dispensing, storage, compressors and transportation; routes of operation; and phased timeline of fleet deployment.

Three distinct categories of public sector transit bus fleets have been considered for this report to match Kerala's (and India's) bus fleets. 1) inter-city 13-meter long-haul buses that travel up-to 500 Kms/day; 2) intra-city 13-meter short-haul buses which range from [250 – 450] Kms/day; 3) the emerging category of 9-meter buses for dense city traffic and unorganized routes.

The approach is divided into three interconnected models:

STEP I: LOAD PROFILE ANALYSIS is the starting step to determine fuel cell engine and battery sizes (by bus category) required to provide the average power for specific load profiles. This step also calculates expected fuel efficiency of the FC engine/ battery combination for each load profile, which in turn is used to estimate Hydrogen (as a fuel) consumed per trip, by simulating the performance of the FC engine/ battery hybridizations. Actual Hydrogen fuel consumption may vary based on live operations. The inputs provided to the model ideally would be the 'power' vs 'time' load profiles of comparable BEV buses operating on routes under consideration and other parameters. In the absence of 'power' vs 'time' data, proxy data that could be used are a combination of i) 'speed' vs 'time', ii) gps data along the route to provide gradient and altitude information, iii) 'load' vs 'time' profile by estimating number of passengers getting on and off from start to finish and every bus stop, iv) auxiliary power required for the bus HVAC system, v) unloaded weight of the bus.

The fuel consumption / efficiency and other bus specifications are fed to the subsequent STEP II below.

STEP II: HYDROGEN HUB LOCATION AND CAPACITY OPTIMIZATION model is used to suggest refueling hub locations, hydrogen capacity per day required by hub, and the type of HRS [onsite generation + dispensing] vs [delivered hydrogen + dispensing], taking into consideration inputs: i) routes, ii) fuel efficiency, iii) on-board hydrogen fuel tank size, iv) levelized costs of HRS sub-systems, and v) Hydrogen supply / transportation costs.

The model uses the output from STEP I and other parameters discussed in detail below.

STEP III: HYDROGEN PRODUCTION COST MODEL to design different networked HRS infrastructure options using output parameters from step II on i) Hydrogen hub type, ii) hub location and iii) hub capacity required / day. This is a project specific hydrogen production cost model which uses the output from STEP II of Hydrogen hub capacities, Type of Hub and Locations to develop levelized cost of delivered (at the pump) Hydrogen projections.

5.2.1 Load Profile Analysis

The cost of a Hydrogen Fuel Cell (HFC) bus needs to be competitive to the incumbent Battery Electric Buse in India. The biggest capital cost is from the MEA (Membrane Electrode Assembly) stacks made of PEMs (Proton Exchange Membranes) in the engines. Their cost currently ranges from [$1,200 - $1,700] / kW. Besides their high initial cost of procurement, it's useful life cycle (durability) determines the number of replacement cycles during the overall useful life of the HFCEV mobility asset, adding to the overall FCEV capital cost. For example, the typical useful lifetime of a public transit diesel bus in India is ten years and ZEV transit buses are expected to be a bit longer. If the MEA stacks are to be replaced every [3- 4] year, the fleet operator will have to factor the replacement costs to the total HFC bus cost.

The purpose of this step is to simulate load profiles from operating BEV buses of similar size and loads on specific routes across Kerala, where HFC buses are being considered for operation. The output of the simulation exercise will be the optimal FC engine and battery size hybridization, required to provide the [average] power to operate a fully loaded HFC bus along the routes.

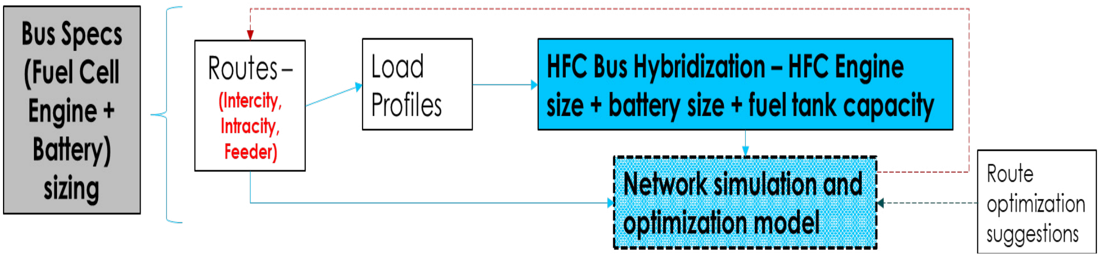


Figure 7- Load Profile Analysis to model Fuel Cell Engine and Battery Size Specifications

These simulations are typically done by the fuel cell engine vendor, auto-OEM or an independent third party, who has the programs / tools to simulate the performance of PEM fuel cell engines. The inputs to the model are: i) Load profile data - "Power" vs "Time", ii) "Speed" vs "Time", iii) Route Distance, Stops, Turns, Gradients, iv) "Bus Load" vs "Time" – number of passengers on board at any time base, v) Temperature, Humidity, vi) Average weight of the bus, vii) Fully loaded weight of the bus.

The model simulates these input conditions and tests the performance of varying available sizes of fuel cell engines to supply the average power. The role of adding batteries is to smoothen the power withdrawal or demand from the fuel cell engine, such as during vehicle startup or sudden accelerations or bursts of power needed for traversing inclines. This reduces the degradation rate of the MEA stacks. Batteries are also used to harvest power from regenerative breaking, which could be as high as 20% in intra-city buses.

5.2.2 Hydrogen Refueling Hub Capacity and Location Optimization Model

Timely and adequate availability of Hydrogen at the refueling hubs is vital for the smooth uninterrupted service of HFC public transit fleets. An approach to determine the optimal capacities and locations of refueling infrastructure to meet a HFC transit fleets needs is presented here.

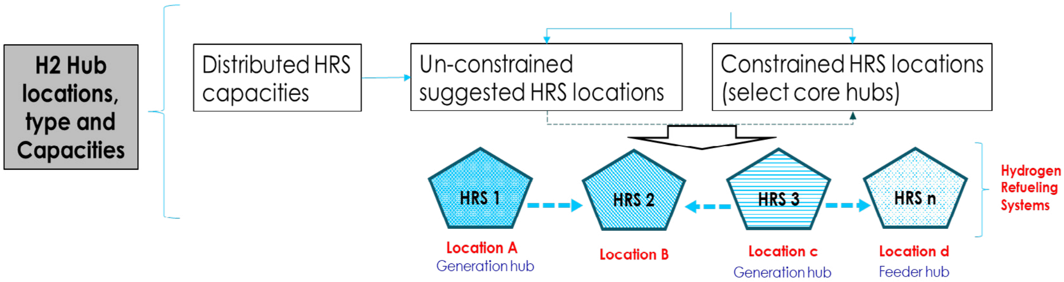


Figure 8- Hydrogen Hub Location and Capacity Optimization Model

Approach: The suggested locations to deploy H2 dispensing, on-site H2 generation infrastructures and their capacities are determined by solving an optimization (minimization) function, whose objective is to arrive at the minimum levelized cost of hydrogen (LCOH) / kg at all hub locations, to meet the demand from the HFC fleet.

Cost of setting up H2 generation and refueling (dispensing) infrastructure, along with cost of transportation of H2 from on-site generation locations to refueling (dispensing) locations comprise the total levelized cost. This cost may be viewed as a fixed cost of supplying H2 at a location. The optimization problem may be stated thus: *determine the minimum number of locations to generate / supply fuel to the buses such that all routes are covered and a bus has sufficient fuel to make a return journey.* The problem can be viewed as a type of facility location problem. Facility location problems belong to the class of discrete optimization problems that are typically hard to solve. Here, the problem is formulated as an integer program as shown in the next section. Inter-city routes have greater distances and are widely distributed (spatially). Hence, they are considered as input for the optimization model regarding location of HRS. Since the intra-city and feeder routes are likely to operate in Kochi, it is assumed there is an on-site H2 generation plant in Kochi. Parameters, decision variables, sets, objective function of the optimization model are presented below. The actual results of the simulation to execute the optimization routine are in **Section 5.4.2.**

Optimization Function: Parameters, Decision variables, Objective function, Outputs

Parameters:

C_{OH} : Levelized cost of onsite generation of H2

C_H : Levelized cost of setting up a H2 Refill Station (HRS)

C_{TH} : Cost of transport of H2 per kg per km

d_{hi} : Fuel required to travel from stop h to stop i

F_u : Maximum fuel tank capacity

F_e : Fuel efficiency kg/km

Decision Variables:

f_i^k : Fuel level of bus on route k at stop i

$r\_f_i^k$:Fuel level of bus on return trip on route k at stop i

$i\_f_o^k$:I nitial fuel level of bus on route k at origin o

H_i : binary indicator variable takes a value 1 if HRS located in stop i

OH_i : binary indicator variable takes a value 1 if onsite H2 is generated at stop i

TH_i : Distance from stop i to nearest onsite generation location

Sets:

S : Set of all stops

O : Set of all origin stops

D : :Set of all destination stops

S(k): Set of all stops on route k

S(H): Set of all stops with HRS

PROBLEM FORMULATION

Objective Function:

	$\min \sum_{\forall i \in S} (C_{OH} OH_i + C_H (H_i - OH_i) + C_{TH} TH_i)$	(1)

Subject to:

	$fik \leq fhk - dhi \; \forall \; k, i \in S \, / \, (O \cup SH)$	(2)
	$f_i^k \leq i\_f_i^k \; \forall \; k, i \in O$	(3)
	$f_i^k \geq F_u \; \forall \; k, i \in S(H)$	(4)
	$0 \leq f_i^k \leq F_u \; \forall \; k, i$	(5)
	$f_h^k - d_{hi} \geq 0 \; \forall \; k, h \in S$	(6)
	$r\_f_i^k \leq r\_f_i^k - d_{hi} \; \forall \; k, i \in S \, / \, (D \cup S(H))$	(7)
	$r\_f_i^k \leq f_i^k \; \forall \; k, i \in D$	(8)
	$r\_f_i^k \geq F_u \; \forall \; k, i \in S(H)$	(9)
	$0 \leq r\_f_i^k \leq F_u \; \forall \; k, i$	(10)
	$r\_f_h^k - d_{hi} \geq 0 \; \forall \; k, h \in S$	(11)
	$i\_f_h^k \leq F_u - \min_{\forall i \in S(k): H_i \neq 0} d_{hi} H_i \; \forall \; k, h \in O$	(12)
	$TH_i \leq bigM \, * H_i \; \forall \; i \in S$	(13)
	$TH_i \geq \min_{\forall j: OH_j \neq 0} (OH_j d_{ij} F_e) \; \forall \; i \in S(H), j \in S$	(14)
	$\sum_{\forall i} OH_i \geq 1$	(15)

Equation 1 is the objective function which is to minimize the overall levelized cost of producing H2, setting up HRS, and delivering H2 from production locations to HRS locations. Equations 2 – 6 update the fuel levels in the bus as it moves from one stop to the next. Equations 7 – 11 update the fuel levels in the bus as it moves from one stop to the next in its return trip. Equations 4 and 9 ensure the bus refills fuel if the *stop has a HRS. Equations 3 determines initial fuel level in the bus as it starts from the origin while equations 8 determine the fuel level at destination as the bus starts its return journey.*

Equation 12 determine the initial fuel level at the origin for each route based on distance of the origin to the nearest HRS on that route. Equations 13 constrains the TH_i variable to zero if there is no HRS at stop i. Equation 14 determine the distance of HRS location to the nearest onsite generation hub.

Finally, equation 15 ensures there is at least one onsite generation location. The optimization model was coded in Python and solved using Google™ OR-Tools CP-SAT library.

5.2.3 Hydrogen Production Cost Model

Levelized cost of Hydrogen is split into the levelized cost of production and the levelized cost of dispensing. The cost of packaging (compressing) and transportation of hydrogen from the production source to the dispensing location, is bundled in with the levelized cost of production in the approach used by the *Hydrogen Delivery Scenario Analysis Model (HDSAM)[9]*. This is an Excel-based bottom-up tool that Argonne National Laboratory has been developing since 2005, which provides cost estimates of various hydrogen delivery and refueling options, and uses a design calculation approach to size the components based on various market demand scenarios and to quantify each delivery component's contribution to the hydrogen cost. The data in the model are based on quotes from vendors, open literature, proposals submitted to public solicitation/funding, industry and stakeholder input, and basic engineering design calculations. (The model output has been validated with industry experts and several global HRS infrastructure economics).

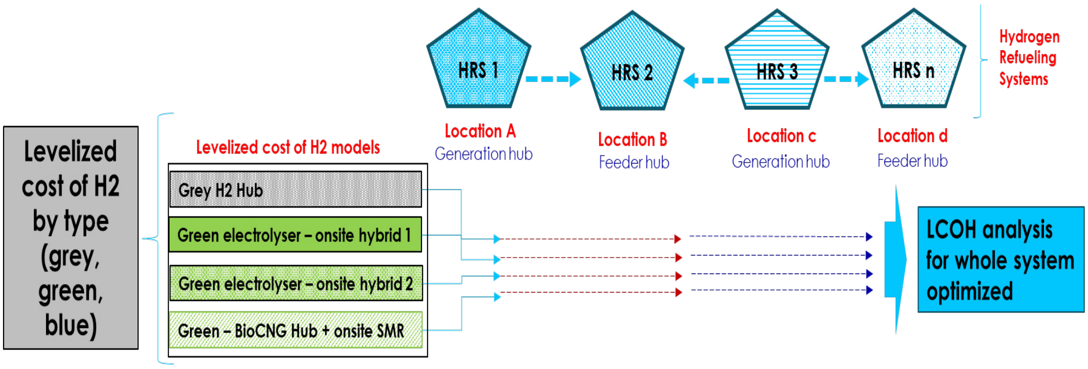


Figure 9- Hydrogen Production Cost Model to develop levelized cost of Hydrogen

The current design of the HDSAM model is suited to model the segregation of a Wells-To-Pump Hydrogen supply chain into three distinct categories – *i) production, ii) packaging and transportation*, iii) *dispensing*. Each of these categories has a distinct set of sub-systems, technology and cost curves. (Table 13). This approach provides flexibility to gather insights on the relative sensitivities of sub-systems, such as electrolysers, compressors, storage, dispensing systems on the levelized cost of Hydrogen, and to forecast how scale of adoption will influence future cost curves.

The industry meanwhile has been busy innovating and creating integrated modular on-site Hydrogen generation and dispensing products by removing the need for transportation. The HDSAM is limited from modeling on-site generation integrated with dispensing systems in its current form. This report could not use the HDSAM model due to this limitation and model project specific 350 HRI systems.

Table 13- Sub-systems in Hydrogen Generation, Transportation and Dispensing

Production	Packaging & Transportation	Dispensing
Electrolysers (PEM, Alkaline)	Compressors	Dispensing Systems
Steam Methane Reformers	Underground Storage	Compressors
Renewable Energy Generation	Tube Trailers	Above ground storage
Gasification Systems (Biogenic)	Pipes (H2 Transport)	Underground storage
Digestor Systems (Biogenic)		Coolants
Pressure Swing Absorbers		Heat Exchangers

Instead, a Hydrogen production cost model built from the ground up to model project specific costs and hydrogen production pathways in India, using data collected from vendors, available information on existing projects, and gaps filled from sources outside India, was used for this report.

The supply chain for Hydrogen production, packaging and transportation of fuel cell grade (99.999% purity) gaseous or liquid hydrogen is non-existent and needs to be developed in India. To de-risk reliance on the Hydrogen packaging and transportation supply chain, emphasis on building the HRI using modular on-site Hydrogen generation systems of 0.25 TPD, 0.50 TPD and 1.0 TPD modular building blocks was prioritized.

Quotations from global vendors of modular Electrolysers (PEM and Alkaline) and SMR integrated with compression, storage and dispensing systems, PSA (Pressure Swing Absorbers) systems, Indian EPC vendors dealing with Gas infrastructure development, maintenance and support, Waste-to-Bio-CNG production, Hydrogen tube trailers equipped with type III tubes, and Single hose 350-bar dispensing systems were used for the CAPEX / OPEX of the systems in the model.

A summary of all the inputs used is provided in **Table 14** The inputs are grouped under three groupings – i) Hydrogen Generation, ii) Hydrogen Packaging and Transportation, iii) Hydrogen Dispensing.

Table 14: Hydrogen production cost assumptions

Electrolyser[1]		
Electrolyser Type	PEM	Alkaline
Electrolyser Conversion Efficiency- 2021 (kWh/Kg-H2)	59	52
Electrolyser Capital Cost- 2021 ($/kW)	850	750
Electrolyser OPEX Cost- 2021 ($/kW-yr)	139	149
Electrolyser Stack Lifetime (Operating Hours)	95000	95000
Electrolyser Full Load Hours per year	5000	5000
Biogenic Hydrogen		
Bio-Methane Production CAPEX ($/MMBtu)	33	
SMR Without CCS CAPEX ($/kW-H2)	1250	
Bio-Methane Production OPEX (% of CAPEX/yr)	1	
SMR Without CCS OPEX (% of CAPEX/yr)	1	

[1] Hydrogen Refueling System's costs are assumed to fall at the same rate as Electrolyser costs. HRS costs include Compressor, Hydrogen storage and dispenser with single nozzle costs.

Grey Hydrogen		
CAPEX of Hydrogen Purification for 1 TPD system ($)	600,000	
OPEX for Hydrogen Purification (% of CAPEX/year)	4%	
Financial Assumption		
WACC (%)	9.4	
Inflation (%)	4.2	
USD to INR rate (Rs/$)	73.1[2]	

Table 15: Hydrogen refueling systems

[3]Hydrogen Refueling System (HRS)	
Hydrogen Dispensing System CAPEX for 1 TPD system ($mill)	2.8
Hydrogen Dispensing System OPEX for 1 TPD system ($mill/Yr.)	0.4
Auxiliary Electricity Consumption- Compressor (kWh/kg-H2)	3.7
Auxiliary Electricity Consumption- Dispenser (kWh/kg-H2)	0.4
Operational Life (Years)	20

Table 16: Hydrogen packaging and transportation

Hydrogen Packaging and Transportation	
Compressor (20 bar-350 bar) CAPEX for 1 TPD system ($)	881,333
Cost of hydrogen transportation (Rs/km/kg-H2)	1
Cost of Bio-Methane transportation (Rs/km/kg-H2)	1

5.3 HFCEV Bus Fleet Specifications and Fleet Demand Scenarios

The rationale behind selecting the three distinct route types was discussed in Section 5.2. It additionally helps to design HFCEV bus specifications (fuel cell engine and battery size hybridizations), by bus categories (inter-city, intra-city, feeder), for the State Transport Undertaking (STU) to structure procurement criteria by route and intended usage. This minimizes confusion from mis-interpretation by the auto-OEM market and additionally aids in forecasting and setting procurement targets for fuel cell engine capacities, which is the single biggest cost in a HFC vehicle.

For example, intra-city public sector buses make frequent stops every few minutes at bus stops, accelerate and decelerate frequently, and have very low average speeds of operation. Their loads vary along the routes and by hour with rush hour being the heaviest. For such load profiles, a relatively smaller fuel cell engine and larger battery will be optimal to harvest energy from regenerative breaking. For long haul inter-city routes, buses travel faster, longer with much fewer stops, and a more even average load. Such load profiles will need a bigger fuel cell engine and a smaller battery. Both of these buses currently are 13-meter buses in India. A third popular emerging category of buses in India are 9-meter-long buses, especially for intra-city routes, where its smaller

2. Electrolyser OPEX cost includes labor and spares costs. Electricity costs are modeled separately

3. The conversion efficiencies of 1.3%, 59% and 19% are assumed for biomass to biogas, biogas to bio-CNG and bio-CNG to hydrogen conversion processes.

size allows it to be nimbler in heavily congested traffic. We have considered routes for the Kochi Metro feeder buses as 9-meter buses.

The rest of the report will address the three distinct route types / HFC bus categories as SCENARIO A, B & C. SCENARIO A – inter-city long haul 13-meter HFC buses, SCENARIO B – intra-city short haul 9-meter HFC buses used for feeder routes, SCENARIO C – intra-city short haul 13-meter HFC buses.

5.3.1 Scenario A: Inter-city Long-Haul 13-meter Bus Routes

Kerala Road Transport Corporation (KSRTC) provided a set of 16 routes to deploy 50 HFC 13-meter inter-city long haul buses. These 16 routes connect 13 distinct

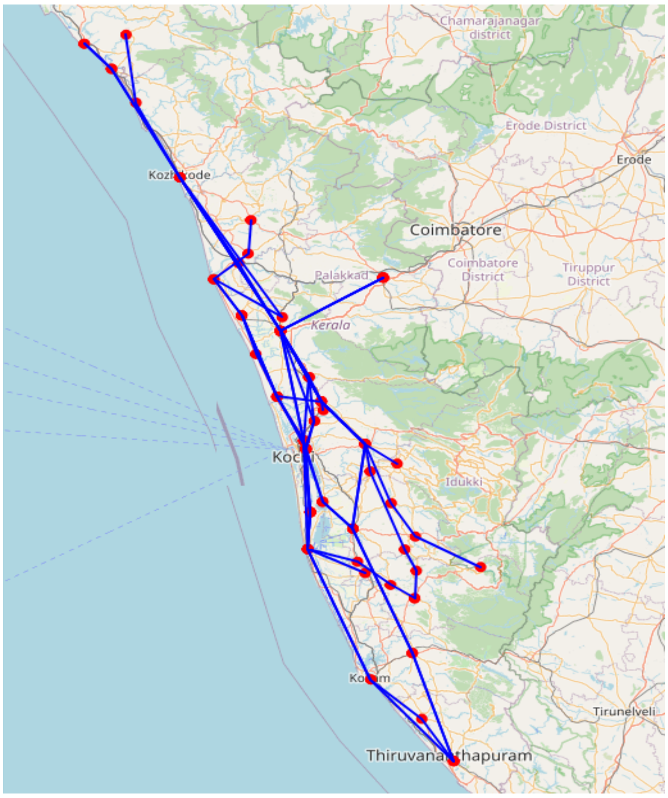


Figure 10- Scenario A Routes: 16 Long Haul inter-city 13-meter buses

O-D (Origin-Destination) pairs and in total pass through 42 unique stops (red dots in **Figure 10** below).

The origin-destination (O-D) pairs of these routes along with their distance are listed in the **Table 17** The average route length is 255 km and maximum route length is 394 km (route-1). Details of individual routes are provided in **Appendix-A2** for the benefit of the readers.

This scenario will require the design of a network of hydrogen refueling stations due to the dispersed set of O-D route pairs to meet the refueling needs of the fleet. **Figure 15** shows the output from the HRS Location and Capacity optimization model that suggests the locations, capacities and the type of Hydrogen Refueling Infrastructure by site.

5.3.2 Scenario B: Last Mile Feeder Routes – Kochi Metro Rail Limited (KMRL)

Kochi Metro is a rapid transit system for the city of Kochi in Kerala. The 25.612 km

Table 17-16 Long Haul inter-city 13-meter bus routes (Scenario A)

Sr. No.	Origin	Destination	Route Length (in Km)	Route no
1	Kozhikode	Pathanamthitta	394	1
	Pathanamthitta	Kozhikode	310	2
2	Thiruvananthapuram	Palakkad	353	3
	Thiruvananthapuram	Palakkad	346	4
3	Alappuzha	Kannur	345	5
4	Kottayam	Kannur	354	6
5	Vytilla Mobility Hub	Thiruvanathapuram	205	7
	Thiruvananthapuram	Vytilla Mobility Hub	209	8
6	Vytilla Mobility Hub	Kozhikode	197	9
7	Malappuram	Vytilla Mobility Hub	158	10
8	Kottayam	Palakkad	201	11
9	Alappuzha	Palakkad	202	12
10	Kannur Airport	Cochin Airport	258	13
11	Guruvayoor	Thiruvalla	178	14
11	Guruvayoor	Nilakkal (Sabarimala)	218	15
13	Thodupuzha	Palakkad	167	16

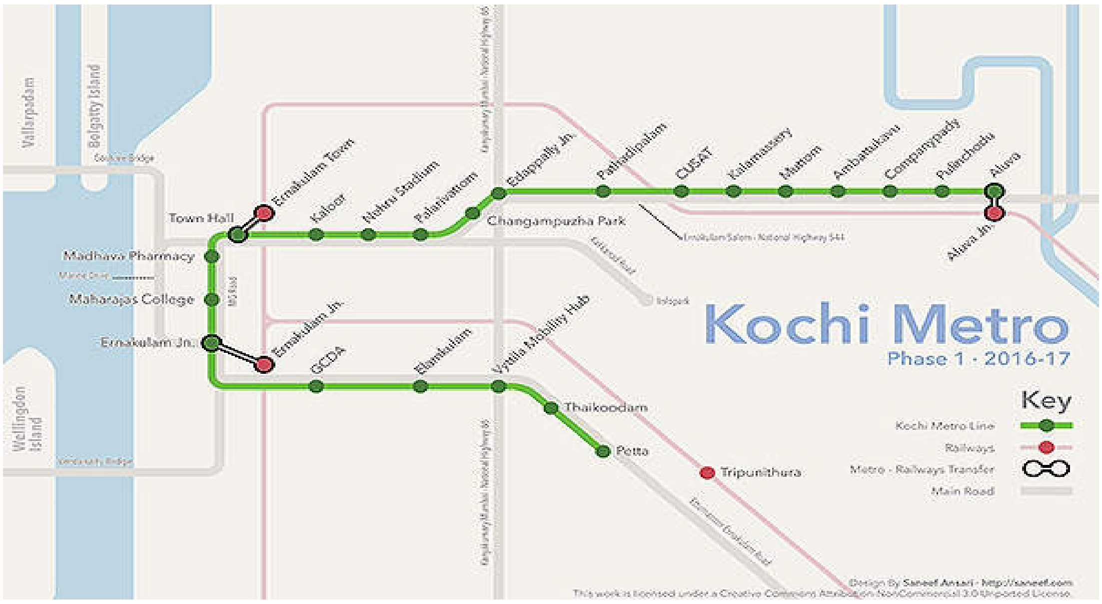


Figure 11- Kochi Metro Phase I Map

metro line will run from Aluva to Petta and will include 22 stations. The metro rail project is also known as Komet or K-3C. [12]. The metro's benefits are to reduce traffic congestion, provide safe and rapid transportation, reduce pollution and noise levels.

KMRL is an integral rapid transit backbone of Kochi's ambitious vision to make the city's entire public transportation system of metro, buses, boats, ferries, auto-rickshaws (3-wheelers) and taxies work together seamlessly as an integrated system.[13]

Feeder services enable seamless travel between different transportation modes. The design and integration of public sector feeder services should be to improve the overall operational efficiencies of the integrated public sector mobility network while *simultaneously developing low carbon mobility infrastructures*. Integration of last mile feeder services with rapid transit corridors should be enabled via an open data platform that allows the market to build and provide innovative LEV, ZEV mobility-as-a-service (MaaS) products and services.

KMRL provided a set of 15+ routes for fifty (50) feeder buses, from which a set of eight routes (shown in **Figure 12)** were selected to deploy the first fleet of ten (10) 9-meter [45–65] KW FC buses. An obvious observation is the non-convergence of the eight O-D pairs of routes. Typically, intra-city transit buses will have a central re-fueling hub for the buses to be refueled, serviced and parked overnight. The logic for selecting these routes was based on *Vytilla* being a likely site for setting up a central Hydrogen

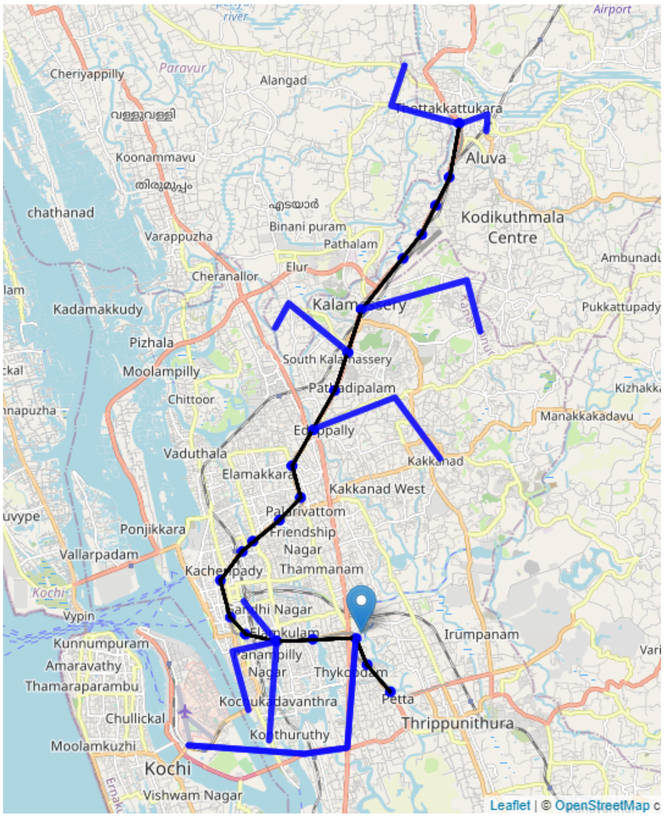


Figure 12- Scenario B Routes: 8 Routes for Feeder Buses to service Kochi Metro

refueling hub. One that would minimize the deadhead distances for the initial fleet of 10 buses but also the additional expanded phases.

A three phased approach of fleet deployment and related supporting HRI infrastructure of 10, +20 and +20 buses to a cumulative fleet size of 50 buses is assumed for this report. **Figure 17** in the section on Hydrogen hub locations and capacities discusses the stages of HRI development for the Kochi Metro feeder routes. The first phase of

Table 18- Kochi Metro Feeder RoutesPhase I Deployment of 10 Buses

Route No.	Route	Distance (km)	No. of trips/ day	# Buses
1	Kadavanthara metro to Ravipuram	4.7	32	1
2	Kalamassery metro to Govt. medical college	11.3	24	1

Route No.	Route	Distance (km)	No. of trips/ day	# Buses
3	Aluva metro to Railway station	5.6	30	1
4	Vytilla metro to Theavara	16.7	18	2
5	CUSAT metro to Manjumel	6.5	30	1
6	Edappally metro to Civil station	9.4	24	1
7	KSRTC bus station to SH college	16.7	16	2
8	Aluva metro to UC college	9.7	22	1

ten 9-meter feeder HFC buses will consist of two buses on Routes 4 and 7, and one bus each on the remaining six routes. **Table 18** summarizes the routes for the first phase of deploying a fleet of 10 HFC buses.

5.3.3 Scenario C: Overview of short-haul Intra-City Bus Routes in Kochi

A 2016 study commissioned by KURTC (Kochi Urban Road Transport Corporation) for the introduction of low carbon city bus routes in Kochi was used to determine a set of routes for the purpose of this report, to model demand from ten 13-meter short

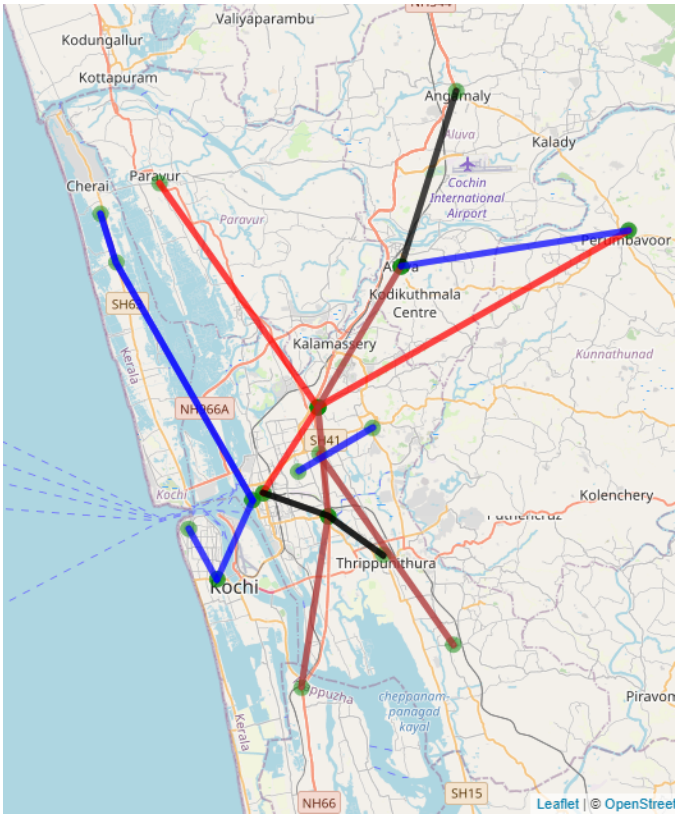


Figure 13- Scenario C Routes: 14 Kochi Intra-City Routes

Table 19-14 Kochi intra-city routes and their route lengths.

Route No.	Route	Distance (km)	Phase I (#buses)
1	MG Road – Edapally	10.5	3
2	Edapally – Paravoor	18.5	
3	Edapally – Perumbavoor	23.6	
4	Edapally – Aluva	12.6	
5	Vytilla _ Aroor	12.4	3
6	Edapally – Vytilla	7.0	2
7	Palarivattom – Mulanthuruthy	18	
8	Aluva – Angamaly	14.3	
9	MG Road – Vytilla – Thripunithura	11	2
10	Aluva – Perumbavoor	16.2	
11	Menaka – Vypin – Cherai	25.3	
12	Thopumpady – Fort Kochi	5.0	
13	Menaka – Thopumpady	8.8	
14	Kaloor – Kakkanad	8.1	

haul intra-city buses. *The report identified 14 corridors having high demand for public transit, and these routes were considered as potential intra-city routes in this study*. Maximum, minimum, and average lengths of these routes are 25.30 km, 5.0 km, and 13.66 km respectively. A map of these routes is shown in the figure below.

Out of these 14 routes (Figure 5.3.3), four routes, route no. 1, 5, 6, and 9 are planned to operate in the first phase with 3, 3, 2, and 2 buses on each route respectively. Thus, a total of 10 HFC buses were used to model across the four intra-city routes in Kochi. The expected number of trips per day per bus on route 6 is 19, route 5 is 12, while those on routes 1 and 9 are 13 each, factoring in the travel times along the routes.

5.4 HRS Infrastructure Planning and Design Results

The following sections will discuss each of the three different models, inputs, assumptions, outputs from the three HFCEV fleet demand scenarios modeled and a summary with recommendations.

Table 20- Fuel Cell Engine Size + Battery Size specification by average load profiles by scenario

FCHEV Configuration	Route Type	Loading
45kW FCE + 45 kWh ESS	9m Intracity – Kochi Metro Feeder Routes	Full Weight
90 kW FCE + 80 kWh ESS	13m Intracity – Kochi Intra-City	Full Weight
120 kW FCE + 80 kWh ESS	13m Intercity – Kerala Intercity	Full weight

5.4.1 STEP I: Hydrogen Fuel Cell EV Engine + Battery Sizing (Load Profile Analysis)

Table 20 summarizes the model output (FC engine size + battery size) from simulations performed by route, bus size, and average and full load of the bus.

The modeling exercise also provides the amount of Hydrogen used by load profile and

HFCEV specification, which was used to determine its fuel efficiency. This provided the basis to estimate the total daily hydrogen demand for the fleets by scenario.

Table 21 summarizes the amount of Hydrogen used by simulating the Fuel Cell Engine specifications from Table 5.4.1 for each scenario's average power requirements over 6 hours, for a fully loaded bus.

5.4.2 STEP 2: Hydrogen Refueling Hub Location and Capacity Optimization Model

The results from the optimization model of the HRS Hub and capacity locations, based on the cost (total) minimization formulation described in section 5.2.2, from the execution of multiple scenarios are discussed below. The *four key input parameters* considered are:

- **C1:** This is for modeling the cost of an **On-Site Hydrogen Generation and Refueling Hub**. C1 is the weighted average capital cost of setting up a 0.25 TPD, 0.5 TPD and 1.0 TPD onsite electrolyser system, Hydrogen storage, compressor and a single hose dispenser, amortized over 15 years. **[Rs. 300/kg]**
- **C2:** This is for modeling the cost of a **350 Bar Hydrogen Dispensing Hub**, to which Hydrogen will be supplied via tube-trailers or pipeline. This is the capital cost of a single hose dispensing system, above ground tube-trailer storage (at 500) bar and adequate compressor, amortized over 15 years. **[Rs. 85/kg]**
- **C3:** Cost of **transporting Hydrogen**. For designing a hub-and-spoke HRS network infrastructure, with Hydrogen generated at a single central hub and transported to feeder hubs, the cost of transporting Hydrogen in gaseous form at 500 bar in tube trailers is assumed. C3 is the capital cost of type III storage tubes amortized over 15 years and the prevailing cost of transporting CNG/Km in India. **[Rs.0.5/Kg/Km to Rs.3 /kg/km]**

F: On- board Hydrogen Fuel tank capacity of the bus. This is a variable that determines the interval between refueling events based on the size of the fuel tank. **[20 Kg-H2 – 70 Kg-H2]**

Table 21 shows the results of the model by varying the [onboard hydrogen fuel tank] capacities and [cost of transporting] Hydrogen to Hydrogen Hub Locations and capacities. Cost of transporting Hydrogen using tube trailers @ 200 bar, (as this the currently approved pressure from PESO, India), is assumed and at prevailing costs for Bio-CNG transport. The cost per km was varied from 0.5 Rs/Km to 2.5 Rs/Km. The onboard hydrogen capacities were varied from 20 Kg to 50 kg. Levelized cost of setting up on-site H2 generation unit and cost of setting up HRS are kept constant as and Rs. 85/kg respectively. The output is the [number of onsite-hydrogen generation and dispensing hubs], [number of dispensing hubs with hydrogen delivered to them], [location of the hubs] and the [daily capacities] at each hub.

At lower fuel tank capacities, the number of HRS required is high, and this reduces with increased fuel tank capacity across all values of transportation cost. Further, an increase in number of on-site H2 generation stations can be noticed with higher costs of transportation of H2 (Rs. 2 and above).

The actual locations of the Hydrogen hub locations from Table 21 are presented in **Appendix-B.** The variation of total cost (objective value) across scenarios is presented in the figure above.

Table 21- : Hubs, Types by varying H2 Tank Capacities and H2 Transportation Costs

Cost of transporting H2 (Rs/kg/km)	Fuel tank capacity (kg)	Dispensing Hubs (H2 is transported)	On-Site Generation + Refueling Hubs
0.5	20	8	1
	25	6	1
	30	4	1
	35	3	1
	40	3	1
	45	2	1
	50	2	1
1.0	20	6	3
	25	5	2
	30	3	2
	35	2	2
	40	3	1
	45	2	1
	50	2	1
1.5	20	6	3
	25	4	3
	30	2	3
	35	1	3
	40	2	2
	45	2	1
	50	2	1
2.0	20	5	4
	25	4	3
	30	2	3
	35	1	3
	40	2	2
	45	2	1
	50	2	1
2.5	20	5	4
	25	3	4
	30	2	3
	35	1	3
	40	2	2
	45	2	1
	50	2	1

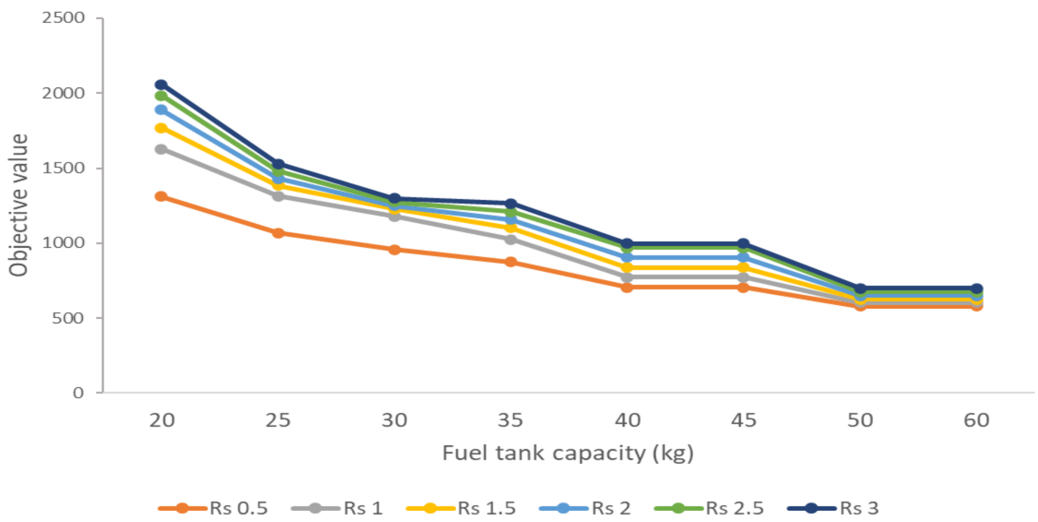


Figure 14- Objective value (cost) optimization by varying H2 tank capacity and H2 transport cost

The results demonstrate the relationship to higher tank sizes to overall total Hydrogen Refueling Infrastructure design and cost. Larger tank sizes will allow for more kilometers travelled per fill and lower the levelized cost of Hydrogen Transport and Dispensing. The physical limitation of the capacity available to install tanks and related supporting equipment will need to be factored.

Determining the actual physical location of the hubs, land area required, and right of way access provisions is not the scope of this report, but an important exercise which will need a detailed analysis of the impact to the environment, safety, and economics.

Results and Recommendations

The Hydrogen Hub Location and Capacity Optimization Model (H2LCM) was used only for SCENARIO A in this report. The other two SCENARIOs, B and C, serving intra-city routes is assumed to start with a single central hub for overnight refueling in Kochi. The design of future expansion phases, will need a whole system design thinking approach, and the use of an optimization model, such as H2LCM, to identify additional Hydrogen refueling sites and capacities.

Project specific vs Program specific HRI planning and design

While undertaking the design of a project specific HRI program, considerations that would impact the capital allocation timeline to build out the entire network of HRI in a region, should be an integral part of the planning and design process. For example, specific to the Kerala Metro Feeder service HFC bus program, the following considerations would need to factored:

1. What will the final networked HRI design for the entire program look like? Will this be a central hub and spoke model or a decentralized model with emphasis on on-site generation?
2. Should capacity allocation for the entire program be developed upfront or built-in phases?
3. Demand projections from Intra-City Short-Haul and Inter-City Long-Haul routes.
4. Will HFCEVs of other classes such as cars, that needs 700 bar dispensing systems, be filled from these hubs?

5. Kerala state's larger strategy to develop infrastructure across the state to incentivize the adoption of HFCEV mobility.

The scope of this report doesn't allow for modeling these considerations, but it calls for a sustained and detailed assessment of the pathways to decarbonization, and evaluate policies and incentives needed to stimulate the transition.

In the section on production costs of hydrogen (5.4.3), further questions and modeling of the impact of a phased implementation of HRI on the overall programs levelized cost of hydrogen is addressed.

It also evaluates the various HRI and hydrogen sourcing options to calculate the levelized cost of hydrogen at the pump for project specific vs program specific HRI development.

5.4.2.1 Scenario A: HRI Design- 50 inter-city 13-meter HFC long Haul Buses

The total demand from the entire fleet size of 50 Inter-City 13-Meter-Long Haul HFC buses across the 16 routes is 3,145 Kg/H2-day. The optimization model output using a 45 Kg/H2 onboard tank size recommends three Hydrogen refueling hubs within a distance of 80 Kms from each other, creating a network of three HRS hubs at Kochi, Angamaly and Thrissur is recommended.

Figure below shows the model inputs and suggested locations of the three HRS sites. 1) **Kochi site** – Onsite Generation from either electrolysers (Green H2) or SMR (BioCNG or Natural Gas feedstock) of 3,145.0 Kg/H2-day to cover demand from all three hubs, with a Kochi site HRS demand of 1,470.0 Kg/H2-Day, 2) **Angamaly site** – Delivered demand of 1075.0 Kg/H2-day from the Kochi site, 3) **Thrissur site** – Delivered demand of 600 Km/H2-Day from Kochi site.

Scebario S15	
Fuel Tank capacity (kg)	45
Cost of H2 transporation (Rs/kg/km	1
Cost of on-site H2 generation (Rs/kg)	300
Cost of HRS set-up (Rs./kg)	85
On-site-1	HRS - 2
Kochi	Angamaly Thrissur

Figure 15- Scenario A Hydrogen Hub Locations, Types and Capacities

Figure below is a phased implementation scenario across three phases over five years. This scenario scales to a final central generation capacity of 3.5 TPD from the Kochi site, starting with a first phase of a 1.0 TPD generation and dispensing node.

The Second phase adds an additional feeder or receiving hub at Thrissur, 84 Kms away, with a dispensing station, onsite storage and compressor, with hydrogen delivered via trailer tubes from the Kochi site. The second phase adds an additional generation capacity of 1.0 TPD at the Kochi site, increasing to a total 2.0 TPD generation capacity, with an additional 0.5 TPD demand at Kochi and transporting 0.5 TPD to Thrissur.

The third phase adds an additional 1.5 TPD generation and storage capacity at Kochi, with a new dispensing site at Angamaly 40 Kms away. This phase increases delivery capacity to Thrissur to 1.13 TPD and new transportation capacity of 0.63 TPD to Angamaly.

The design philosophy behind this approach is the use of modular additive on-site generation infrastructure building blocks. Vendors of modular generation and dispensing units are catering to demand by building 0.25 TPD, 0.5 TPD and 1.0 TPD modular systems. These systems include generation, storage, compressors, cleansing and dispensing sub-systems using electrolysers or SMRs.

The next section on production cost modeling, sensitivity to phasing the implementation across several years on the total 'program' blended levelized cost of Hydrogen vs levelized cost of building full capacity at the beginning is explored.

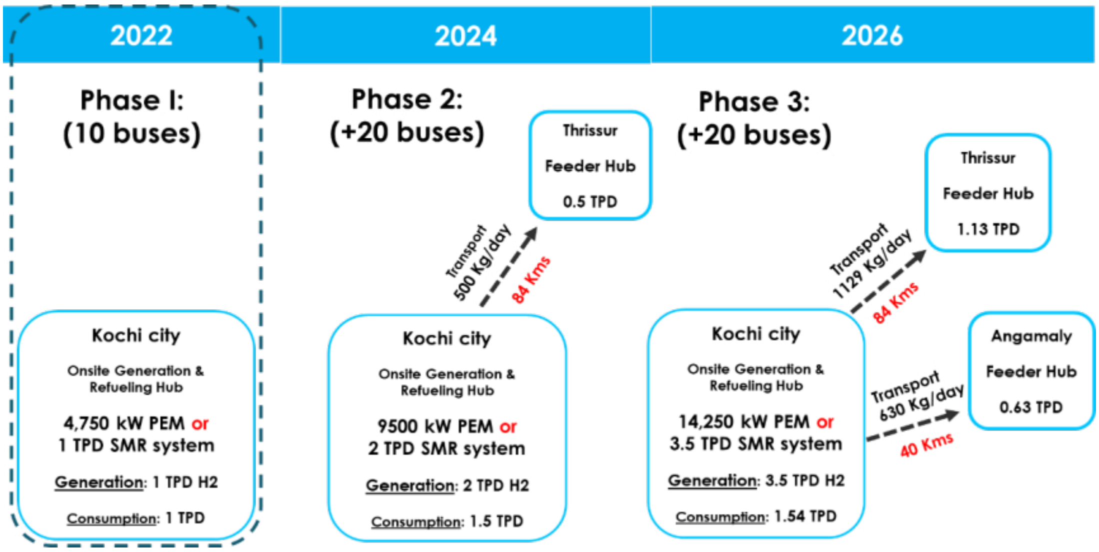


Figure 16- Phased implementation timeline of HRI network capacity (Scenario A)

5.4.2.2 Scenario B: 10 intra-city 9-meter HFC Short Haul Feeder Buses

The Kochi Metro Feeder route demand is for 50 buses across 8 routes, of which an initial demand from 10 buses is designed in this report. The use of the H2LCT tool (or similar) would be necessary to optimize the entire HRI system design, taking into account each routes O-D (origin-destination) locations, bus schedule, frequency and anticipated transportation capacity increase projections. This exercise would suggest the number of HRS hubs and capacities needed for the entire program.

Due to the limited scope of this report, SCENARIO B is assumed to be developed over three phases, of which the first phase will be limited to 10 buses as discussed and summarized in **Table 18** Further, the HRS hub is assumed to be a single central hub in one location for the current and future phases. *The whole system HRI modeling and optimization process was not done for this scenario.*

The daily demand from these routes for the first phase is 153 Kg/ H2-day. The second phase will add another 10 buses to increase fleet size to 20 buses with a total demand of 382 Kg-H2/Day. The third phase will add another 30 buses to increase the fleet to a final size of 50 with total demand of 765 Kg-H2/Day.

Following the design philosophy of using modular additive building blocks of HRI assets, and provisioning for a 10% buffer capacity, a 0.25 TPD, 0.5 TPD and 1.0 TPD HRI system capacity for phase I, II and III will be required. Table 17 depicts the phased timeline and capacities of the single HRS hub for SCENARIO B.

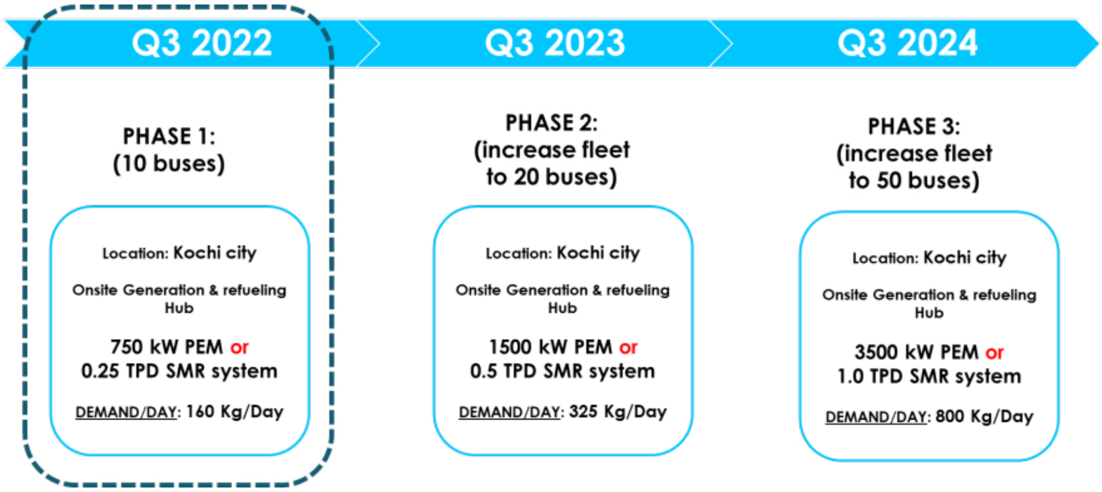


Figure 17- Phased implementation timeline of HRI network capacity (Scenario B)

5.4.2.3 Scenario C: 10 Intra-City 13-Meter HFC Short-Haul Buses (KURTC)

Similar considerations and assumptions as in SCENARIO B were used to arrive at a phased implementation approach starting with a 10-bus implementation phase, that will need a single central overnight refueling hub in Kochi city. Selection of routes that can be refueled from a single central hub was prioritized for this phase (Table 19). Expansion of the fleet in future phases will need use of the optimization model (or similar process) to locate additional hubs for servicing additional route O-D (origin destination) pairs.

The demand from the 10 buses for this phase is 348 Kg/H2-Day**.** The next section will explore several HRI design options by sourcing Hydrogen across several pathways and compare their levelized costs of Hydrogen at the pump.

Figure 18 shows a Hydrogen production options P1, P2 and P3. These are the same as for other scenarios.

Figure below shows the P4 production route of Chlor-Alkali H2 trucked across all phases.

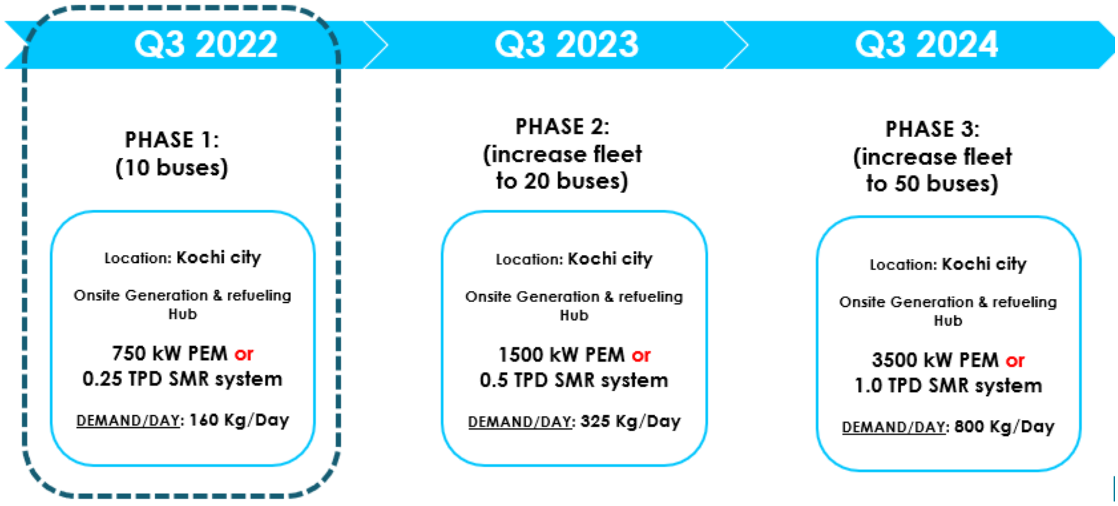


Figure 18- Phased implementation timeline of HRI network capacity (Scenario C) with P1, P2 and P3 Hydrogen production pathway

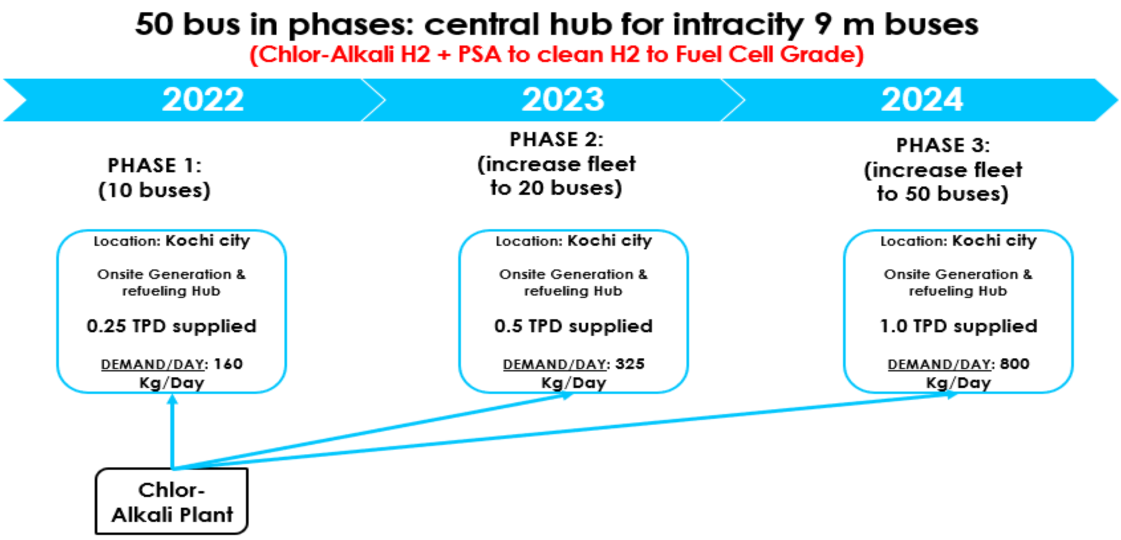


Figure 19- Phased implementation timeline of HRI network capacity (Scenario C)-Chlor-Alkali H2 (P4)

5.4.3 STEP 3: Hydrogen Production Cost Model

INPUTS – HRI Consumption Demand by Hub Location

The table 22 below summarizes the Hydrogen consumption demand for all three scenarios A, B, and C. These were determined from the load profile modeling step based on inputs of actual routes, trips, load vs time, trip durations provided by KSRTC for the long-haul intercity routes and Kochi Metro on the feeder routes. Fuel efficiency and hence demand for Intra-City short-haul routes were obtained using proxy methods by simulating indicative load profiles of intra-city buses from the state of Tamil Nadu. *The Hydrogen Hub Location, Capacity and HRI type optimization model was used only for SCENARIO A and was out of scope for SCENARIO's B and C.*

The OPEX of the HRI will be determined by Table 22 capacities.

Table 22- Hydrogen Consumption Demand by hub locations (used for HRI OPEX)

SCENARIO	Total H2 Demand / Day (Kg / H2-Day)	Hydrogen Hub Location	HRS Type	Hydrogen Consumption Demand/Day (Kg/H2-Day)	H2 Source Options
A: Inter-City (KSRTC) 50 Buses across all phases	3,145.00	KOCHI	Central Generation Hub + Dispensing	1,470.00	On-Site Generation – i) Electrolysers ii) Steam Methane Reforming of BioCNG or Natural Gas
		ANGAMALY	Delivered Hub (Dispensing only)	600.00	Delivered from Kochi
		THRISSUR	Delivered Hub (Dispensing only	1,075.00	Delivered from Kochi
B: Feeder service (Kochi metro) 10 buses (Phase I)	153.00	KOCHI	Onsite Generation or Delivered hub with Dispensing	153.00	On-Site Generation – i) Electrolysers ii) Steam Methane Reforming of BioCNG or Natural Gas Delivered from Grey Sources
C: Intra-City (KURTC) 10 buses (phase II)	348.00	KOCHI	Onsite Generation or Delivered hub with Dispensing	348.00	On-Site Generation – i) Electrolysers ii) Steam Methane Reforming of BioCNG or Natural Gas Delivered from Grey Sources

INPUTS – HRI Generation Capacity Provisioning by Hub Location

The provisioning of HRI capacity will be predicated by available modular blocks of HRI infrastructure required for both the generation and dispensing of Hydrogen. Based on discussions with various global HRI product vendors, the market will see a proliferation of modular i) combined generation + dispensing units, ii) modular generation only units, iii) dispensing units. These range from 100 Kg-H2/day systems to 1.0 TPD systems. Table 23 summarizes the final HRI capacity used in the cost models, taking into account a +5% buffer capacity to Table 22 demand, and available HRI building blocks.

The consumption capacity required is rounded up to the nearest 100 Kg/Day blocks or 250 kg/Day or 500 Kg/day modular building blocks of generating modular HRI. The CAPEX of the HRI will be dictated by Table 23 capacity.

Table 23- Hydrogen Generation CapacityProvision by hub locations (use for HRI CAPEX)

SCENARIO	HRS Site	Model Consumption Demand (Kg-H2/Day)	+ 5% Buffer to account for losses (Kg-H2/day)	Modular 100 Kg/Day, 0.25 TPD, 0.5 TPD,1.0 TPD HRI	Generation Capacity (Kg-H2/Day)	HRI capacity provisioned (Kg-H2/Day)
A	Kochi	1,470.00	1,544.00	1.5 TPD + 0.25TPD		1,750.00
	Angamaly	600.00	630.00	0.5 TPD + 0.25 TPD		750.00
	Thrissur	1,075.00	1,129.00	1.0 TPD + 0.25 TPD		1,250.00
	Kochi			3 TPD + 0.5 TPD	3,500.00	3,500.00
B	Kochi	153.00	161.00	200 Kg/Day	200.00	200.00
C	Kochi	348.70	366.00	200 Kg/Day	400.00	400.00

INPUTS – Hydrogen Production Pathways

The following four Hydrogen production pathways were used for calculating levelized costs of hydrogen production for HRI generation capacities (Table 23) for SCENARIOS A, B and C.

As of this writing, it has been impossible to get the cost of Grey Hydrogen from the BPCL refinery facility in Kochi. *The P4 Hydrogen production pathway is modeled as Hydrogen with GHG emission intensity [20-90] % lower than SMR Grey route [12].* Travancore Cochin Chemicals (TCC) in Kochi, a public sector Chlor-Alkali plant, is estimated to have a generation capacity of 1.5 TPD of by-product Hydrogen which can be potentially cleaned to fuel cell grade Hydrogen. P4 for all three scenarios assumes up-to 1.5 TPD of H2 delivered from the TCC plant, and the rest of the Hydrogen generated from on-site grid connected modular electrolyser units.

Table 24- Hydrogen Production Pathways

	HYDROGEN PRODUCTION PATHWAYS
P1	100% Green Electrolytic Hydrogen. Captive Solar + Open Market Procurement +RECs
P2	26%* Green Electrolytic Hydrogen. Captive Solar + Open Market Procurement
P3	100% Biogenic Hydrogen. Steam Methane Reformation (Bio-CNG Feedstock)
P4	i) Fuel Cell grade H2 from Chlor-Alkali plant up to a daily capacity of 1.5 TPD potential from TCC. ii) Additional capacity above 1.5 TPD is generated from Electrolysis of water from grid connected power.

**26% of the power needed comes from captive solar and the rest from the grid.*

INPUTS – Energy Sourcing for Electrolysers

Table 25- Energy Sourcing for Electrolytic Hydrogen Generation

PARAMETER	VALUE
Primary Source of Electricity	Captive Solar (In-State)
Secondary Source of Electricity	Open Market + RECs
Landed cost of Captive Solar Power (Rs/kWh)	4.73
Landed Cost of Open Market Power (Rs/kWh)	5.4
Cost of RECs (Rs/MWh)	1800

Hydrogen production costs are developed for the following:

a. SCENARIO A: Provision 100% HRI capacity for the entire planned fleet of 50 inter-city buses with 100% utilization This assumes all 50 buses will be deployed from the start.

b. SCENARIO A: Provision HRI capacity in three phases over a period of five years to meet H2 demand from 10, +20, +20 inter-city buses per phase.

c. SCENARIO B: Phase I demand of ten (10) intra-city 9-meter HFC bus fleet for Kochi Metro.

d. SCENARIO C: Phase I demand of ten (10) intra-city 13-meter HFC bus fleet for Kochi city.

5.4.3.1 Scenario A: Inter-city bus fleet across 16 inter-city routes.

Levelized cost of Hydrogen was modeled for two Hydrogen Refueling Infrastructure (HRI) capacity provisioning scenarios.

i) ***100% of HRI capacity commissioned at the start of the program*** for the entire 50 bus fleet consumption demand of 3,302.00 Kg-H2/Day by provisioning generation capacity of 3,500.0 Kg-H2/day across all three HRI hubs. For the LCOH (at the pumps) to be economical, the utilization of the HRI needs to high as possible. If all the 50 buses are deployed from the start of the program, the LCOH's for the four H2 production scenarios P1, P2, P3 and P4 are as shown below (table 26). *The LCOHs are pretty close to each other with a +/- 8% variation.*

Deployment of the 50 HFC buses in phases over several years will result in lower HRI utilization and increase project LCOH. But there are advantages, which along with the risks of provisioning 100% of the HRI upfront, need to be assessed for every project. The advantages are in i) completing the civic, environmental permitting, land acquisition, site preparation, foundation works for the entire program; ii) utilities capacity and connections for power, water, natural gas and waste effluent treatment and disposal are allocated for the entire program's needs, iii) de-risks the program from service interruptions during times of upgrades or adding new HRI capacity.

Table 26- SCENARIO A: Full HRI capacity provisioning at the onset of the program

	DEMAND		GENERATION				HRS			TRANSPORTATION			PROJECT	
Hydrogen Production Pathways	Hydrogen Generation Demand (Kg-H2/Day)	Hydrogen Consumption Demand (Kg-H2/day)	Electrolyser Capacity (kW)	CAPEX (Cr.Rs.)	OPEX (Cr.Rs./Year)	LCOH (Rs/Kg-H2)	CAPEX (Cr.Rs.)	OPEX (Cr.Rs/Year)	LCOH (Rs/Kg-H2)	CAPEX (Cr.Rs.)	OPEX (Cr.Rs./Year)	LCOH (Rs/Kg-H2)	Project LCOH (Rs/Kg-H2)	Total Project CAPEX (Cr. Rs.)
P1	3500	3302	14,242	84	34	313	68	10	123	30	6	69	501	182
P2	3500	3302	14,242	84	30	273	68	10	123	30	6	69	461	182
P3	3500	3302	0	166	16	188	68	10	123	30	11	110	395	264
P4	3500	3302	5,615	30	12	269	68	10	123	20	6	114	470	118

ii) ***Development of the HRI in phases over several years.*** This approach has the following advantages:

a. being able to leverage the anticipated rapid drop in costs of several sub-systems within the Hydrogen Generation, Packaging, Transportation and Dispensing HRI from scale and volume of demand. For example, electrolysers costs are expected to drop by 50% over the next decade, storage by 30% - 40% and dispensers by 30% - 50%.

b. Besides drop in costs, improvements in the product quality, performance enhancements from product revisions and continued innovation are expected in this nascent industry.

c. The other drop in costs is expected to come from renewable energy globally, though it remains to be seen how the renewable energy market in India will evolve. *The landed cost of electricity is assumed to be constant across the phases for this report.*

d. The HRI capacity utilization will be 95% or more as it's deployment will closely match the demand from the phased HFC bus fleet expansion.

A YoY 15% rate of drop in costs for electrolysers, storage, power and dispensers are assumed. This will result in using the blended LCOH's from the individual phases of HRI deployment. *As expected, table 5.4.3.1b shows that the **blended LCOH's** are lower than the previous model by [8 – 10] %.*

Table 27- SCENARIO A: Phased HRI Capacity Provisioning in alignment with HFC Fleet Deployment

	DEMAND		GENERATION				HRS			TRANSPORTATION			PROJECT	
Hydrogen Production Pathways	Hydrogen Generation Demand (Kg-H2/Day)	Hydrogen Consumption Demand (Kg-H2/day)	Electrolyser Capacity (kW)	CAPEX (Cr.Rs.)	OPEX (Cr.Rs./Year)	LCOH (Rs/Kg-H2)	CAPEX (Cr.Rs.)	OPEX (Cr.Rs/Year)	LCOH (Rs/Kg-H2)	CAPEX (Cr.Rs.)	OPEX (Cr.Rs./Year)	LCOH (Rs/Kg-H2)	Project LCOH (Rs/Kg-H2)	Total Project CAPEX (Cr. Rs.)
P1	3500	3302	14,242	61	35	298	66	10	114	32	6	69	462	159
P2	3500	3302	14,242	61	33	292	66	10	114	32	6	69	460	159
P3	3500	3302	0	166	15	187	66	10	114	32	11	110	390	263
P4	3500	3302	5,615	28	11	252	66	10	114	20	6	114	451	114

5.4.3.2 Scenario B: Kochi Metro Feeder Service Fleet

This scenario models demand from feeder services at the Kochi Metro. Table **28** lists specific energy sourcing options considered due the availability of current excess rooftop solar capacity and anticipated additional capacity from additional solar at CIAL (Kochi International Airport).

This scenario assumes all the hydrogen is generated and dispensed at Kochi hub. For sensitivities P1 and P2, the primary source of energy is the surplus energy available from the solar generation at Kochi International Airport (CIAL), including a small scale 427 kW floating solar plant installed at the Kochi Airport Golf Course.

For the P3 sensitivity, it is assumed the Hydrogen is produced at the TCC Chlor-Alkali facility in Kochi and dispensed from that location, eliminating the need for transportation. If H2 needs to be transported to a location other than TCC for dispensing, additional costs for transporting via tube trailers will need to be factored in.

Table **29** shows the cost bread down for all sensitivities. The CAPEX of the HRI for the Biogenic Hydrogen Generation route is high due to the additional onsite storage requirement for Bio-CNG besides Hydrogen. The LCOH for green electrolytic hydrogen is highest due to high cost of electricity from CIAL and the open market.

The P4 procurement pathway is the least expensive option with a LCOH of 234 Rs/

Table 28- Scenario B: Energy Sourcing Options

Item	Value
Primary Source of Electricity	CIAL Surplus, Floating Solar
Secondary Source of Electricity	Open Market + RECs
CIAL Surplus Energy (kWh/day)	10,000.00
CIAL Energy Cost (Rs / kWh)	7.5
Floating Solar Plant Installed Capacity (kW)	427
Landed cost of Captive Floating Solar Power (Rs/kWh)	4.73

Table 29- SCENARIO B: HRI Capacity Provisioning for Phase I.

	DEMAND		GENERATION				HRS			TRANSPORTATION			PROJECT	
Hydrogen Production Pathways	Hydrogen Generation Demand (Kg-H2/Day)	Hydrogen Consumption Demand (Kg-H2/day)	Electrolyser Capacity (kW)	CAPEX (Cr.Rs.)	OPEX (Cr.Rs./Year)	LCOH (Rs/Kg-H2)	CAPEX (Cr.Rs.)	OPEX (Cr.Rs/Year)	LCOH (Rs/Kg-H2)	CAPEX (Cr.Rs.)	OPEX (Cr.Rs./Year)	LCOH (Rs/Kg-H2)	Project LCOH (Rs/Kg-H2)	Total Project CAPEX (Cr. Rs.)
P1	200	161	693	4	3	459	6	1	221	-	-	0	685	10
P2	200	161	693	4	1	273	6	1	221	-	-	0	513	10
P3	200	161	-	8	1	187	6	1	221	-	0.03	5	449	14
P4	200	161	-	1	0.03	13	6	1	221	-	-	0	234	7

Kg-H2. This Hydrogen is as green as the renewable energy mix in the grid used to supply electricity to the Chlor-Alkali plant. Switching to a 100% RE source should help in lowering the Co2-eq emissions/ Kg-H2. Since the available capacity of the by-product H2 is limited to 1.5 TPD, Kerala should consider using this source for back-up to improve its HRI resiliency. Kerala should prioritize developing 100% green HRI for future expansion phases, by which time the cost drops of electrolysers and RE should make the Green H2 competitive.

5.4.3.3 Scenario C: Kochi Intra-City HFC Bus Fleet

The relative HFC Engine and Battery sizing for the Intra-City short-haul 13-meter buses took into account the following considerations: i) frequent stops, ii) rapid acceleration and deceleration, iii) much lower average speeds, iv) fully loaded buses at peak hours, v) operating in Kerala's year-round hot weather, vi) and Kochi roads. Compared to Diesel, BEV and HFC ZEVs consume very little power during vehicle idling time and stops. They additionally capture [15-20] % energy from regenerative braking, improving fuel consumption economics, and bridging the gap between the current high cost of Hydrogen with incumbent Diesel.

Similar to Scenario B, the report focuses on HRI capacity provisioning for an assumed initial fleet size of 10 HFC buses. Table 30 summarizes the four Hydrogen Production options.

*The P4 production pathway is the cheapest source of Hydrogen at Rs- 157.00/ Kg. This is cheaper compared to Scenario B's P4 route. This is from the higher HRI capacity utilization of Scenario C's **91.5%** compared to Scenario B's **80%**.*

Table 30- SCENARIO C: HRI Capacity Provisioning for Phase I.

	DEMAND		GENERATION				HRS			TRANSPORTATION			PROJECT	
Hydrogen Production Pathways	Hydrogen Generation Demand (Kg-H2/Day)	Hydrogen Consumption Demand (Kg-H2/day)	Electrolyser Capacity (kW)	CAPEX (Cr.Rs.)	OPEX (Cr.Rs./Year)	LCOH (Rs/Kg-H2)	CAPEX (Cr.Rs.)	OPEX (Cr.Rs/Year)	LCOH (Rs/Kg-H2)	CAPEX (Cr.Rs.)	OPEX (Cr.Rs./Year)	LCOH (Rs/Kg-H2)	Project LCOH (Rs/Kg-H2)	Total Project CAPEX (Cr. Rs.)
P1	400	366	1,579	9	4	307	9	1	144	-	-	0	469	18
P2	400	366	1,579	9	3	273	9	1	144	-	-	0	435	18
P3	400	366	-	18	2	186	9	1	144	-	0.06	5	370	26
P4	400	366	-	2	0	29	9	1	144	-	-	0	157	10

5.4.4 Summary and Recommendations

Architecting a new energy transition strategy requires both demand and supply vectors to be synchronized. Especially at its nascent stage to help its adoption. The strategy of developing clean technology infrastructure projects with demand and supply tightly coupled should result in its least total cost of ownership (TCO). However, this also depends on the type of infrastructure being developed. For example, bridges or a new highway isn't built to meet current demand, but to meet forecasted capacity over the lifetime of the capital infrastructure. In the case of BEV charging or HRI capacity provisioning, it would be ideal to build supply infrastructure for future projected growth. However, given the uncertainty in how the ZEV market would shape up, infrastructure developers will and rightfully shy away from investing in building excess capacity. This leads to the classic chicken vs egg first quagmire.

Table 31- Apportion of levelized cost of Hydrogen by HRI sub-systems

SCENARIO A	GENERATION	PACKAGING & TRANSPORTATION	DISPENSING (HRS)
100% Green H2	62.0%	24.4%	13.6%
26% Green H2 + Grid	58.7%	26.5%	14.8%
100% BioCNG – H2	44.6%	29.2%	26.1%
Grey + Green H2	53.2%	24.3%	22.5%

This report prioritizes project (fleet size) specific Hydrogen demand capacity to design and provision HRI capacity. This benefits the Hydrogen production cost model to maximize capacity utilization of the HRI, upwards of 95%, factoring in maintenance downtime, repairs and replacements. Table 26, 29 and 30 shows the breakdown of the levelized cost of hydrogen at the pump into three sub-categories of Hydrogen Generation, Hydrogen Packaging and transportation and Hydrogen Dispensing LCOH's for the three scenarios respectively. The table below for SCENARIO A shows a [50 – 60] % of the cost attributable to generation, [24 – 30] % to packaging and transportation and [13 – 22] % to Dispensing.

The design philosophy of using modular on-site Hydrogen generation combined with dispensing HRI with minimal need for transportation was prioritized in all three scenarios and the four production pathways (P1-P4). The only fuel transportation

Table 32-Summary of HRI designs by SCENARIOs

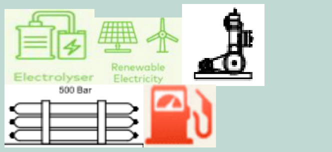
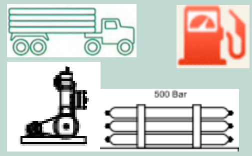
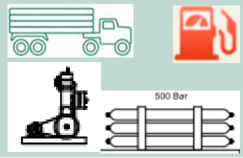
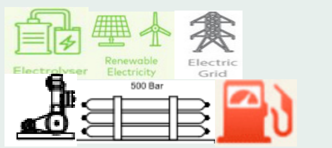
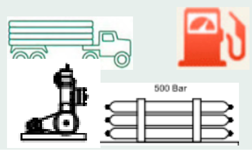
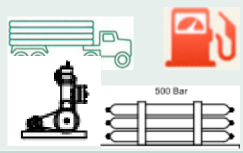
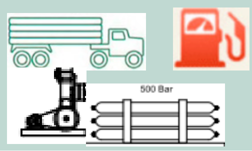
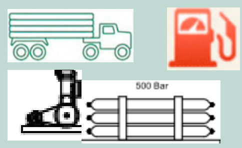
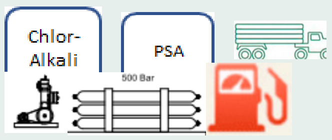
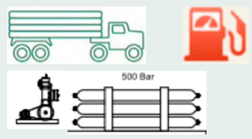
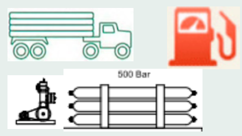
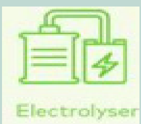
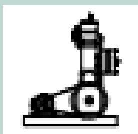
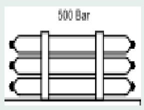
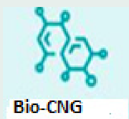
H2 Production Pathways	SCENARIO A, B, C Kochi Generation + Dispensing Hub	SCENARIO A (Thrissur) Dispensing Hub	SCENARIO A (Angamaly) Dispensing Hub	SCENARIO B/ C
P1				No Additional Hubs
P2				No Additional Hubs
P3				No Additional Hubs
P4	Chlor-Alkali PSA 			No Additional Hubs

Table 33- Legend of Hydrogen Generation, Packaging and Transportation Sub Systems

	Onsite Modular Electrolyser Generation		Compressors (20 to 200 bar) and (200 – 500 bar)		Natural Gas Feedstock	Chlor-Alkali	H2 from Chlor-Alkali Electrolysis
	Captive Solar		Onsite Modular Steam Methane Reformer Generation (SMR)		Onsite above / below ground 500 Bar Storage	PSA	Pressure Swing Adsorbers
	Grid Connected Power		BioCNG Feedstock		BioCNG / H2 tube trailer transport at 200 Bar		

cost used in the models was for production pathway P3 for all three scenarios, the cost of transporting Bio-CNG via trucks to the on-site SMR H2 generation units. For both intra-city routes (Scenarios B & C), a central overnight on-site generation and refueling hub (with no fuel transport) shows a [45 – 65] % for generation and [55 – 35] % for dispensing HRS costs.

Table 32 and Table 33 summarizes the sub-systems of the HRI's required for the four H2 production pathways, P1 – P4, and the composition of HRI at the three hub locations (Kochi, Thrissur and Angamaly), for the three route / HFC bus fleet categories (Scenario A – C).

In summary, the P4 pathway of sourcing Hydrogen from the TCC Chlor-Alkali plant is recommended for supplying H2 to the two intra-city HFC bus fleet Phase I Scenarios B and C. Increasing the renewable energy mix of the power supplied to TCC from KSEB to 100% or procuring RECs should be explored to green the H2 supply. Subsequent phases of HRI development for Scenarios B & C should consider 100% electrolytic Hydrogen generation, with the P4 route supplying H2 as back-up to enable a resilient HRI.

The P2 or P3 production pathways should be explored for Scenario A's fleet of 50 inter-city long haul HFC buses by building a central generation hub at Kochi via SMR of natural gas. Switching to bio-CNG as a fuel for future phases or adding a Carbon Capture and sequestration (CCS) system would ensure making the Hydrogen green or blue respectively.

Once the costs of electrolysers and renewable energy drops to levels needed to generate green Hydrogen competitively, the Kerala Hydrogen Mobility program should consider electrolytic Hydrogen for all subsequent expansion phases.

6

HYDROGEN FUEL CELL ELECTRIC VEHICLE (HFCEV) PUBLIC TRANSIT GLOBAL PROJECTS

In this section, we aim to understand different types of risks associated with operating and maintaining a fleet for HFCEV buses by public transit agencies. The scope is restricted to understanding how transit agencies are evolving the design of Hydrogen sourcing, generation, storage and dispensing infrastructures to mitigate various operational and economic risks. All of these programs started with a small fleet of 1 - 3 buses, a central overnight HRI hub, which scaled over time to larger fleet sizes, expanded HRI hub capacities and additional hub locations.

Some key Hydrogen Fuel Cell transit bus initiatives from different parts of the world are reviewed in this section. This review is based on primary data collection from meetings with HFC transit bus operators and secondary data from publicly available reports.

6.1. SUNLINE TRANSIT AGENCY, CA

Established in July 1977, Sunline Transit Agency serves the Coachella valley and Riverside downtown in Riverside County, CA, USA. As part of their ‘clean fleet’, aimed at transitioning to zero emissions, the agency currently operates 17 HFC buses. The agency is working to convert all of its fleet to a mix of electric, CNG and HFC buses and plans to operate 60 HFC buses by 2035. A HFC bus operated by the agency is shown in Figure 20 below.

Figure. 20- HFC bus operated by SunLine Transit Agency (Source: SunLine Transit Agency)

The area covered by HFC bus operations is about 1100 sq. miles with *67 miles being the longest one-way route length*. Nine inter-city routes with most stoppages in rural and peri-urban areas are served by the HFC bus fleet. An HFC bus, on average, travels a distance of 280 miles in a day, with a typical loading profile of 40-60 passengers per trip. The HFC bus fleet of 17 buses operated by the agency is comprised of two models, details of which are given in **Table 34**.

The agency was one of the first to own, install, and operate a Hydrogen Refueling Station (HRS) in the U.S. in 2006. Hydrogen is generated on-site by electrolysis and has sufficient capacity to match the requirement of 400 Kg-H2/Day. Refueling at the central hub is done at 350 bar and usually overnight to keep the fleet available for operation the next morning. The HFC buses operate from morning 0500 to 2300 hrs. with an average speed of 45 miles/hr.

Table 34- Specifications of HFC bus variants operated by SunLine Transit Agency (Source: SunLine Transit Agency)

SPECIFICATION	MODEL-1	MODEL-2
Name	Eldorado National	New Flyer
Fleet size	11	05
Domination	Fuel cell	Battery
Length	40'	40'
H_2 storage capacity	50kg at 5000psi	37kg at 5000spi
HFC Engine power	85kW	65kW
Battery power	120kW	100kW

The agency emphasized the importance of having a Hydrogen supply infrastructure resiliency design and arrangement planned. Transit operators in the US are penalized severely for downtime in operations that disrupt services. Transit agencies in the US don't have alternate ZEV or LEV (Low Emission Vehicle) excess buffer capacity to meet such disruptions. Due to these constraints, provisioning for excess HRI capacity, either on-site or through arrangements with outside Hydrogen vendors are strategies used for developing resiliency.

The Sunline transit agency has a contractual arrangement with PraxAir, an air products company, to supply Hydrogen based on pre-determined SLAs (service level agreements). PraxAir needs a 72-hour notice to deliver Hydrogen at a cost several times higher per Kg-H2 compared to what SunLine can generate on-site.

SunLine is building an additional Hydrogen dispensing system, 60 miles from its current HRS location at the other end of the valley, that uses a direct liquid Hydrogen refueling technology, that's funded by the state of CA.

Key Milestones of the HFC program

- Motivation to go for HFC instead of BEV for SunLine Transit Agency- Good operability in extreme temperatures of Coachella valley, along with lower noise and maintenance costs compared to BEV
- 1992: Decision to transform to 100% clean fleet, started with few CNG buses. First step towards clean energy
- 1994: 100% CNG fleet
- 2000: First H2 fueling station powered by steam (SMR) installed
- 2004: First hybrid (20% H2 + 80% CNG) bus introduced with a range of 220-250 miles

- 2006: Owned H2 generation and dispensing station. First transit agency to do so
- 2019: 900 kg/H2-Day Electrolyser station commenced operations, capable of refueling 32 HFC buses
- Played major role in reducing HFC technology costs. E.g., In 2000 a HFC bus would cost $2.0M and same costs $1.15M in 2021
- Max. range 350 miles
- Plans to refuel HFC trucks on inter-state highway

More details can be found on https://www.sunline.org/

6.2. AC Transit Agency

AC Transit, founded in 1960 serves the western portions of Alameda and Contra Costa counties in the East Bay of the San Francisco Bay Area, CA, US. Its headquarters is situated in Oakland, CA, US and operates on more than 140 routes. The agency ventured into HFC buses in the early 2000s as part of their 'Zero Emissions Bus' initiative. This was mandated by the state for transit operators with more than 200 buses and was aimed at the gradual transition of the fleet from diesel to zero-emission bus fleet – CNG, electric, and HFC.

AC transit began operating a 30ft HFC bus as the first step in 2002 with a HRS. In 2006, three more HFC buses were introduced with a HRS. And between 2010 and 2019, the agency further added 13 more HFC buses and three HRS. The strength of HFC buses in its current fleet is 19, which provide 3 types of services – a) intracity b) CBD to suburbs, and c) school service. A HFC bus used by the agency is shown in Figure 21 below.

Figure 21- HFC bus operated by AC Transit (Source: AC Transit)

There are two variants of HFC buses that the agency operates, and their specifications are listed in Table 35 The typical load profile on these buses is 42 seated + 20 standing passengers, the total service area is around 344 Sq. Miles. The agency currently operates two Hydrogen Refueling Systems with capacities of 360 Kg-H2/ Day and 1750 Kg-H2 / 10 Hours respectively. *Refueling is done at 380 bar and each kg of H2 costs $7.80 to the agency.*

Table 35- Specifications of HFC bus fleet operated by AC Transit (Source: AC Transit)

SPECIFICATION	MODEL-1	MODEL-2
Name	New flyer	Van Hool
Fleet size	10	09
Dominant Energy Source	Battery	Battery
Length	40 ft	40ft
H_2 storage capacity	38 kg	40 kg
Energy efficiency	8.5 miles/kg	4.5 miles/kg

The agency initially employed ionic compression, however, due to high refueling times and high costs incurred, it shifted to cryogenic pumping – which takes only 6-8 minutes per bus to refill. It is important to note from the company's experience the high costs involved in – a) maintenance of HRS ~ $180,000 per year, and b) civil work involved in installing HRS. Another challenge the agency faced was the operation of HRS during prolonged (more than a day) power cuts, which require sufficient emergency battery capacity as a backup.

Key Milestones:

- State legislation mandated transit operators with >200 buses to test and adopt alternative fuel technology, thus AC transit ventured into ZEBs
- 2002- first H2 fueling facility was installed and testing with a single 30ft HFC began
- 2006- pilot began with 03 first-generation HFC buses and single fueling station
- 2010- 13 second-generation HFC buses were added to the fleet and second fueling station was established
- 2013- agency added one solid oxide stationary fuel cell
- 2014- on-site H2 fueling station was installed and commenced operations
- 2017- agency surpassed 25000 operating hours on HFC buses, a milestone set by US dept. of Energy

More details can be found on https://www.actransit.org/

6.3. HFC Buses in Groningen, the Netherlands

Qbuzz is a public transit operator having major services in South Holland, Utrecht, Drenthe, and Groningen, in the Netherlands. Qbuzz, in July 2019 initiated the construction of a Hydrogen fueling station and the purchase of 20 HFC buses. This decision was preceded by a Qbuzz pilot which started with two HFC buses operating on a regular timetable starting the December of 2017. The contract for the construction of the Hydrogen re-fueling station and supply of Hydrogen was awarded to Shell Netherlands, while that for HFC buses to Van Hool. Operations commenced from December 2020 with a HFC bus range of 350-400 Km/ Fill as per the manufacturers. Specifications of the VanHool HFC buses are in Table 36.

Figure 23- HFC bus operated by Qbuzz (Source: Qbuzz)

Table 36- Specifications of the Qbuzz fleet of HFC buses by VanHool

Length	12.155 m
Height	3.420 m
Width	2.550 m
Seats	36 seats (~20 standees)
Engine	Ballard systems
Fuel cell type	Proton Exchange Membrane (PEM)

The funding for the 20 HFC buses and the Hydrogen fueling station is provided by Ministry of Infrastructure and Environment of the European Union. More details can be found here https://www.qbuzz.nl/english//.

Details of similar HFC bus initiatives from around the globe are summarized in **Table 37.**

Table 37- Summary of Global HFC Bus Projects

Project / Initiative	H_2 supply infrastructure	HFC bus fleet	Operations	Outcome/Results
4.Clean Hydrogen in European Cities [2010-16] https://fuelcellbuses.eu/sites/default/files/documents/CHIC_publication_final_0.pdf	On-site production from renewable sources (Solar, Wind) + Tube Trailer delivery of Liquid/ Gaseous H_2	London-8, Aargau-5, Milan-3, Bolzano-5 Fuel cell system power [kW]: 75 to 150 Passenger capacity: 49 to 101 Range: 350+km	Urban & Suburban routes Refueling time: less than 10 mins Efficiency: 9kg H_2 per 100km	Bolzano, Aargau- ceased Ops, to observe developments in HFC & take call London- fleet expansion Milan- Ops continue 6800 Tonnes of CO_2 saved
5.BC Transit [2010-12] https://www.nrel.gov/docs/fy14osti/60603.pdf	Liquid H_2 storage Gaseous dispensing	Whistler, Canada-20 42 ft long bus Li-phosphate battery	Urban routes H_2 station capacity: 800kg/day Efficiency: 15.48kg H_2 per 100km Avg monthly distance per bus: 4000 km	Demonstration successful; continued till March, 2014

Project / Initiative	H_2 supply infrastructure	HFC bus fleet	Operations	Outcome/Results
6.OC Transit Agency https://www.octa.net/Bus/Hydrogen-Fuel-Cell-Electric-Bus/Overview/	Liquid H_2 storage Capacity: 18000 gallons	Orange County, CA, USA – 10 40 ft long buses Li-ion battery [100 kWh] Storage capacity: 37.5kg at 5000 psi	Urban routes Avg. speed: 17 mph	Active operations since 2020
7.TFL & 3E Motion Hydrogen Mobility [since 2011] https://static1.squarespace.com/static/5a668f1080bd5e34d18a7e76/t/5c9401cd71c10b2160f88c2f/1553203697824/Hydrogen+Fuel+-Cell+Buses.pdf	Trailer delivery of gaseous H_2	London: 11 Buses 39 Ft long HFC buses Fuel cell system power [kW]: 75, 83 Passenger capacity: 34 seats	Urban routes: 17 hours/day, all 7 days Refueling time: 10 mins	Ops continue
8.City of Burbank demonstration project [2010-11] https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_Report_No._0014.pdf	On-site production using natural gas + Trailer delivery (backup)	Burbank-1;35 ft long bus Fuel cell system power [kW]: 32 Li-titanate batteries	Refueling station-1;	Service restarted in 2012
9.CT Transit demonstration project [2007-09] https://www.transit.dot.gov/sites/fta.dot.gov/files/FTA_Report_No._0014.pdf	Liquid H_2 storage Gaseous dispensing	Hartford, CT, US -1; 40 ft long bus Fuel cell system power [kW]: 120 Sodium Nickel Chloride batteries Passenger capacity: 30 seats	Urban route-1 (shuttle) Refueling station-1	Demonstration successful, Ops continue till date with FTA funding Plans to expand to other routes

6.4 Comparison of SunLine Transit, AC Transit, Kerala HFC Mobility Programs

A. SunLine Transit Agency
Service area: 1100 Sq. Miles
Routes: 09 (Inter-city)
Passengers per trip: 40 to 60
Average distance travelled by HFC bus per day: 280 miles
Route map is shown in Figure 24.

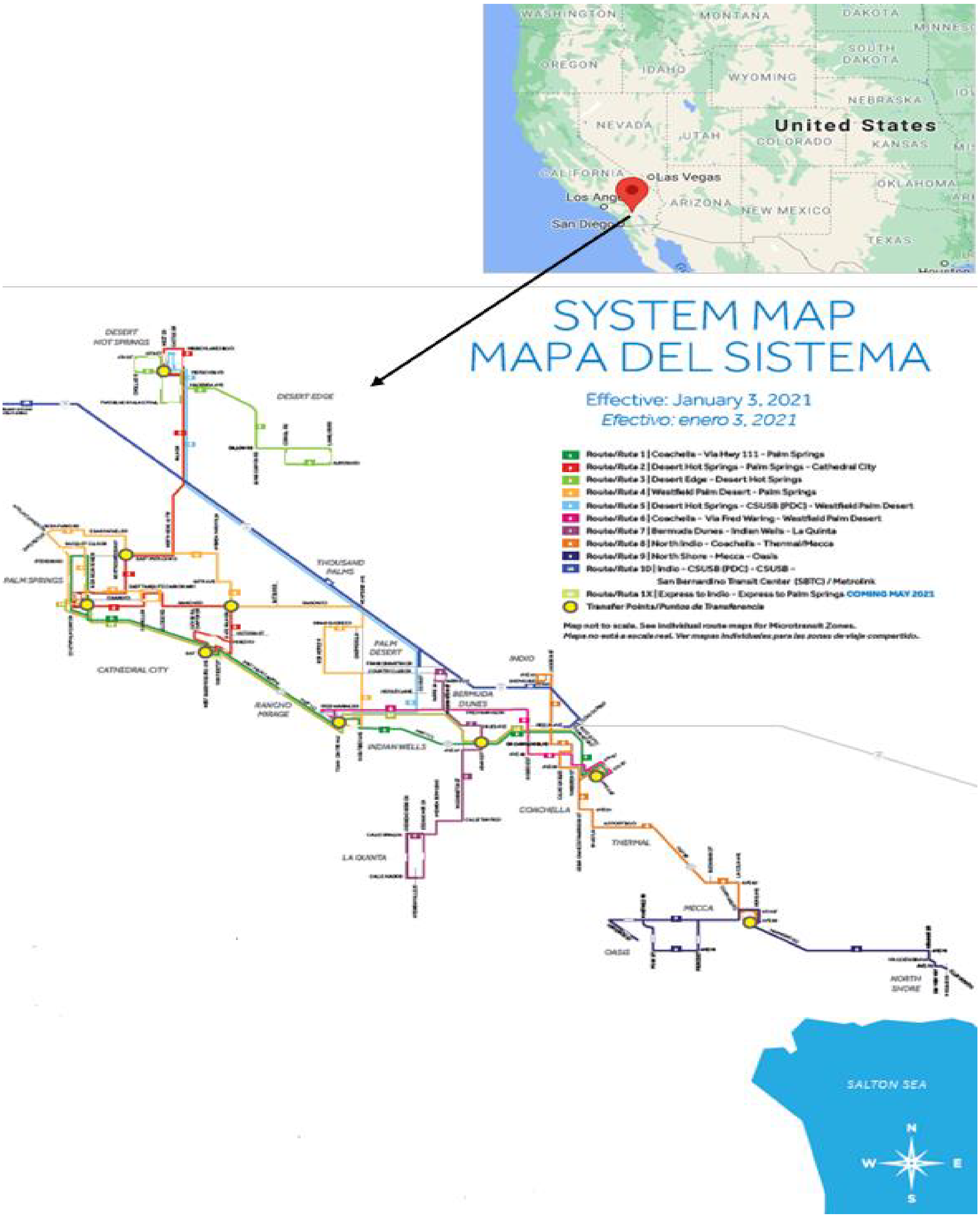


Figure 24- Route map of HFC bus operations by SunLine Transit (Source: SunLine Transit Agency)

B. AC Transit

Service area: **344** Sq. Miles

Routes: **Intra-city, School service**

Passengers per trip (peak hour): **42** (seated) + **20** (standees)

Route map is shown in **Figure 25** below

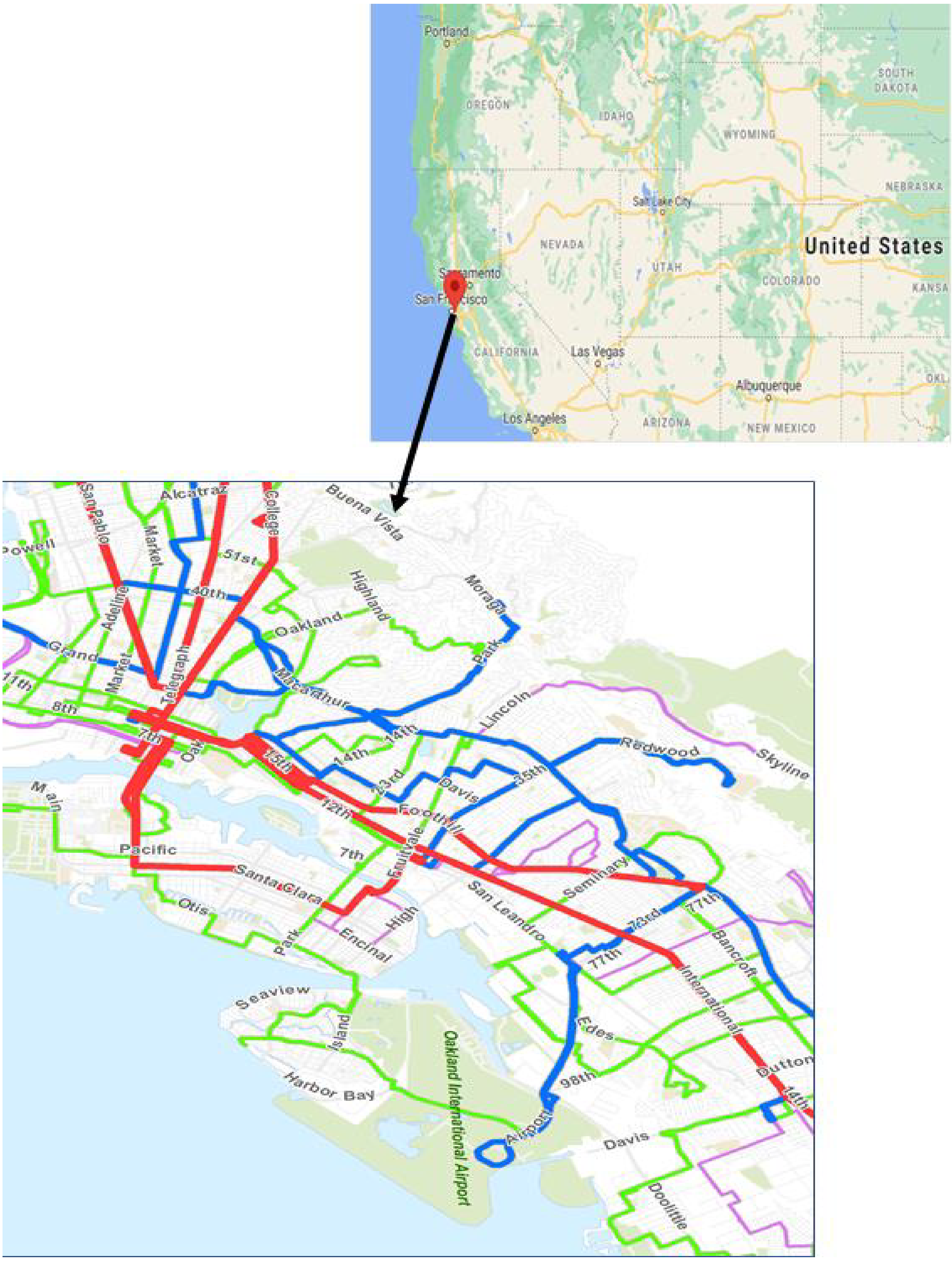


Figure. 25- Route map of HFC bus operations by AC Transit (Source: AC Transit)

C. Kerala H2 Mobility Program

The Kerala H2 Mobility Program started in June 2019 by signing and MoU with Spotimyze Energy to help implement a HFCEV mobility pilot. The intended outcome was to enable the state to understand the i) opportunities, ii) risks, iii) gaps in skills needed to support the operation of HFCEVs, iv) safety related regulations, procedures and stakeholders,

v) commercial and economic viability timeline of private and public HFCEV adoption, vi) Hydrogen generation, sourcing and refueling strategies and vii) GHG reduction potential. To support this, a pilot consisting of two inter-city HFC buses travelling between Thiruvananthapuram and Kochi, a distance of 280 Kms, and two Hydrogen dispensing stations at these two destinations with Hydrogen supply arrangements with BPCL or elsewhere was under consideration.

Kerala became the *first state in India to include HFCEV mobility as part of its ZEV transition strategy*, though a roadmap with targets across transportation sectors and vehicle categories is yet to be defined.

I. ZEV targets should prioritize, i) reaching decarbonization levels in line with India's Nationally Determined Contribution (NDC) commitment to the Paris Climate Agreement of 33% - 35% of CO2 emissions reductions by 2030; ii) air pollution reduction to meet ambient air quality standards set by India's pollution control board, iii) tackle congestion and noise pollution, iv) close mobility inequity and environmental injustice gaps across communities.

II. ZEV programs take shape by defining regions, zones or corridors inside a city (or cities) in a state or a cluster of adjacent municipalities, towns and cities, that would create a boundary within which to pilot low to zero carbon mobility technologies. Defining these zones helps to develop multi-stakeholder integrated ZEV transition programs and build key social and civic engagement for change management needed for adoption.

III. The third dimension is to architect the new energy transition through infrastructure (HRI) design, technology and capacity that provides Hydrogen at costs for the TCO of HFC ZEV fleet deployment to be at par with incumbent Diesel, CNG and BEV fleets.

IV. Understanding investments needed to fund the gaps to support and scale the transition through market traction and state, central government policies.

In consideration of the above general criteria, three ZEV zones, each that would require a specific HFCEV bus variant that would be representative of the dominant bus category to decarbonize within that zone, has been proposed for consideration in this report.

It is important to note that this report did not start with the delineation of the ZEV zones first, rather the routes provided by the Kerala STU operating the dominant bus variants and managing related transit services.

The three proposed initiatives for consideration under Kerala's H2 Mobility program's key metrics and scope are generalized below. It is not the intent for all three HFC mobility initiatives to be simultaneously considered for deployment. The techno-commercial feasibility analysis has been covered in earlier sections. (Scenarios A, B &C correspond to the three ZEV zones). The intent of this section is to connect these scenarios to ZEV zones and corridors to expand upon during program design, which is beyond the scope of this report.

ZEV Zone I: Thiruvanathapuram to Palakkad corridor interconnecting 42 towns

Key Metrics of the proposed Inter-City Long-Haul HFC Bus Program (SCENARIO A)

No. of routes: **16** (inter-city)

No. of buses: **50** (inter-city)

Service area: **15,005** Sq. Miles (Kerala state)

No. of Cities/Towns covered: 42 **(Figure. 26)**

Average route length: **255** Km (Max Route Length: **394**)

Route map: a detailed maps for each of the **16** inter-city routes are presented in **Appendix-A2**, while a schematic network diagram of the same is given in **Figure 26** below.

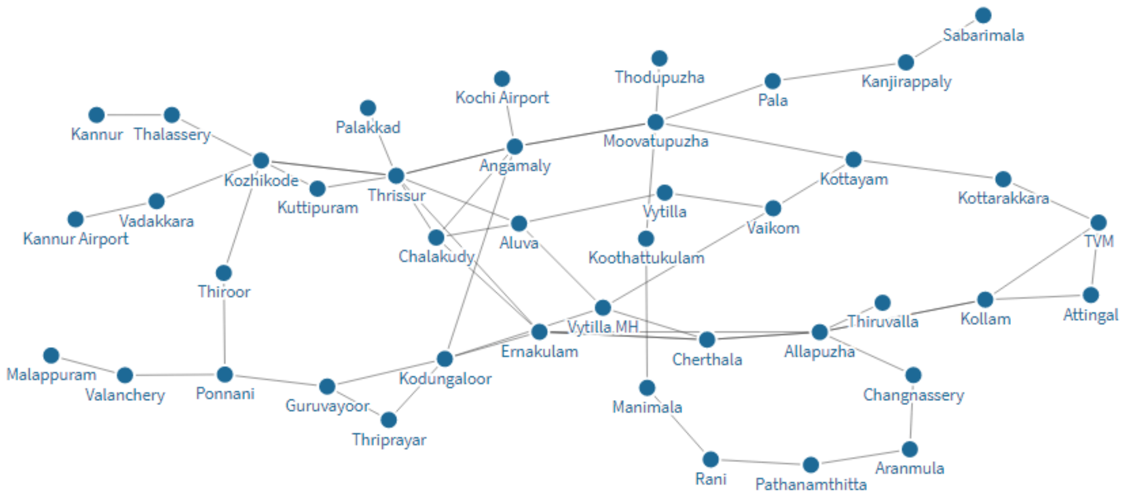


Figure 26 - Schematic network diagram of 16 inter-city routes in Kerala, India

ZEV Zone II: Kochi Metro Rail – HFC Feeder Routes

Key Metrics of the proposed Intra-City feeder HFC Bus Fleet (SCENARIO B)

No. of routes: **8** (intra-city) – this is the Phase I of Scenario B

No. of buses: **10** (intra-city)

Service area: **~ 500** Sq. Kms (Kochi City) = 25 kms [between Aluva <-> Kadavanthara the two OD stops of the Metro] x [10 Kms feeder coverage - east] x [10 Kms feeder coverage - west]

No. of Cities/Towns covered: 20+ **(Figure. 27)**

Average route length: **10** Km @ 30 minute / trip, two trips / hour, 12 hrs/day

Route map: a detailed map for each of the **8** intra-city routes are presented in **Appendix-A1**, while a schematic network diagram of the same is given in **Figure 27** below.

ZEV Zone III: Greater Kochi Urban Center – KURTC intra-city HFC Fleet

Key Metrics of the proposed Intra-City feeder HFC Bus Fleet (SCENARIO C)

No. of routes: **14** (intra-city) – this is the Phase I of Scenario C

No. of buses: **10** (intra-city)

Service area: **~ 650** Sq. Kms (Kochi City)

No. of Cities/Towns covered: 20+ **(Figure.19)**

Average route length: **15** Km

Route map: Figure 19

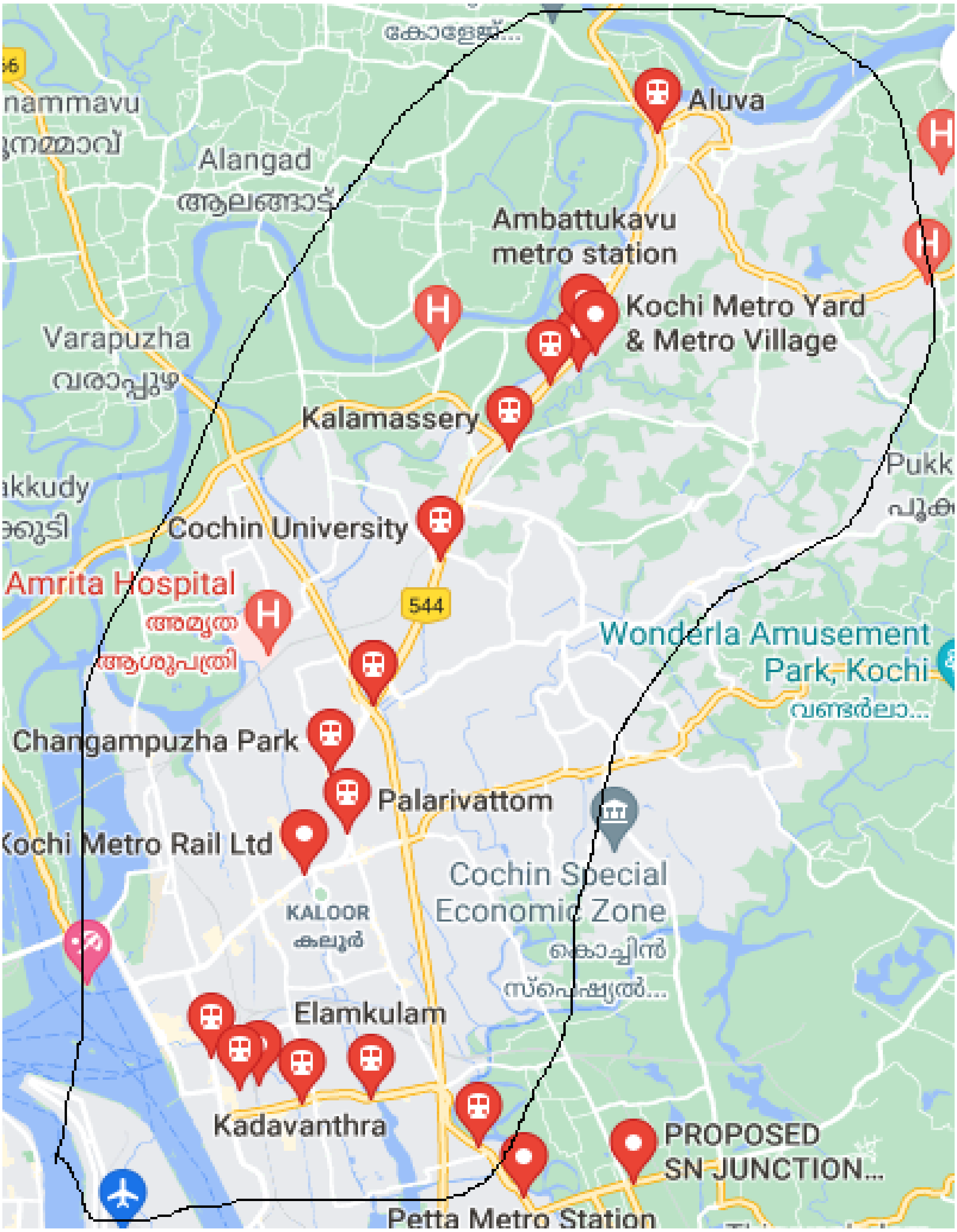


Figure 27- Kochi Metro Rail corridor and feeder service area coverage – SCENARIO B

7

GHG EMISSIONS LIFE CYCLE ANALYSIS (LCA) OF BUSES POWERED BY ALTERNATE ENERGY SOURCES

Diesel has been the conventional source of energy for powering heavy-duty vehicles including buses since the 1980s[1]. High torque[2], [3], [4], [5]&[6]production and higher efficiency [7] of diesel engines relative to gasoline engines make them ideal for heavy-duty jobs. The Internal Combustion (IC) engine in diesel buses combust air-diesel mixture and convert chemical energy into mechanical energy for powering the trucks. This combustion process releases emissions into the atmosphere causing adverse health as well as environmental impact [8]. The transportation sector alone contributes to 14% of total global GHGs emissions, annually [9]. With the increasing awareness of the impacts of emissions on health and the environment, efforts have been done by agencies across the world to reduce the emissions from transportation. There are emission norms established by countries such as Bharat Stage VI [10]&[11], China [12]&[13] and Euro VI [14]&[15] to name a few. However, enforcement of norms alone will not be sufficient to mitigate the Climate Changes as well as the depletion of limited sources of fossil fuels. Hence, it is inevitable to explore other sources of energy to power the mobility of people. Additionally, for a country like India which imports most of its crude oil demands from other countries (87.6% in the year 2020 [16]), shifting to alternative sources of energy will empower the country in achieving self-reliance.

The popular alternative sources of energy in mobility include Electric Vehicles (EVs) and Compressed Natural Gas (CNG) powered vehicles. Electric Vehicle technology is the most promising future for cleaner mobility. EVs are propelled by the traction motor which is driven by the electricity provided by an onboard power supplier. Battery Electric Vehicles (BEVs) and Hydrogen Fuel Cell Electric Vehicles (FCEVs) are the most propitious EV technologies. As the name suggests, in BETs the electricity is stored in rechargeable batteries, while electricity is produced in a Fuel Cell by oxidation-reduction reaction of Hydrogen with oxygen in FCEVs.

Since there is no combustion of fuel in EVs, there are no harmful emissions during the operation of the vehicles. Hence, they are deemed as a cleaner alternative for the future of mobility. Emissions from FCEVs depend on the sources and production method of hydrogen and also on the compression methods deployed. Also, generally, the FCEVs have a hybrid configuration of onboard storage of energy –Hydrogen stored in its fuel tanks, converted by Fuel Cells, and a rechargeable battery[17], [18], &[19]. BEVs have rechargeable batteries as the only onboard energy storage [20], &[21]. The production of both the rechargeable batteries and fuel cells are energy and emission-intensive processes. Since the BEVs are plugged into charging sockets powered by the electric grid for recharging the battery pack, the cleanliness of the energy will depend on the sources of electricity. Therefore, a need to compare the emissions from the different sources and mix of energy (to power mobility) arises to make informed decisions.

Because there are differences in emissions in the stages of usages of the energy, a comprehensive analysis of emissions is required to be able to compare the environmental friendliness of the vehicles powered by different energy sources, fairly. Life Cycle Analysis (LCA) is the tool that will facilitate that. LCA is discussed in detail in the subsequent sections.

7.1 Life Cycle Analysis

LCA is a tool to analyze the impact a product has on the environment over its lifetime. According to ISO standards 14040 and 14044, LCA for a product can be accomplished with the following phases:

- Definition of Goal and Scope
- Inventory Analysis.
- Impact Assessment.
- Interpretation.

The following sub-sections contain the details of the aforementioned phases of the LCA. The analysis for each vehicle technology has two components; vehicle cycle, and fuel cycle. The vehicle cycle includes various stages of life of a vehicle, right from obtaining raw materials to the end of life (EOL) of the vehicles. Vehicle production stages are similar except for the differences in parts and hence differences in materials used. Similarly, the fuel cycle includes all the stages of an energy source, from production to the usage phases. Since there are variations in the life cycle of all the fuel types, the boundary of the study system has been demarcated separately.

7.1.1 Definition of Goal and Scope:

The goal of LCA in this report is to estimate, assess, and compare the environmental impact of operating diesel buses, CNG buses, BEBs, and FCEBs for the state of Kerala. Since EOL and recycling of vehicles in India is an unorganized sector, emission data for these phases are unavailable. Hence, it has been omitted in the study.

7.1.2 Vehicle Cycle:

As stated earlier, the vehicle cycle will include all the stages of life of a vehicle along with associated energy consumption and GHG emissions. For simplifying the LCA, the vehicle cycle can be split into the following stages; raw materials for vehicle production, vehicle assembly, vehicle distribution, vehicle maintenance, and end-of-life (EOL).

7.1.3 Fuel cycle:

Diesel, electric, CNG, and hydrogen have different production, distribution, storage as well as utilization pathways. Hence, the stages included in the fuel cycle will be discussed separately in the following sections. The stages of the life cycle of diesel can be split into the following stages; feedstock production, feedstock transport, fuel production, fuel distribution, and fuel use. The following figures highlight the system boundaries of the vehicle cycles and fuel cycles. Since the tail-pipe emissions from BEBs and FCEBs are zero, the GHG emissions for operations in the case of these buses refer to the emissions from upstream which is required for operating the bus per km.

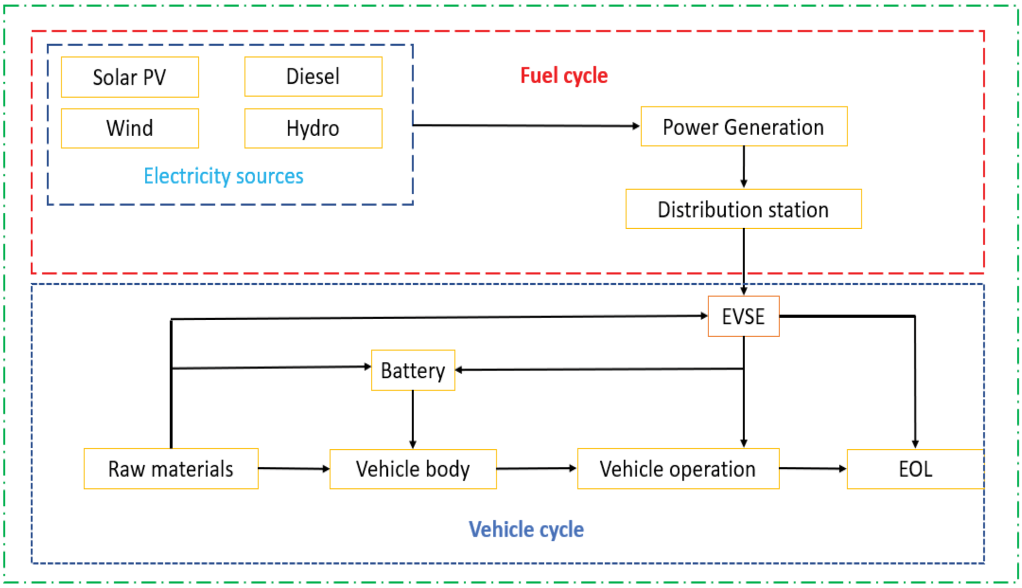


Figure 28- Electricity production pathways and BEB cycle

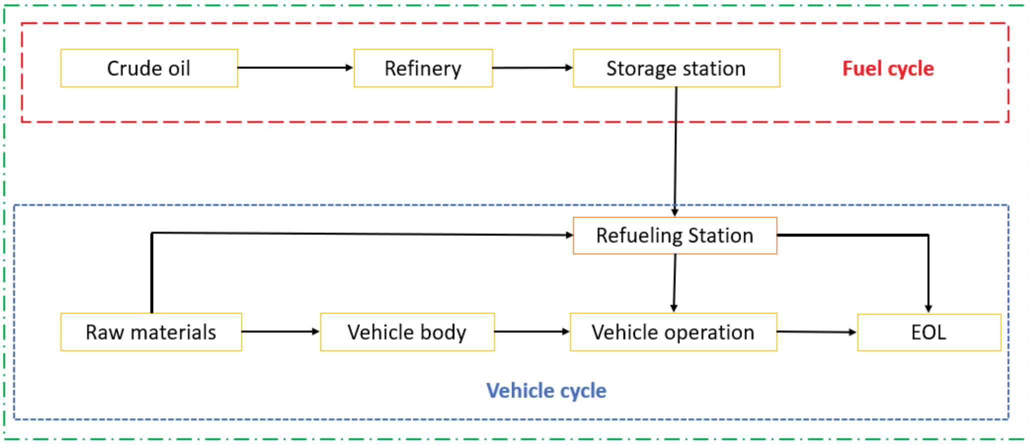


Figure 29- Diesel and CNG Buses system boundary

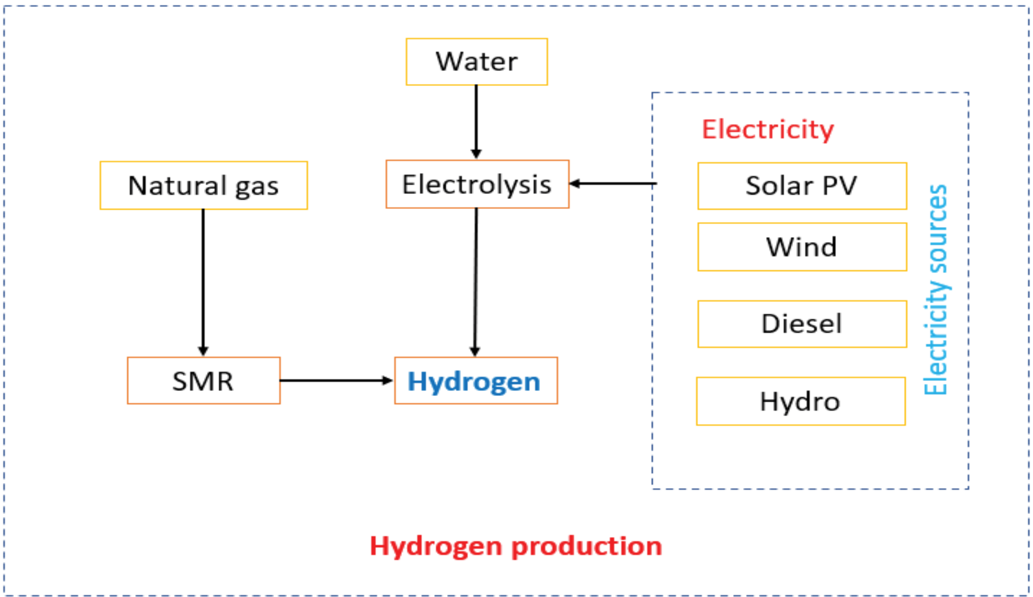


Figure 30- H2 production pathways

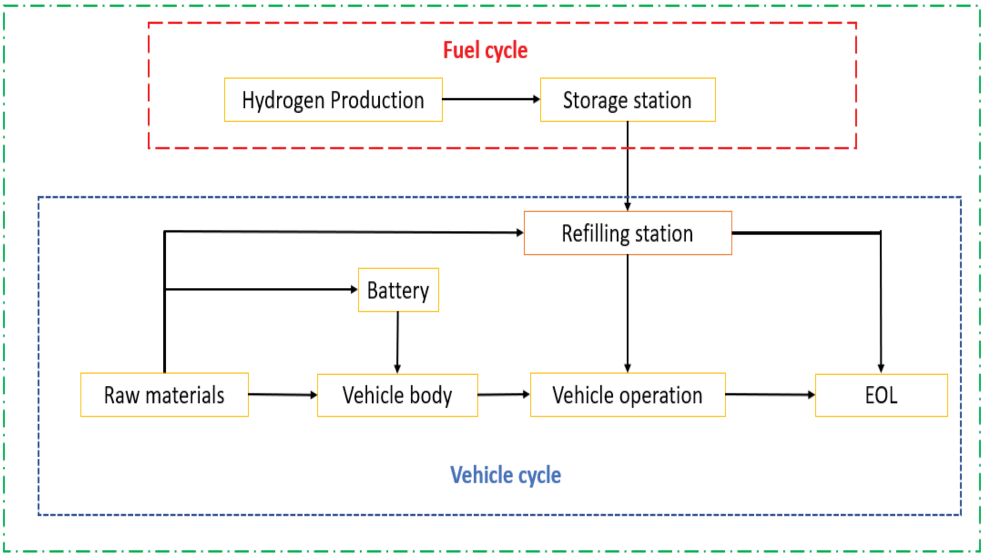


Figure 31- Fuel Cell Electric Bus Cycle

7.2 GHG (Green House Gases) Inventory analysis:

The impact of emissions in the LCA is expressed in terms of Global Warming Potential (GWP) in 100 years of time horizon. The unit used for expressing the GWP is CO2eq. Therefore, the functional unit chosen for is expressing the impact is kg CO2eq km-1.

Before listing the inventories, the underlying assumptions in the study are as below:

1. IC engines of diesel and CNG buses, batteries, and the traction motor BEBs and HFC engine of HFCEBs will last throughout the vehicle's lifetime and will need no replacing.
2. The weight of the bodies of all buses is the same as the dry weight of the diesel buses. BEBs and FCEBs will have the additional weight of the onboard battery packs.
3. Emissions in the manufacturing of vehicle body and battery packs are functions of the weight of the bus and energy storage capacity of the battery pack, respectively.
4. The transmission of electricity from captive sources is assumed to be lossless as the loss due to long-distance transmission and power theft will not exist for captive sources.

The unit emissions in the manufacturing of vehicle bodies are 8 kg CO2eq kg-1[22] and battery production is 258 kg CO2eq kWh-1[23], respectively. The unit emission in the manufacturing of Electric Vehicle Supply Equipment (EVSE) is 250 kg CO2eq [23]. Emissions in manufacturing of Fuel Cell engine is taken to be 61 kg C02eq[24]. Although the emission may be different for engines of different capacities, due to the unavailability of data, it has been assumed to be the same. The empty weight of 9 m buses and 13 m buses are taken as 4 tonnes and 5.52 tonne [21], respectively. The unit weight of the onboard battery is 6.4 kg/kWh [25]. The energy efficiency of the battery in terms of charging/discharging is 88% [26]. The total weight of maximum ridership is estimated to be 4.03 tonne for all routes (Feeder route, intracity, and intercity).

Upstream emissions in the production of electricity for Battery Electric Buses (BEBs) as well as for production of hydrogen for Fuel Cell Electric Buses (FCEBs) using electrolysis will depend on the electricity generation mix. For the state of Kerala, the generation mix is listed in table 38. The table also contains the emissions in terms of GWP from each source. The grid system suffers transmission loss of 12.47% [25], resulting in an efficiency of 87.53%.

Table 38- Electricity Generation Mixes in the power grid for the state of Kerala

Grid mix	Internal Generation				Import	
Monthly average mix	Hydro	Thermal*	Solar	Wind	CGS	LTA
for 2020-2021 [25]	28.74	0.54	0.54	0.53	36.41	32.06
Unit GHG Emissions (gCo2eq/ MJ) [26]greenhouse gas (GHG	2.40	279.00	6.20	6.20	279.00	279.00
GHG Emissions (gCo2eq/MJ)	0.69	1.51	0.03	0.03	101.60	89.45
GHG Emissions (kgCo2eq/MJ)	0.001	0.0	0.00	0.00	0.1016	0.0894

Currently, the electrical energy required for the production of hydrogen is 59 KWh for a kilogram of yield using electrolysis. The GHG emissions from the production of natural gas is 423.84 (g co2eq/l). For producing a kilogram of hydrogen from Natural Gas using Steam Methane Reformation (SMR), 9 CO_{2eq} [29] of GHG is produced with an efficiency of 75% [30]carbon dioxide, and hydrogen sulfide as impurities and, depending on use, may require further purification. The primary steps for purification include: • Feedstock purification – This process removes poisons, including sulfur (S & [31].

If the biomass used for producing hydrogen is sourced from Municipal Solid Waste (MSW), organic waste constitutes 51% [32]urbanization, and population. However, another aspect of higher economic development has resulted in increased waste generation and consumption of natural resources, and hence ecological degradation and pollution. As awareness increases of the detrimental effects of currently used waste disposal methods on the environment, accountability is needed for an effective waste management system. This paper presents the existing situation of municipal solid waste (MSW of the total weight. It is assumed that these organic wastes are composed mostly of food waste. Hence the emissions in producing Renewable Natural Gas (RNG) from anaerobic decomposition is -87 $gCO_{2eq.}$/MJ of RNG [33]due to low feedstock cost, and environmentally favorable, due to avoided emissions from conventional waste management practices. In this study, we evaluate the life cycle greenhouse gas (GHG. The calorific value of MSW is low in India [32]urbanization, and population. However, another aspect of higher economic development has resulted in increased waste generation and consumption of natural resources, and hence ecological degradation and pollution. As awareness increases of the detrimental effects of currently used waste disposal methods on the environment, accountability is needed for an effective waste management system. This paper presents the existing situation of municipal solid waste (MSW, hence emissions in producing RNG are taken as 75% of the value in the literature. The resultant emission factor used in the study is -2.74 kg $CO_{2eq.}$/kg of RNG.

Hydrogen will be produced from RNG using SMR similar to natural gas. The produced hydrogen gas, typically, has 20 bar [34] pressure which has a very low density making it very inefficient to store and transport it. Hence the hydrogen fuel is compressed for storing and transporting as well as for filling in the vehicles. It is assumed that hydrogen will be compressed to a pressure of 200 bar for transportation and distribution and 350 bar for refilling the buses. The energy needed to compress hydrogen from 20 bar to

200 bar is 9 MJ/kg and 200 bars to 350 bar is 2 MJ/kg [35]transportation, storage and transfer. The same is true for hydrogen in a “Hydrogen Economy”. Hydrogen has to be packaged by compression or liquefaction, it has to be transported by surface vehicles or pipelines, it has to be stored and transferred. Generated by electrolysis or chemistry, the fuel gas has to go through theses market procedures before it can be used by the customer, even if it is produced locally at filling stations. As there are no environmental or energetic advantages in producing hydrogen from natural gas or other hydrocarbons, we do not consider this option, although hydrogen can be chemically synthesized at relative low cost. In the past, hydrogen production and hydrogen use have been addressed by many, assuming that hydrogen gas is just another gaseous energy carrier and that it can be handled much like natural gas in today’s energy economy. With this study we present an analysis of the energy required to operate a pure hydrogen economy. High-grade electricity from renewable or nuclear sources is needed not only to generate hydrogen, but also for all other essential steps of a hydrogen economy. But because of the molecular structure of hydrogen, a hydrogen infrastructure is much more energy-intensive than a natural gas economy. In this study, the energy consumed by each stage is related to the energy content (higher heating value HHV. The combined value for both stages of compression is 11 MJ/kg which is equal to 3.06 kWh/kg, which is in the range of 2 kWh to 4 kWh/kg as provided in [36]the National Renewable Energy Laboratory commissioned an independent review of hydrogen compression, storage, and dispensing (CSD. It is assumed that all the compressors will be powered by electric motors. Hence the emissions from the compression processes are computed using the emissions from electricity sources.

Additionally, in hydrogen production from electrolysis, it is assumed that the same source of power supplied to the electrolysers will power the compressors. The SMR of NG and RNG, and the production of RNG from Biomass, it is assumed that the compressors will be powered by electricity from the grid.

The emissions from compression processes are added to the emissions from Well-to-Tank (WTT) of hydrogen fuel production and supply. The fuel efficiency of a 9-meter feeder FCEB powered by a [45 kW FCE + 45 kWh ESS] is 0.083 kg-H_2/km, 13-meter intracity FCEB powered by [90 kW FCE + 80 kWh ESS] is 0.33 kg-H_2/km, and 13-meter intercity FCEBs powered by [120 kW FCE + 80 kWh ESS 0.071 kg -H_2/km]. The fuel efficiency of BEVs for feeder route (non-ac), intra-city route, and inter-city routes are 1.25, 0.77, and 1.61 km/kWh [37], respectively.

The Well-to-Tank (WTT) GHG emissions for diesel and CNG are 18175 g CO_{2eq}/million BTU, and 11471 g CO_{2eq}/million BTU, respectively [27]heating, power generation, and transportation, among many other uses. It is produced mainly from crude oil refining and natural gas processing activities. LPG consists of light hydrocarbon compounds, predominantly propane and butane, with ratios depending on the region and feedstock. In raw form, LPG is not considered a greenhouse gas (GHG. The emission factors for diesel and CNG buses are listed in table 39 and Table 40, respectively. The emission factor values are taken from [32], in which the data were collected for intracity routes of buses. Due to the unavailability of data, the emission factors were accordingly downscaled for feeder routes as well as intracity as a function of the fuel efficiency of the respective buses. The mileage of the feeder, intracity, and intercity diesel buses are 7 km/l, 3.75 km/l, and 4.44 km/l, respectively. The mileage of the feeder, intracity, and intercity CNG buses are 4 km/l, 2.22 km/l, and 4.6 km/l, respectively.

Table 39- GHG Emission factor for diesel buses

Emissions	Intracity Buses		Feeder Buses		Intercity Buses		GWP [33], [27]
	Factor (g/km)	CO2eq (g/km)	Factor (g/km)	CO2eq (g/km)	Factor (g/km)	CO2eq (g/km)	
CO	1.42	0.0043	0.788	0.002	0.6853	0.00206	3
THC	0.04	0.0010	0.022	0.001	0.0193	0.00048	25
NOX	13.58	4.0468	7.537	2.246	6.5538	1.95304	298
CO2	781.38	0.7814	433.666	0.434	377.1008	0.37710	1
PM	0.009	0.0270	0.005	0.015	0.0043	0.01303	3000
	Total (CO2eq/km)	4.86		2.70		2.34	

Table 40- GHG Emission factor for CNG buses

Emissions	Intracity Buses		Feeder Buses		Intercity Buses		GWP [33], [27]h
	Factor (g/km)	CO2eq (kg/km)	Factor (g/km)	CO2eq (kg/km)	Factor (g/km)	CO2eq (kg/km)	
CO	3.18	0.00954	1.7036	0.0051	2.6858	0.0081	3
THC	1.455	0.036375	0.7795	0.0195	1.2289	0.0307	25
NOX	5.35	1.5943	2.8661	0.8541	4.5186	1.3465	298
CO2	729.74	0.72974	390.9321	0.3909	616.3345	0.6163	1
PM	0.0065	0.0195	0.0035	0.0104	0.0055	0.0165	3000
	Total (CO2eq/km)	2.39		1.28		2.02	

7.3 GHG Impact Assessment

The average emissions in terms of kg CO_{2eq}/km can be estimated for the diesel bus using equations 1 and 2.

$$GHG_{D,avg.} = GHG_{D,fuel,avg.} + GHG_{D,O,avg.} + (GHG_{D,M,avg.} \times P_D) \qquad (1)$$

$$= GHG_{D,fuel,avg.} + GHG_{D,O,avg.} + (\frac{GHG_{D,M.}}{VKT_D \times P_D} \times P_D) \qquad (2)$$

The average emissions in terms of kg CO2eq/km can be estimated for the CNG bus using equations 3 and 4.

$$GHG_{C,avg.} = GHG_{C,fuel,avg.} + GHG_{C,O,avg.} + (GHG_{C,M,avg.} \times P_C) \qquad (3)$$

$$= GHG_{C,fuel,avg.} + GHG_{C,O,avg.} + (\frac{GHG_{C,M}}{VKT_C \times P_C} \times P_C) \qquad (4)$$

The average emissions in terms of kg CO_{2eq}/km can be estimated for the BEBs using equations 5 and 6.

$$GHG_{E,avg.} = (GHG_{E,Elect,avg.} + GHG_{E,M,avg.}) \times P_E \qquad (5)$$

$$= \left(\frac{(\Sigma GHG_{E,Elect} \times GM)}{\eta_G \times \eta_T \times P_E} + \frac{\Sigma GHG_{E,M.}}{VKT_E \times P_E} + \frac{GHG_{E,Bat} + GHG_{E,EVSE}}{VKT_E \times P_E}\right) \times P_E \qquad (6)$$

The average emissions in terms of kg CO_{2eq}/km can be estimated for the FCEV using equations 7 and 8.

$$GHG_{H,avg.} = GHG_{H,fuel,avg.} + ((GHG_{H,M,avg.} + GHG_{H,Bat,avg.} + GHG_{H,FC,avg.}) \times P_H) \qquad (7)$$

$$= GHG_{H,fuel,avg.} + \left(\left(\frac{GHG_{H,M}}{VKT_H \times P_E} + \frac{GHG_{H,Bat}}{VKT_H \times P_E} + \frac{GHG_{H,FC}}{VKT_H \times P_E}\right) \times P_H\right) \qquad (8)$$

Table 41- Notations used in GHG LCA Emissions Calculations

Notations	Explanation
$GHG_{D,avg.}$	Average emissions from diesel bus (kg CO_{2eq}/km)
$GHG_{D,fuel,avg.}$	Diesel Well-to-Tank (WTT) of diesel (kg CO_{2eq}/km)
$GHG_{D,O,avg.}$	Average emissions from the operation of diesel bus (kg CO_{2eq}/km)
$GHG_{D,M,avg.}$	Average emissions from the manufacturing of diesel bus (kg CO_{2eq}/km)
$GHG_{D,M.}$	Emissions from the manufacturing of diesel bus (kg CO_{2eq})
VKT_D	Vehicle Kilometre Travel by diesel bus (kms)
P_D	The payload for diesel bus (kgs)
$GHG_{C,avg.}$	Average emissions from CNG bus (kg CO_{2eq}/km)
$GHG_{C,fuel,avg.}$	Well-to-Tank (WTT) of CNG (kg CO_{2eq}/km)
$GHG_{C,O,avg.}$	Average emissions from the operation of CNG bus (kg CO_{2eq}/km)
$GHG_{C,M,avg.}$	Average emissions from the manufacturing of CNG bus (kg CO_{2eq}/km)
$GHG_{C,M}$	Emissions from the manufacturing of CNG bus (kg CO_{2eq})
VKT_C	Vehicle Kilometre Travel by CNG bus (kms)
P_C	The payload for CNG bus (kgs)
$GHG_{E,avg.}$	Average emissions from BEB (kg CO_{2eq}/km)
$GHG_{E,Elect,avg.}$	WTT emissions for electricity (kg CO_{2eq}/km)
$GHG_{E,M,avg.}$	Emissions from the manufacturing of BEBs (kg CO_{2eq}/km)
$(\Sigma GHG_{E,Elect} \times GM)$	Emissions from the grid (kg CO_{2eq}/KJ)
η_G	The efficiency of transmission of grid
η_T	Tank to Wheel (TTW) efficiency of BEBs
P_E	The payload for BEBs (kgs)
$GHG_{E,EVSE}$	Emissions from the manufacturing of EVSE (kg CO_{2eq}/km)
$GHG_{E,Bat}$	Emissions from the manufacturing of battery (kg CO_{2eq}/kWh)
VKT_E	Vehicle Kilometre Travel by BEBs (kms)
$GHG_{H,avg.}$	Average emissions from CNG bus (kg CO_{2eq}/km)
$GHG_{H,fuel,avg.}$	Well-to-Tank (WTT) of H2 (kg CO_{2eq}/km)
$GHG_{H,O,avg.}$	Average emissions from the operation of HFEBs (kg CO_{2eq}/km)
$GHG_{H,M,avg.}$	Average emissions from the manufacturing of HFEBs (kg CO_{2eq}/km)
$GHG_{H,Bat,avg.}$	Average emissions from the manufacturing battery of HFEBs (kg CO_{2eq}/km)
P_H	The payload for HFEBs (kgs)
$GHG_{H,M}$	Emissions from the manufacturing of HFEBs (kg CO_{2eq})
VKT_H	Vehicle Kilometre Travel by HFEBs (kms)
$GHG_{H,Bat}$	Emissions from the manufacturing of HFEBs (kg CO_{2eq})
$GHG_{H,FC,avg.}$	Average emissions from the manufacturing of Fuel Cell (kg CO_{2eq}/km)
$GHG_{H,FC}$	Emissions from the manufacturing of Fuel Cell (kg CO_{2eq})

The results are computed and tabulated in Table 42, Table 43, and Table 44.

Table 42- GHG emissions from 9-m feeder buses

Bus	Process	Power source		Emissions (kg CO_{2eq}/km)
FCEB	Hydrolysis	Existing Grid		4.29
		Captive sources	Solar and/or Wind	0.31
			Hydro	0.23
		RES grid		0.28
	SMR	Natural Gas		1.50
		Bio-Mass (Bio-CNG)		0.63
BEB	Existing Grid			0.80
	Captive sources	Solar and/or Wind		0.09
		Hydro		0.08
	RES grid			0.09
Diesel buses				3.00
CNG buses				1.38

Table 43- GHG Emissions from 13-m Intra-City Short-Haul Buses

Bus	Process	Power source		Emissions (kg CO_{2eq}/km)
FCEB	Hydrolysis	Existing Grid		11.11
		Captive sources	Solar and/or Wind	0.57
			Hydro	0.39
		RES grid		0.55
	SMR	Natural Gas		2.78
		Bio-mass (Bio-CNG)		1.45
BEB	Existing Grid			1.28
	Captive sources	Solar and/or Wind		0.14
		Hydro		0.12
	RES grid			0.14
Diesel buses				5.34
CNG buses				2.56

Table 44- GHG emissions from 13-m Inter-city Long-Haul Buses

Bus	Process	Power source		Emissions (kg CO_{2eq}/km)
FCEB	Hydrolysis	Existing Grid		6.34
		Captive sources	Solar and/or Wind	0.44
			Hydro	0.34
		RES grid		0.43
	SMR	Natural Gas		1.68
		Bio-mass (Bio-CNG)		0.39
BEB	Existing Grid			0.67
	Captive sources	Solar and/or Wind		0.12
		Hydro		0.11
	RES grid			0.12
Diesel buses				2.67
CNG buses				2.17

7.4 Total Annual GHG Emissions by Vehicle Variant Across Scenarios

Below is the result of the comparison of total annual GHG emissions across the three vehicle variants, HFCEV, e-Bus and Diesel buses for the three scenarios. The estimations were done with the assumption that the buses will operate 365 days a year.

A comparison between the GHG emissions for three Hydrogen production pathways i) grid connected electrolysers, ii) renewable natural gas (from biomass) feedstock for SMR, iii) natural gas feedstock for SMR were further made for the HFCEV buses.

Table 45- Comparisons between annual GHG emissions from different sources of hydrogen

Scenarios	Avg. kms/ bus/ day	Total kms/ day	Annual emissions (kt CO2eq/year)				
			HFCEV			BEB	Diesel
			Elec-tro-lyzers	RNG SMR	Natural Gas SMR		
A: Inter-City (KSRTC) 50 Buses across all phases	669.38	33,469	77.5	11.38	20.48	8.13	32.66
B: Feeder service (Kochi metro) 10 buses (Phase I)	224.26	2,243	3.5	0.52	1.23	0.65	2.45
C: Intra-City (KURTC) 10 buses (Phase I)	136.25	1,363	5.5	0.72	1.38	0.64	2.66

OBSERVATIONS OF DIFFERENT HYDROGEN PRODUCTION PATHWAYS

- The GHG emissions from using Hydrogen generated from the SMR of RNG route is the lowest for operating HFCEV buses across all three scenarios. The GHG emissions from the generation of Hydrogen from electrolysers connected to the grid are the highest.

OBSERVATIONS ACROSS THE DIFFERENT BUS VARIANTS

- Operating HFCEV buses powered by Hydrogen generated from grid connected Electrolysers are the highest across all scenarios.
- Operating e-Buses powered by grid connected electricity is the lowest across scenario A and scenario C, except for scenario B.
- Operating HFCEV buses using RNG as a feedstock for SMR in scenario B is the lowest.

7.5 CONCLUSIONS

Since the current fleet of operating buses in Kerala are fueled by diesel, the GHG emission comparisons across bus variants are done with emissions from diesel buses. The existing electricity mix relies significantly on thermal power, because of which the GHG emissions for FCEBs, powered from grid connected electrolysers are significantly higher than diesel buses. The difference is as high as 81.38 % in the case of 13-meter intercity buses. However, the emissions from FCEBs drop drastically if electricity is sourced from renewable sources.

If the hydrogen is produced from biomass using SMR, there is a reduction in emissions of 66.54 % compared to diesel buses. BEBs are more energy-efficient and produce lower emissions as compared to FCEBs. However, BEBs are limited by the lower range and longer charging durations. FCEBs can be refilled almost as fast as diesel and CNG buses [37], they maintain a good balance between longer range operability and environment friendliness. The LCA results combined with the longer range and quick refilling make it one of the best contenders for the future of mass mobility.

8

TOTAL COST OF OWNERSHIP AND SENSITIVITY ANALYSIS

8.1 TCO Methodology

Typically, Total Cost of Ownership (TCO) analysis provides an understanding of the true cost of buying goods or services over its useful life. Two important components of the TCO model are capital expenditure (CAPEX) and operational expenditure (OPEX). CAPEX (also known as one-time cost) includes procurement cost of capital assets (HFC Buses) while OPEX (also known as recurring cost) includes operational and maintenance (O&M), fuel, labor, and other miscellaneous costs.

The breakdown of the inputs that constitute the TCO calculation are as follows:

Table 46- Breakdown of TCO Capital and Operation Costs

	Capital Cost		Operational Cost
i.	Vehicle Cost (including battery + fuel cell stack replacement costs)	i.	Labor Cost
ii.	Hydrogen Refueling / Electric Vehicle Charging Infrastructure Cost	ii.	Utilities
iii.	Taxes	iii.	Power Cost
iv.	Insurance	iv.	Replacement Cost
v.	Financing costs	v.	Maintenance Cost
vi.	FAME II, State Incentives & Subsidies		

Assumptions used after discussions with state STUs and Auto OEMs to model asset utilization, asset useful life timeline and Hydrogen / Electricity supply side infrastructure costs.

Table 47- Assumptions for asset utilization and life

Parameter	Inputs
Vehicle Utilization	No. of Km traveled a day/ no. of days operational in a year
Life / Operational period of a vehicle discount rate	Which indicates the 'time value of money'
Resale value of vehicles at end of useful life	
Useful life of batteries and fuel cell stacks	To get the number of replacements during the useful life of the BEV bus & HFC bus
Design and boundary conditions of the EV Charging Infrastructure, Grid interconnection related upgrades	
Design and boundary conditions of the HFC refueling infrastructure, Hydrogen packaging and transportation	

This methodology takes a realistic approach at calculating costs. There are several different analysis methodologies that use a bottom-up approach for estimating the TCO. It includes sensitivity analysis due to future variations in the cost components and their impact on the TCO.

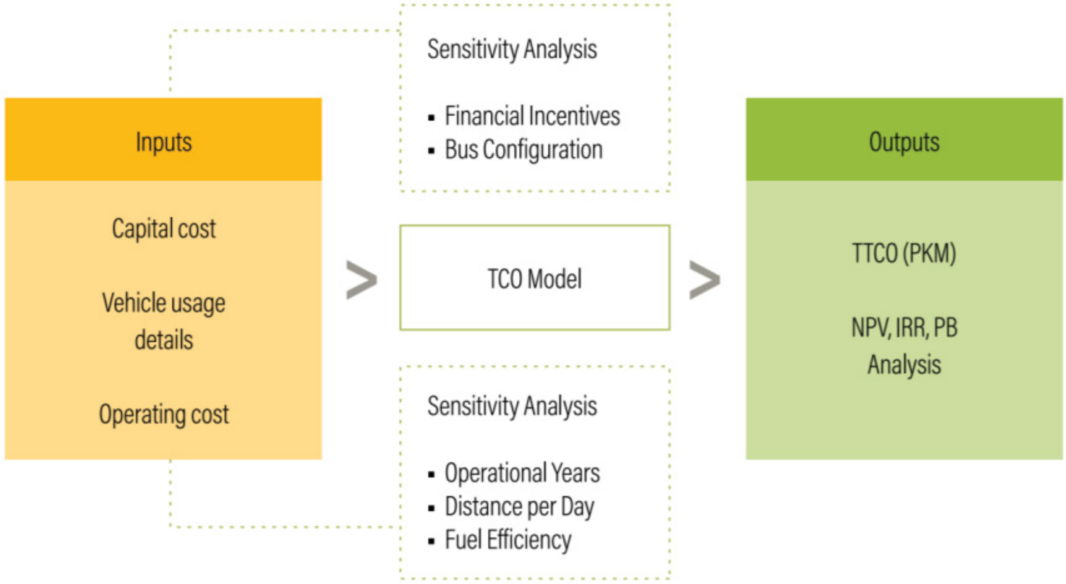


Figure 32- TCO Model

The formula used to determine TCO per km for different vehicle segments is as follows:

$$\frac{\mathbf{TCO}}{\boldsymbol{km}} = \frac{\left(PC - \frac{RV}{(1+r)^N}\right) X\,\mathbf{CRF} + \frac{1}{N}\sum_{n=1}^{N} \frac{\mathbf{AOC}}{(1+r)^n}}{\mathbf{AKT}}$$

PC = purchase cost of the vehicle

RV = residual value of the vehicle at the end of vehicle life

CRF = capital recovery factor

AOC = annual operating cost of the vehicle

AKT = annual kilometers travelled

r = discount factor

N = lifetime of the vehicle (in years)

$$\mathbf{CRF} = \frac{r(1+r)^N}{(1+r)^N - 1}$$

This TCO equation has been modeled in Excel to calculate TCO per km for different bus categories, 'Grey H2 fuel powered HFC Buses', '100 % Green H2 fuel powered HFC Buses', 'Electric Buses (e-Bus)' and 'Diesel Buses'. Input data was collected primarily from stakeholder interviews with HFC technology and HRI infrastructure experts, auto-OEMs and related published literature.

8.2 TCO Input data and assumptions

Based on interviews and literature review, a vehicle holding period of 15 years and a discount rate of 10% was assumed for all vehicle categories. The resale value was assumed to be 5% for HFC buses, and 10% for electric and diesel buses. A YoY decrease of 5% in the price of Hydrogen has been taken into account for over the service period of the bus. Sensitivity analysis was performed to get an understanding of the variations in assumptions on the TCO / km of the vehicles.

In line with the Hydrogen refueling Infrastructure design and modeling that was done for three different scenarios of HFC bus implementation across three types of load profiles / routes, we have done a comparative TCO analysis of each with similar e-bus and Diesel bus demands. Below are the descriptions, inputs and assumptions used in the TCO calculations.

Table 48- TCO Input data and assumptions by SCENARIO A, B and C

	SCENARIO - A	SCENARIO - B	SCENARIO - C
Description	Demand from 50 long haul inter-city 13-meter HFC bus routes (routes by KSRTC)	Demand from 10 last mile Kochi metro feeder 9-meter buses (Kochi Metro routes)	Demand from 10 short-haul intra-city Kochi 13-meter bus routes (Kochi city)
Daily Average Distance / Bus	500 Km (annual kilometer travelled, AKT, 157,000 kms)	150 Km (annual Kilometer travelled, AKT, 47,250 Kms)	220 Km (annual Kilometer travelled, AKT, 69,300 Kms)
Fuel Cell Stack	$ 500/kWh	$500 / kWh	$ 500 / kWh
Battery (Li-ON)	$ 156/kWh	$ 156 / kWh	$ 156 / kWh
Grey H2	184/kg- 314/kg	184/kg- 314/kg	184/kg- 314/kg
Green H2	451/kg- 503/kg	451/kg - 503/kg	451/kg - 503/kg
Electricity price	6/kWh (for BEV charging)	6/kWh (for BEV charging)	6/kWh (for BEV charging)
Diesel costs	90/liter	90/liter	90/liter
OPEX of EV / HRS systems	2% of CAPEX	2% of CAPEX	2% of CAPEX
Service Period	15 years	15 years	15 years

Note: Scenario A hydrogen refueling/charging infrastructure cost is distributed over 50 buses, while in Scenario B and Scenario C that cost is distributed over 10 buses.

Table 49 below summarizes the purchase cost, engine sizes, mileage, and battery capacity of Bus variants. This table provides representative value for purchase cost of the vehicles along with the technological details.

Table 49- Purchase costs of bus variants, engine, battery, and FC sizes by SCENARIO

SCENARIO A - LONG HAUL INTER-CITY ROUTES				
Vehicle Type/Fuel Type	Fixed Cost	FC Engine Sizes (kW; cc)	Mileage (km/kg; km/kWh; km/L)	Battery Capacity (kWh)
HFCEV / Grey-H2	2,67,21,640	120	16.6	80
HFCEV/ Green H2	2,67,21,640	120	16.6	80
e-Bus / Electricity	2,00,00,000	-	1.0	280
Diesel Bus / Diesel	88,00,000	9,360	2.2	-

SCENARIO B - SHORT HAUL KOCHI METRO FEEDER ROUTES				
Vehicle Type/Fuel Type	Fixed Cost	FC Engine Sizes (kW; cc)	Mileage (km/kg; km/kWh; km/L)	Battery Capacity (kWh)
HFCEV / Grey-H2	1,47,69,007	45	16.6	45
HFCEV / Green-H2	1,47,69,007	45	16.6	45
e-Bus / Electricity	1,25,00,000	-	0.77	180
Diesel Bus / Diesel	60,00,000	7,400	2.75	-

SCENARIO C - INTRA-CITY ROUTES				
Vehicle Type/Fuel Type	Fixed Cost ( )	FC Engine Sizes (kW; cc)	Mileage (km/kg; km/kWh; km/L)	Battery Capacity (kWh)
HFCEV / Grey-H2	2,49,14,890	90	16.6	80
HFCEV / Green-H2	2,49,14,890	90	16.6	80
e-Bus / Electricity	2,00,00,000	-	1.0	280
Diesel Bus / Diesel	88,00,000	9,360	2.2	-

Table 50- CAPEX and OPEX cost breakdown of FCEV Buses

CAPEX

Fuel cell bus CAPEX (~ 3 crores INR)
- Fuel cell (Initial) (~ $1500/kW)
- Storage tank
- Chassis cost

Electrolyser CAPEX (~$850/kW)
- Cost of rare minerals used

Refuelling network
- Refuelling station/s
- Pipeline network costs (ex-situ)
- Pipeline network costs (in-situ)
- Total pipeline costs (ex-situ + in-situ)
- Land cost (rented/bought)

Other costs
- Tax
- Interest incurred on any loans taken
- Insurance (Green H_2/Other low-carbon sources)
- Other Health and Safety certification costs

OPEX

Fuel cost (annual)
- Green H_2 (Rs. 550/kg)
- Grey H_2 (Rs. 180-200/kg)
- Other low-carbon H_2 sources (Rs. 250-300/kg)

Maintenance cost
- Staff cost (total CTC)
  - Fleet employees (Rs. 50,000/month)
  - Refuelling station employees (Rs. 60,000/month)
- Fuel cell replacement cost (per kWh) for bus's lifetime of 15 years
- Tyre replacement costs
- Other annual general maintenance costs
- Other consumables cost
- Other miscellaneous costs
- Total annual vehicular maintenance

CAPEX	Cost (INR)	OPEX	Cost (INR)
FC Bus	~3 crores	Green H_2/kg	550
Fuel cell (per kW)	1.10 lakhs	Grey H_2/kg	180-200
Electrolyser (per kW)	62,000	Low-carbon H_2/kg	250-300
H_2 Refuelling station (per kg)	12 lakhs	Fleet employee's cost/month	50,000
Insurance (per year)	1 lakh	Refuelling station employee's cost/month	60,000
		FC replacement cost (120kW) per replacement @ $750 per kW	65 lakhs
		Total annual vehicular maintenance cost	6-6.5 lakhs

8.3 TCO MODEL RESULTS

The break-even points for average daily travel distance for different fuel variant buses is presented followed by a detailed comparison of the TCO of HFCEVs vs e-Bus vs Diesel.

Average Break-Even Daily Travel Distance of HFCEV and BEV 12 m Buses

The daily average travel distance at which the TCO of a HFCEV bus and e-Bus are less with their ICE counterpart is calculated by comparing with the typical daily driving distance of a diesel 12m bus. The calculation of break-even distances for EVs is based on sensitivity analysis of the daily travel distance.

Table 51- Average break-even daily travel distance by bus variants

Type of Bus (13m)	Service Period (years)	Average break-even daily travel distance (km)	Type of Conventional vehicle	Average daily travel distance (km)
e-Bus	15	> 260	Diesel bus (public transport)	~200
HFCEV / Grey-H2	15	> 485		
HFCEV / Green-H2	15	> 725		

8.3.1 Scenario A: Long Haul Inter-City Routes

A TCO of procuring and operating a fleet of 50 Long Haul intercity 13-meter buses and related infrastructures to power them is made for HFC, e-Bus and Diesel buses. The capacity of the HFC engine used is 120 kW, the capacity of the Li-ON battery in the e-bus is 280 kWh.

The cost of setting up a central overnight charging hub to charge a fleet of 50 e-Buses, with a dedicated charger per bus, grid integration and interconnection subsystems, transformers and 3- 4 Kms of T&D lines are used as boundary conditions. The previous sections have covered the gaseous HRS refueling infrastructure design and costs for scenario A. Mileage of e-bus considered is 280 km per charge and HFC bus average mileage of 16.6 km/kg-H2.

Figure 33 shows the TCO/ km of Hydrogen and Electric buses without FAME II

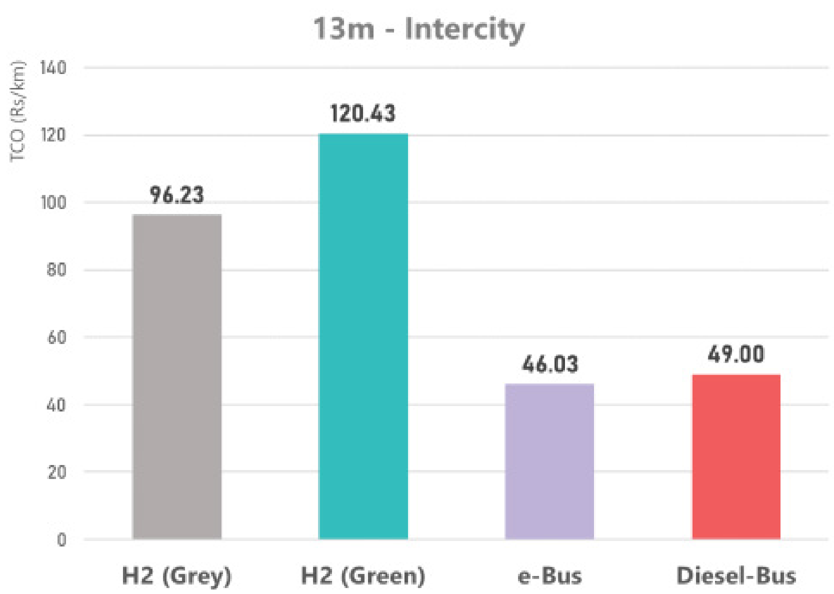


Figure 33- Scenario A TCO comparison across bus variants without FAME II Purchase Subsidy

purchase subsidies. Currently HFC buses are not cost comparable with either the electric or diesel buses. The Grey H2 bus TCO at ₹96.23/km is 2.09 times that of a comparable e-bus at ₹46.03/km and 1.9 times of a diesel bus at ₹49/km. Green H2 variant is significantly higher than all its counterparts at ₹120.43/km.

Figure 34 shows the trend in the year-wise TCO / km of HFC buses vs e-Bus vs Diesel variants over a service period of 15 years. For the initial 2 years the TCO of both variants of HFC buses (Grey/ Green) are almost similar, but over the long run the cost of ownership of a Green H2 bus with an average fuel cell cost of $500/kWh works out to be more per km. Compared to the e-Bus and Diesel bus, both HFC bus variants TCO/ km is higher throughout service period.

A more rigorous modeling of the TCO to sensitivities of decreases in Fuel Cell Stack (comparing to synergies in battery costs from scale and learning) costs and levelized cost of Green H2 (from decrease in renewable energy costs) is needed to arrive at more accurate TCO trends.

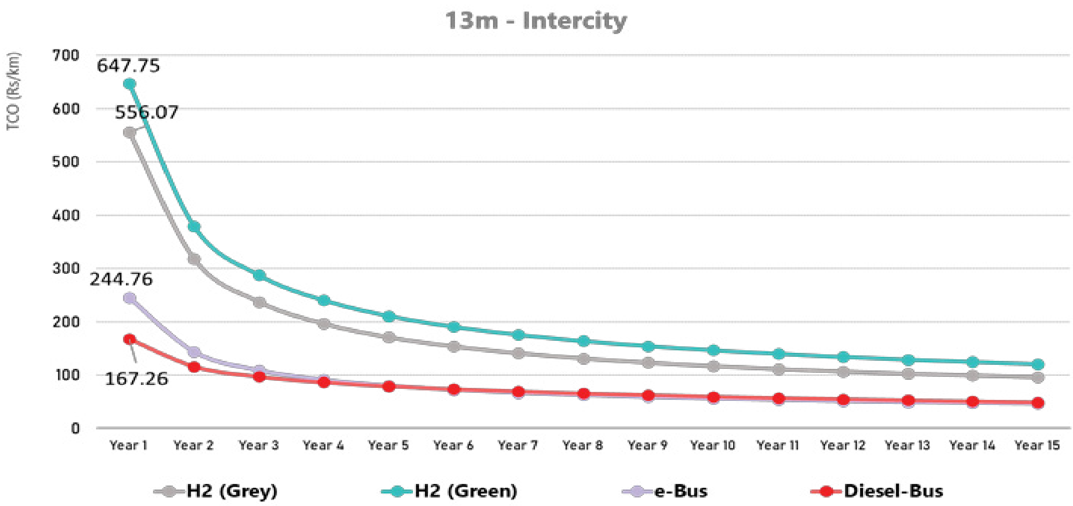


Figure 34- Scenario A TCO YoY comparison across bus variants without FAME II Purchase Subsidies

Applying a purchase subsidy via FAME II, of ₹20,000/kWh not exceeding ₹50,00,000, brings down the TCO of a 280-kWh e-Bus by 10.4% to ₹41.24/km. If similar subsidies were extended to fuel cell buses, the analysis shows that Green HFCEV's TCO drops by 4% to ₹115.65/km, while Grey HFCEV's TCO reduces by 9% to ₹87.47/km making it competitive in a predominant ICE market.

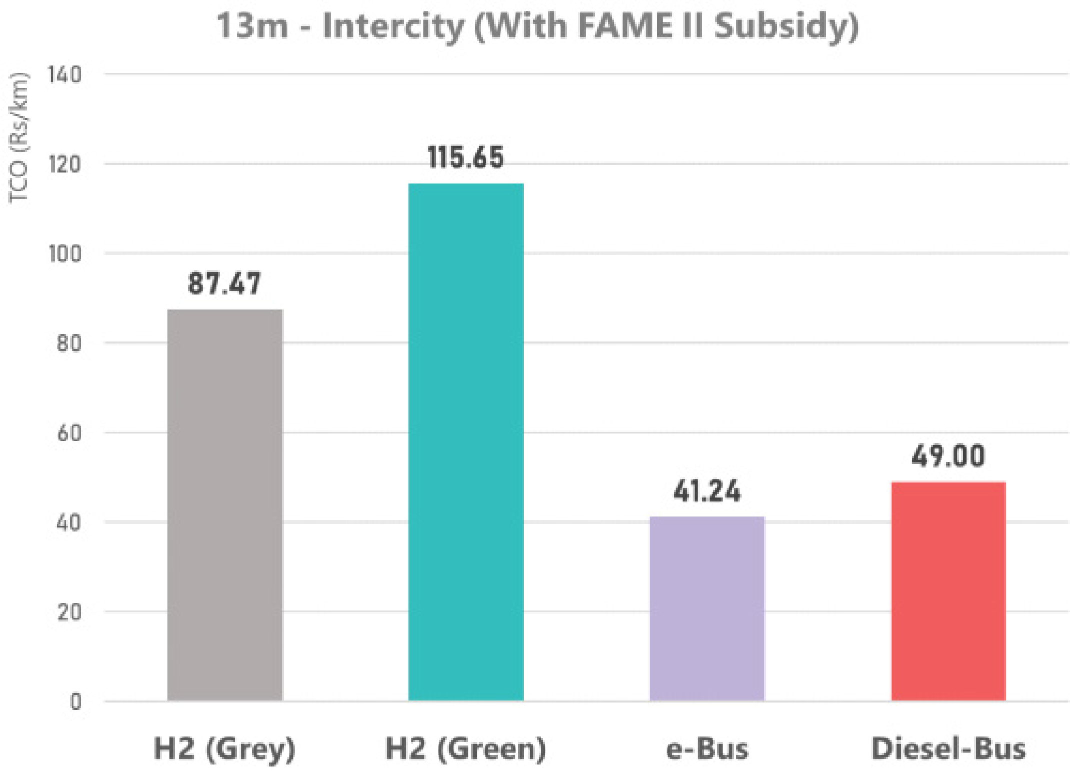


Figure 35- Scenario A – Impact of FAME II subsidies on ZEV variants of e-Bus and HFC

8.3.2 Scenario B: Short-Haul Kochi Metro Feeder Routes

Many cities in India are currently procuring shorter buses with an aim to address their last mile connectivity issues and also to easily maneuver along narrow roads in cities. An analysis of tenders by various cities under FAME II reveals that 81% of buses procured were 9-meter buses. The growing demand is an indication of forthcoming trends in state transport corporation procurements. The daily average range for 'medium-duty' models is between 50 km and 200 km.

TCO of a fleet size of ten 9-meter HFC buses with a smaller Fuel Cell Engine (45 kW – 60 kW) fueled by Grey and Green H2, is compared with the TCO of a fleet of ten 9-meter e-Buses with 180-kWh batteries.

The cost of setting up a central overnight charging hub to charge a fleet of 10 e-Buses, with a dedicated charger per bus, grid integration and interconnection subsystems, transformers and 3- 4 Kms of T&D lines are used as boundary conditions. The previous sections have covered the gaseous HRS refueling infrastructure design and costs for scenario B.

Figure 36 shows the Scenario B: TCO/ km of 9-meter HFC and Electric buses without FAME II purchase subsidies. The HFC buses are not cost comparable with either the electric or diesel buses. The Grey H2 bus TCO at ₹119.97 / km is 1.4 times that of a comparable e-Bus at ₹86.26 / Km and 1.5 times of a Diesel bus at ₹72.51 / km. The Green H2 powered HFC bus cost is significantly higher than all its counterparts at ₹153.45 / km.

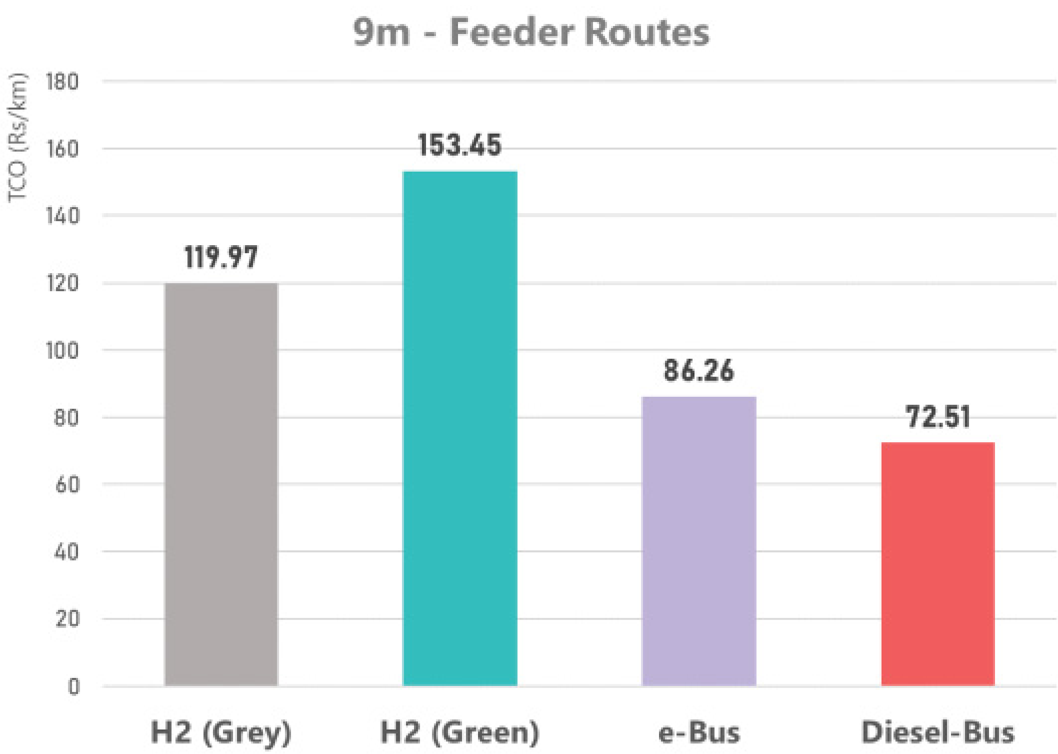


Figure 36- Scenario B – TCO comparison across bus variants

A breakdown of the TCO into [fleet asset capital and operational costs] and [fueling infrastructure capital and operational costs] shows the impact of lower refueling infrastructure utilization (smaller daily H2 demand from lower kms/ day per bus of

100-200 km/day) on the levelized cost of HRS infrastructure almost doubling the TCO / Km compared to Scenario A

Figure 37 shows the trend in the year-wise TCO per km of a fleet of ten 9-meter HFC buses & ten 9-meter e-Buses over a service period of 15 years. A similar trend to what was observed with scenario A across the bus categories. A rigorous modeling of the TCO sensitivity to the fall in Fuel Cell Stack costs from scale and learning and green h2 costs from falling renewables and higher utilization of HRS refueling infrastructure will be needed to truly understand the trend.

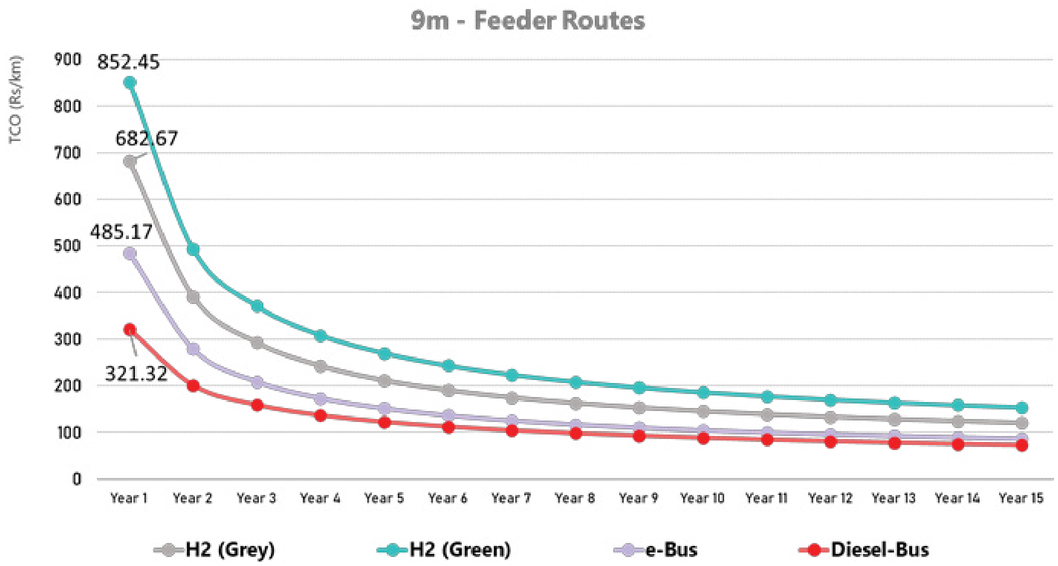


Figure 37- Scenario B TCO YoY comparison across bus variants

Figure 38 shows the impact of FAME II purchase subsidy on TCO reduction is dependent on the size of batteries and fuel cell stacks in the buses. With a 9-meter e-Bus employing a 180 kWh Li-Ion battery, the FAME II discount reduces its TCO by 13% to ₹74.77/km. Assuming the same level of subsidy of ₹20,000 / kW for HFCEVs, both the HFC buses (grey & green H2) with a 45-kW stack, drops their TCO by 17% and 7.5% to ₹98.94 / km and ₹141.96 / km respectively.

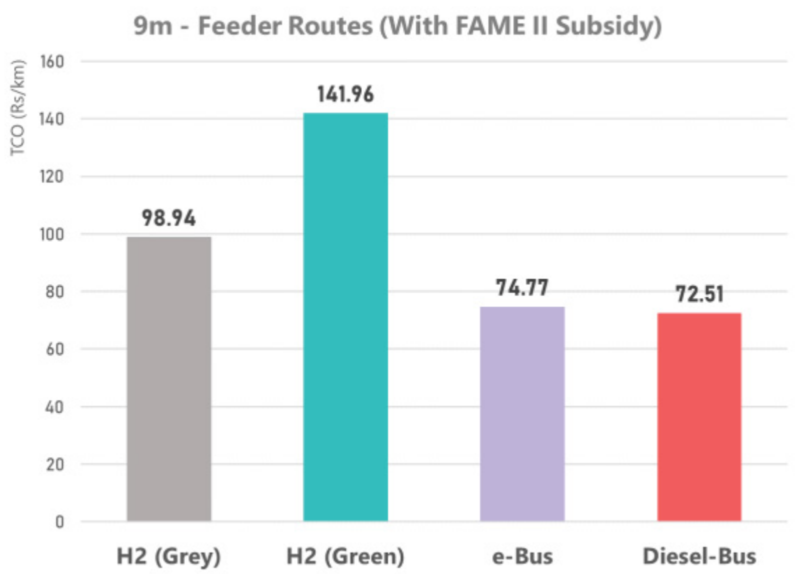


Figure 38- SCENARIO B – FAME II subsidy impact on TCO across bus variants

8.3.3 Scenario C: Short Haul Intra-City Routes

This explores a scenario of medium-haul intracity routes with an average daily travel distance of 220km. TCO of a fleet size of ten 13-meter HFC buses with a Fuel Cell Engine of 90 kW fueled by Grey and Green H2, is compared with the TCO of a fleet of ten 13-meter e-Buses with 280-kWh batteries.

The cost of setting up a central overnight charging hub to charge a fleet of 10 e-Buses, with a dedicated charger per bus, grid integration and interconnection subsystems, transformers and 3- 4 Kms of T&D lines are used as boundary conditions. Since the cost of hydrogen refueling infrastructure is now distributed among 10 buses, the operational expenses are on the higher side. The previous sections have covered the gaseous HRS refueling infrastructure design and costs for scenario C

Figure 39 shows the Scenario C: TCO/ km of 13-meter HFC and Electric buses without FAME II purchase subsidies. The HFC buses are not cost comparable with either the electric or diesel buses. The Grey H2 bus TCO at ₹127.21 / km is 1.54 times that of a comparable e-Bus at ₹82.61 / Km and 1.8 times of a Diesel bus at ₹70.76 / km. The Green H2 powered HFC bus cost is significantly higher than all its counterparts at ₹179.43 / km.

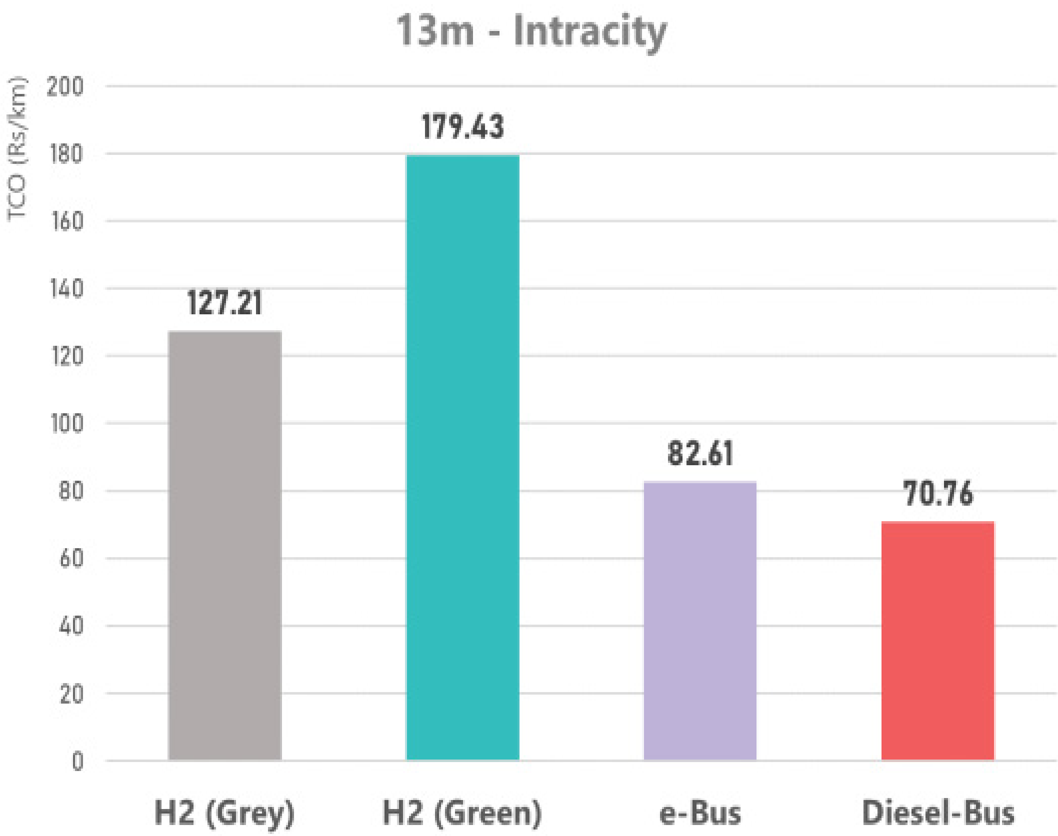


Figure 39- Scenario C – TCO comparison across bus variants

Figure 40 elucidates this point further of the stark difference in the TCOs of the HFCEVs over the service period with that of Diesel buses. The nascency of the HFCEV technology, the higher cost of operation of hydrogen generation makes it a costlier proposition.

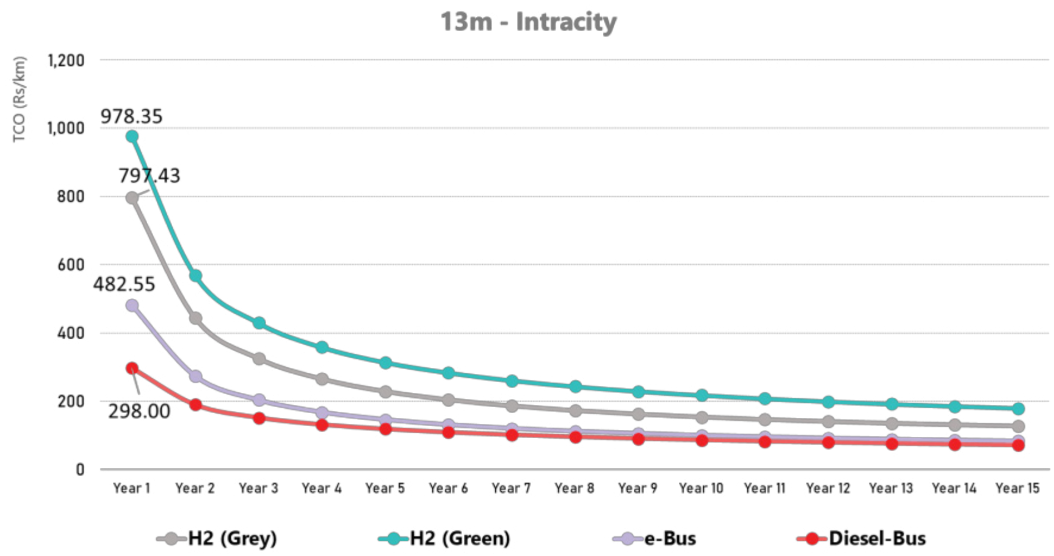


Figure 40- Scenario C TCO YoY comparison across bus variants

Figure 41 shows the impact of FAME II purchase subsidy on TCO reduction is dependent on the size of batteries and fuel cell stacks in the buses. With a 13-meter e-Bus employing a 280 kWh Li-Ion battery, the FAME II discount reduces its TCO by 13% to ₹71.73/km. Assuming the same level of subsidy of ₹20,000 / kW for HFCEVs, both the HFC buses (grey & green H2) with an 80-kW stack, drops their TCO by 16% and 6% to ₹107.30 / km and ₹168.55 / km respectively.

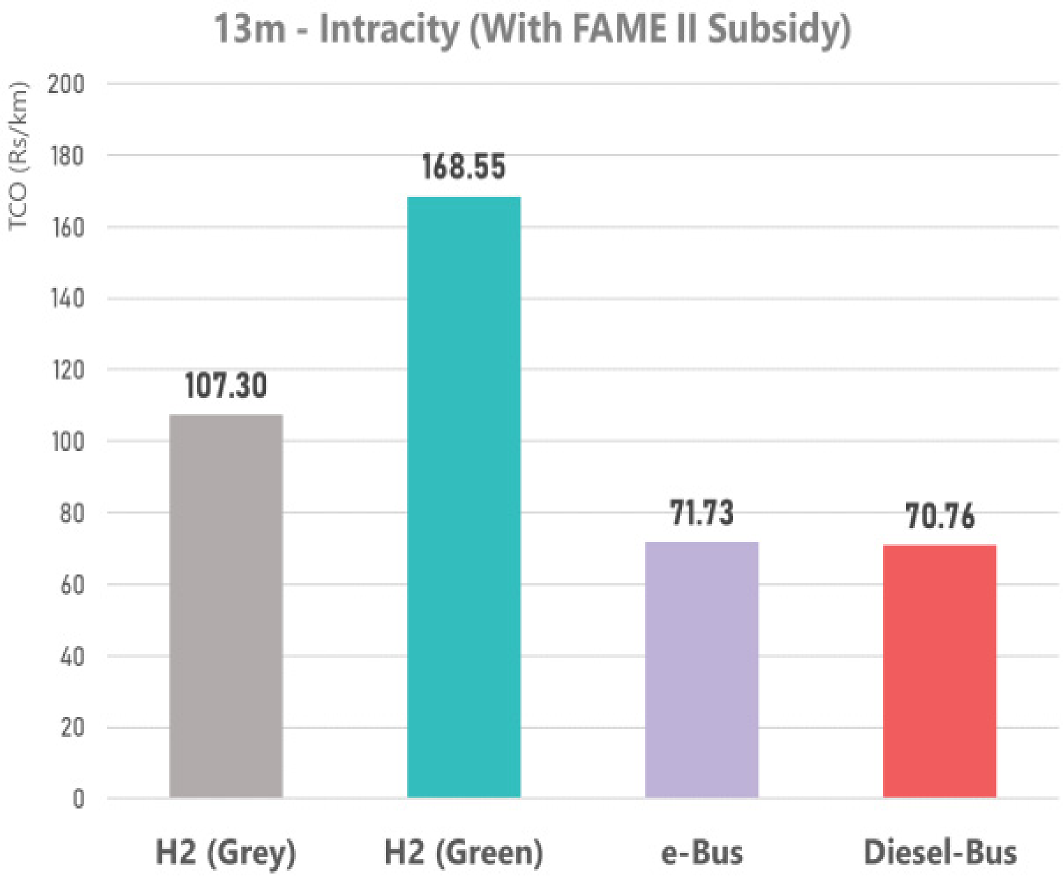


Figure 41- SCENARIO C – FAME II subsidy impact on TCO across bus variants

8.4 Sensitivity Analysis

A sensitivity analysis of the TCO to various costs of a 13-meter bus is modelled and analyzed. Fluctuations in fixed costs such as capital cost, and variable costs, which include vehicle utilization, maintenance costs and fuel costs have been considered. Interpreting and leveraging observations from sensitivity analysis is useful to frame terms for Request for Proposals (RFP) and tenders, to minimize risks for all stakeholders. The percentage variation of cost components used in the sensitivity analysis is provided in Table 52.

Table 52- Variations in Costs of TCO contributing factors

Components	Sensitivity Analysis			
Capital Cost	+10%	+5%	-5%	-10%
Vehicle Utilization	+50%	+25%	-25%	-50%
Fuel Cost				
Maintenance Cost				
Staff Cost	+25%	+50%	+75%	+100%

8.4.1 TCO Sensitivity to Vehicle Purchase Cost

Figure 42 shows the impact of ±50% variation in the purchase cost and its impact on TCO per km of HFC buses in comparison with their ICE counterparts. With a 50% reduction in purchase costs, the TCO / km of a Grey H2 bus drops to ₹80.66 / Km and a 16% drop from its original TCO. Even if the purchase cost of an e-Bus with a 280-kWh battery is increased by 25%, its TCO / km remains lowest amongst all other options considered in the analysis.

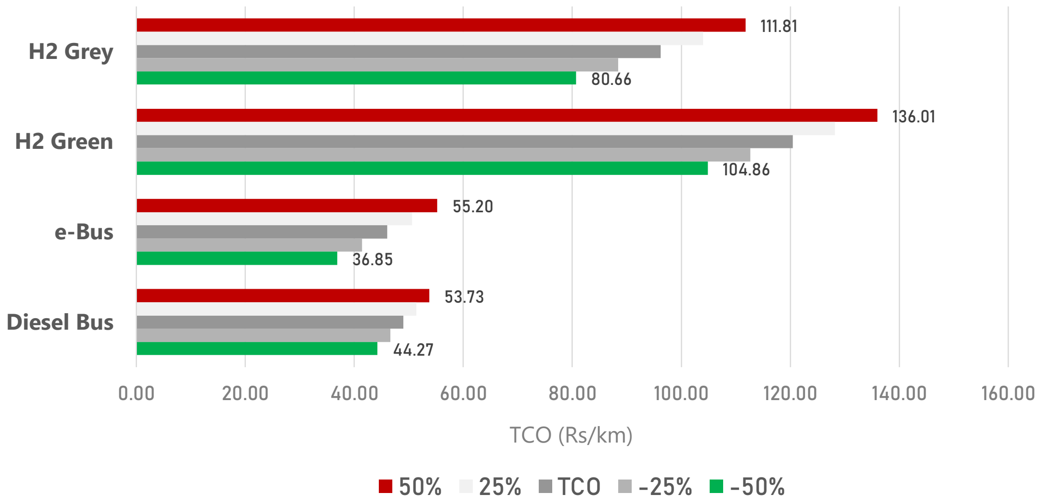


Figure 42- TCO sensitivity to capital costs of bus variants

Table 53- TCO sensitivity to capital costs of bus variants

	50%	25%	-25%	-50%
HFCEV / Grey-H2	16%	8%	-8%	-16%
HFCEV / Green-H2	13%	6%	-6%	-13%
e-Bus / Electricity	20%	10%	-10%	-20%
Diesel Bus	10%	5%	-5%	-10%

Table 53 lists the percentage changes in TCO / Km with a ±50% variation in the purchase cost of buses. As operational costs of HFCEV buses are relatively lower than Diesel ICE buses, the reduction in purchase cost is impactful on their TCO per km when compared to Diesel buses. A ±50% variation in the purchase cost, the TCO per km of HFCEVs ranges between ±13% and ±16% for Diesel buses.

8.4.2 TCO Sensitivity to Vehicle Utilization

Vehicle Utilization is the total average distance travelled by buses. Figure 43 shows the impact of ± 50% variation in vehicle utilization on their TCO / km. A 50% increase in average daily driving distance from a base value of 500 km / day, the TCO / km of a Grey H2 HFC Bus with a 120-kW Fuel Cell Engine becomes comparable to that of a high-cost diesel bus. Vehicle Utilization hence becomes an important factor for bringing parity between different bus options and increase in the distance travelled per day increases the financial viability compared to other bus options.

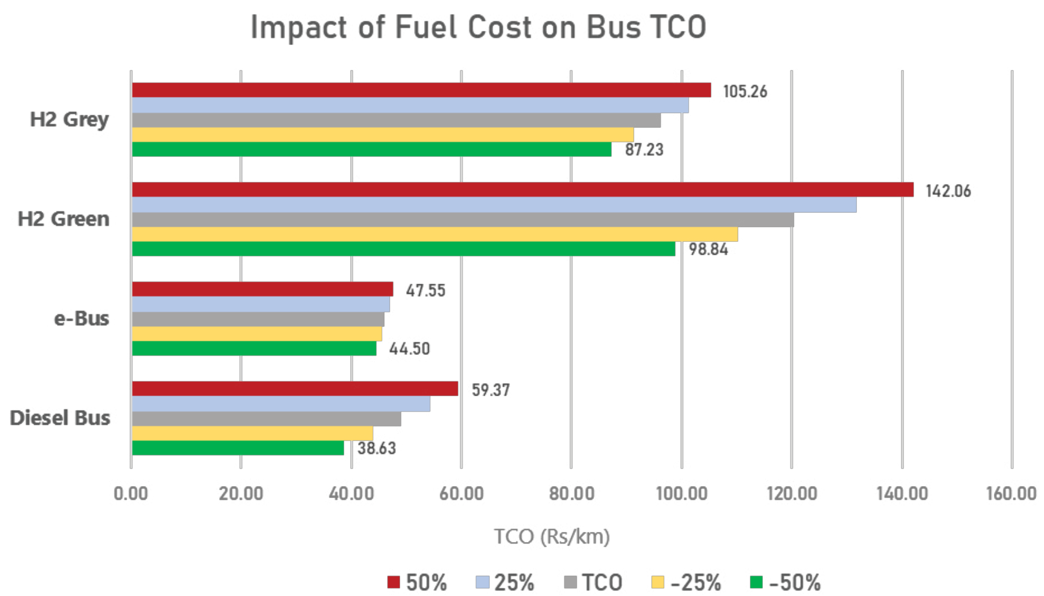


Figure 43- TCO sensitivity to vehicle utilization (daily driven miles / bus)

Table 54- TCO sensitivity to vehicle utilization (kms / day-bus)

	+50% (Increase in utilization)	+25% (Increase in utilization)	-25% (Decrease in utilization)	-50% (Decrease in utilization)
HFCEV / Grey-H2 (TCO/ Km)	-24%	-14%	24%	72%
HFCEV / Green-H2 (TCO / Km)	-21%	-13%	21%	64%
e-Bus (TCO / Km)	-24%	-14%	24%	71%
Diesel Bus (TCO / Km)	-12%	-7%	12%	35%

Table 54 lists the percentage change in TCO / km of HFC, EV and ICE (Diesel) buses with a ± 50 % variation in vehicle utilization (km / day-bus). The table shows a high sensitivity in TCO / km of HFC buses to vehicle utilization as compared to Diesel buses. The financial viability of HFC buses increases with vehicle utilization due to its lower operational costs.

8.4.3 TCO Sensitivity to Fuel Cost

Figure 44 shows the impact of ± 50 % variation in fuel cost on the TCO / km on bus variants. A ± 50% variation in fuel cost, yields the highest sensitivity to TCO / km of Green H2 buses and Diesel buses, due to their high fuel costs. But this warrants a more rigorous analysis of the variations in costs of Green H2 to dropping costs of renewable energy and HRS refueling sub-system costs, which should bring the costs lower than $2.0/Kg (₹ 150.0 / Kg), a key global metric.

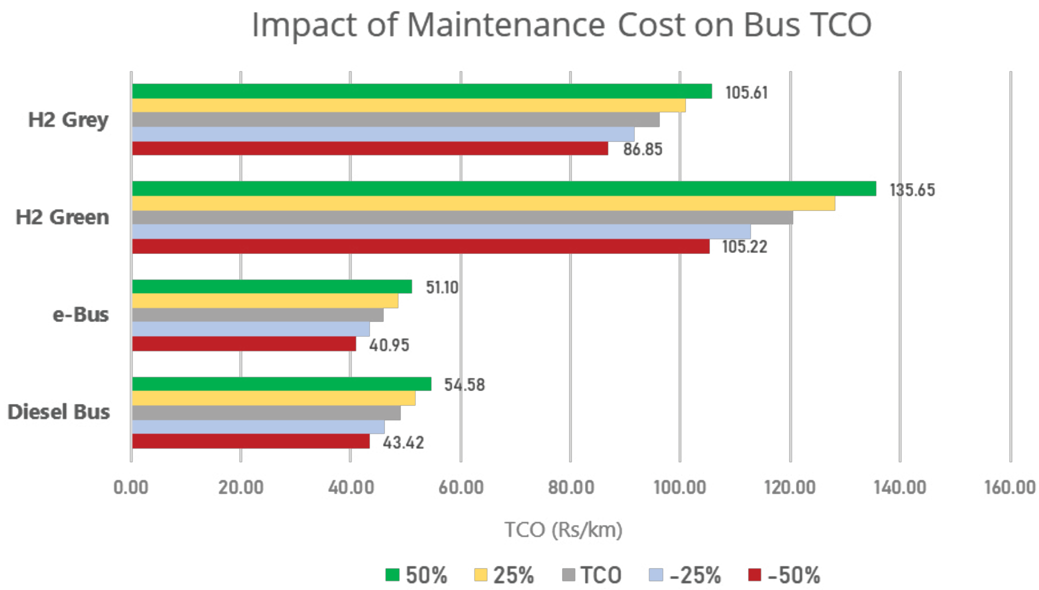


Figure 44- TCO sensitivity to fuel costs

Table 55 shows the TCO / Km sensitivity to changes in fuel costs (+/- 50% variations). A high sensitivity of 14% reduction in TCO of Green H2 powered HFC buses with a 50% decrease in cost of Green H2. As opposed to an 7% decrease in TCO of Grey H2 powered HFC buses. Overall Diesel buses show the largest decrease of 21% in its TCO when Diesel cost decrease by 50%. Besides the high sensitivity of HFC Bus to $ / Kg-H2, its higher fuel efficiency, energy recovery from regenerative braking, less power consumption during idling time plays a significant role

Table 55- TCO sensitivity range to fuel costs range

TCO/Km	+50% (Increase in fuel cost)	+25% (Increase in fuel cost)	-25% (Decrease in fuel cost)	-50% (Decrease in fuel cost)
HFCEV/Grey-H2	7%	4%	-3%	-7%
HFCEV/Green-H2	14%	7%	-7%	-14%
e-Bus/Electricity	3%	2%	-1%	-3%
Diesel Bus	21%	11%	-10%	-21%

8.4.4 TCO Sensitivity to Maintenance Cost

Figure 45 shows the impact of ±50% variation in the maintenance cost on the TCO per km on all bus variants. Maintenance cost includes the cost of buses repairs, labor, and recurring cost of maintaining the hydrogen refueling/charging infrastructure elements. The maintenance costs of HFC buses are higher than EV and ICE buses due to the cost of storage of hydrogen fuel tank and numerous moving parts compared to other variants.

Table 8.9 summarizes the sensitivity ranges in TCO / km to ranges in maintenance cost changes. A ± 50 % variation in maintenance cost, TCO of HFC Buses varies by ± 13% whereas the TCO / km of EV and Diesel buses changes by ±11%

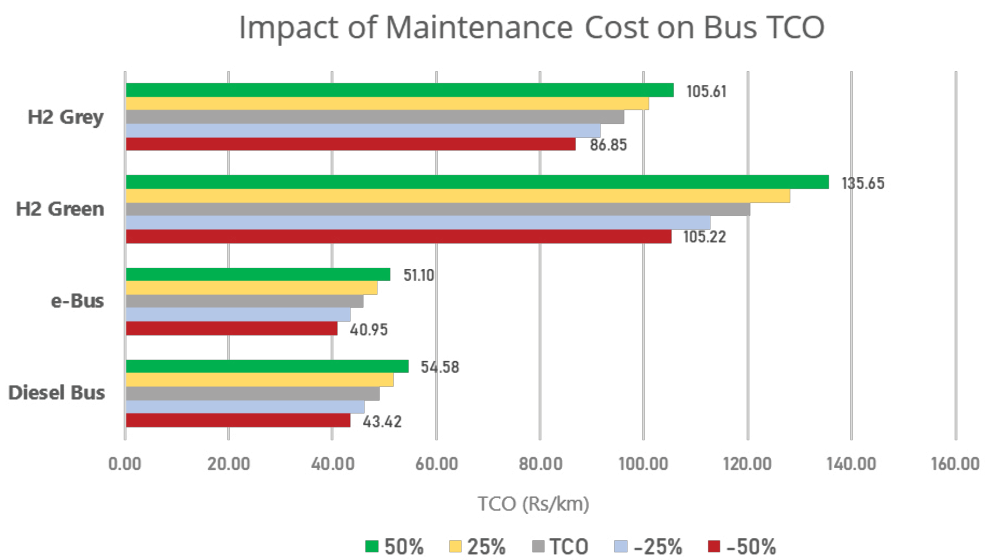


Figure 45- TCO sensitivity to maintenance costs by bus variant

8.4.5 TCO Sensitivity to Staff Cost

A study by Janaagraha, a non-profit organization based in Bengaluru, observed

Table 56- TCO sensitivity to maintenance cost ranges by bus variant

TCO/Km	+50% (Increase in maintenance cost)	+25% (Increase in maintenance cost)	-25% (Decrease in maintenance cost)	-50% (Decrease in maintenance cost)
HFCEV / Grey-H2	10%	5%	-5%	-10%
HFCEV / Green-H2	13%	6%	-6%	-13%
e-Bus / Electricity	11%	6%	-6%	-11%
Diesel Bus	11%	6%	-6%	-11%

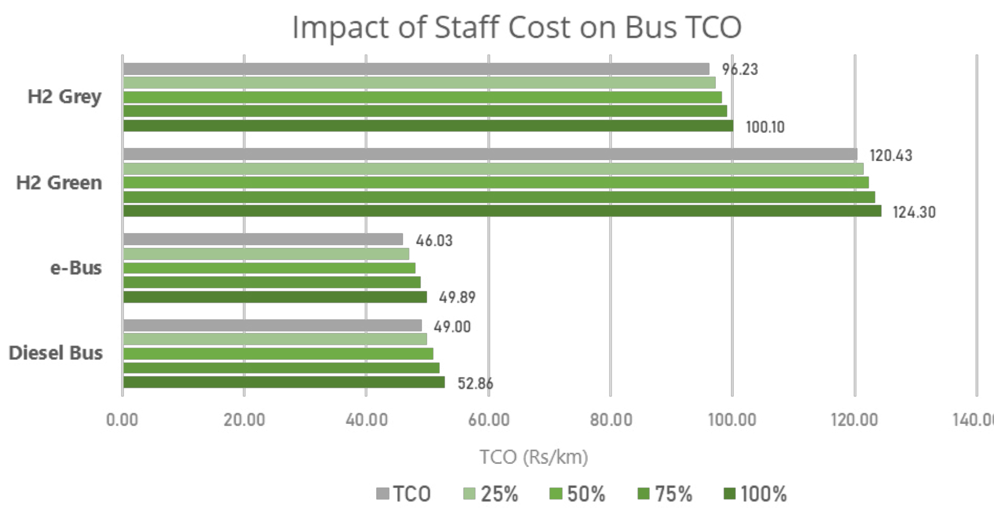


Figure 46 TCO Sensitivity to Staff Cost

that staff costs per kilometer has risen by an average of 16% between 2013 and 2017. BMTC's (Bengaluru Metropolitan Transport Corporation) financial performance reports an average year-on-year rise of 10% for staff costs between the financial years 2012-13 and 2018-19.

Analyses of the impact of a 25 % to 100 % increase in staff cost on the TCO / km suggests increase of 4 % to 7% on the overall TCO per km across all bus variants. Compounding the increase in staff cost over the life of the Bus, the cost increases by 2.59 times the initial staff cost per km by the end of the life of the bus.

8.5 Summary and Recommendations

TCO Sensitivity contributing factors

Total Cost of Operation of HFC Buses is highly sensitive to two contributing factors:

i. **Average daily Driving Distance / Bus:** A drop of 25% in distance travelled increased TCO / Km by (15-24) % in Long-Haul inter-city 13-meter HFC Buses. Similar sensitivities were observed in the 13-meter short haul intracity and 9-meter feeder routes with lower Annual Average Daily Travel (AADT)

ii. **Fuel prices:** Impacted TCOs of all bus variants. Highest sensitivity observed from Green H2 powered HFC Buses, which saw its TCO drop by 27% when the fuel price was slashed by half.

Purchase Subsidies

FAME II capital subsidies are provided to BEV (Battery Electric Vehicle) buses based on the size of batteries at ₹20,000/kWh. Battery Electric Vehicles have a much simpler Bill of Materials (BOM) compared to their distant ICE (Internal Combustion Engine) powered cousins. The cost of the batteries alone is greater than 50% of the BEV costs.

Hydrogen Fuel Cell Electric Vehicles (HFCEV) are powered by Fuel Cells that convert H2 to electricity via Membrane Electrode Assembly (MEA) stacks. HFCEV buses also have an onboard battery used to provide power during bus start-up and sudden surges of power (periods of accelerations and inclinations) for optimal performance of the Fuel Cell Engine. These batteries are typically (25–35) % of the capacity of a similar 100% BEV bus (45 kWh-100kWh). The MEA stacks and Batteries in HFCEV buses form more than 50% of the total bus cost.

NITI AYOG should consider providing similar purchase / capital subsidies based on MEA stack and Battery capacities in HFCEV buses to address cost parity to incumbent competing BEV bus assets.

Approaches to make HFCEV public mobility an attractive proposition in the market:

1. Link subsidy to Average daily travel distances: Provision of impetus to STUs to run short-haul and feeder services while providing gap funding to make it a viable alternative to ICE Diesel buses.

2. Competitive Hydrogen Fuel cost: This requires a combination of:
   - multi-feedstock integrated commodity market to encourage the transition of Waste- to- H2
   - energy market networked policy
   - transitional multi-year interlinked policy to transition from grey to green hydrogen
   - facilitate the adoption of taxation, subsidies and Policy instruments to reduce the cost of energy transfer and cess levied on the fuel stock to make it competitive with existing ICE buses.

9

PROCUREMENT RE-DESIGN AND RE-ALIGNMENT

Public buses account for 7% of the total number of buses in India and carry over 68 million passengers per day with a fleet utilization of 90%. With most state road transport corporations in the country being cash strapped, HFC buses will pose a huge financial burden on them. The government of India has announced various financial incentives for the production and procurement of low carbon emission vehicles including e-buses through the FAME scheme.

The department of Heavy Industries (DHI) the nodal body for the disbursement of financial incentives under the FAME scheme has stipulated that the beneficiaries must procure the buses through Gross Cost Contracting (GCC) model. The DHI[3] notified a list of city/state transport authorities which had been allocated the subsidies against ~6,300 e-buses as of May 2021. It must be noted that under the current FAME II scheme there is no provision for the procurement of HFC buses nor an outlay for the hydrogen Refueling infrastructure.

9.1 Procurement Models

9.1.1 Gross Cost Contract (GCC)

If the current FAME II procurement regulations for Gross Cost Contracts (GCC) can also adopted for the HFC buses. The transport authority procuring the buses would only pay a per kilometer cost to the operator/manufacturer for a specified period. In this model, all the earnings of the bus remain with the transport authority (e.g., SRTUs or city road transport agencies). The transport authority pays a pre-decided sum per unit distance to the operator/service provider. While the transport authority usually provides only the conductor for the bus, the driver is deployed by the service provider/operator.

The service provider/operator also takes the responsibility for setting up the Refueling infrastructure, and the maintenance of both buses and ancillary services required for operation. The transport authority could aid in securing the supply for hydrogen in-case there are any production facilities that are operated by the government entities.

This model ensures that the responsibility of efficient service rests with the HFC bus operator/service provider. Therefore, it is in their best interest to provide requisite Refueling infrastructure, maintenance, and other logistics. The transport authority is responsible for monitoring and data-sharing between the two parties to keep track of the service level benchmarks.

9.1.2 Outright Purchase Model

In an outright purchase model, the transport authority purchases the HFC buses and the Refueling infrastructure, this method while providing complete ownership of the assets (bus and Refueling infrastructure) to the transport authority, also places the entire risk and burden of the assets to the transport authority. The transport authority would be is solely responsible in case of breakdowns, technology upgrades, maintenance, and monitoring of vehicles.

[3] Department of Heavy Industries under the Ministry of Heavy Industries and Public Enterprises, Government of India

The model requires the transport authority to be thoroughly conversant with HFC bus operations and Refueling infrastructure technologies. The capital investments required for the outright purchase would also be significantly higher than a GCC model, impacting the overall financials of the state transport authority. Such scenarios need to be analyzed carefully to decide on a procurement model. This requires increased focus in capacity building for public bus agencies.

9.2 HFCEV Buse Procurement and Green HRI Development

9.2.1 Per Kilometer (PK) Rates for HFCEV Buses

If the current FAME II procurement regulations for Gross Cost Contracts (GCC) were to be adopted for HFCEV buses, the transport authority procuring the buses would only pay a per kilometer cost of the operator / manufacturer of the HFCEV bus, eliminating the upfront cost of bus ownership as well as the cost of developing the Refueling infrastructure and maintenance of the system.

Factors like operational routes, daily average kilometers, vehicle utilization, hydrogen fuel utilization, refueling infrastructure costs would influence the PK rates for HFC buses, therefore it is essential that the operational aspects such as route planning and refueling infrastructure are planned in an optimal manner with consultation and corroboration between all the stakeholders to arrive at a feasible PK rate during the tendering process.

9.2.2 Engagement and consultations with HFCEV Bus OEMs/ Operators

The transport authority should hold extensive consultations with the HFC bus OEMs/ Operators, the state transport authority must understand the tender clauses from the bidders' perspectives and make changes in the tender if necessary to minimize risks for the bidders, lower costs for the bidders and allow flexibility in configurational requirements to maximize the number of participants in the tenders. Sharing operational fleet data with the HFC bus operators prior to the bidding stage can enable the bidders to plan effectively and sign feasible service level agreements.

The range of HFC buses is determinant of the hydrogen storage tank capacity on board the bus, while the bus manufacturer/OEM might design it with certain appropriate considerations. The optimal tank sizing that might be required for a state transport utility might be different, thus a collaborative approach between the OEM/ bus manufacturer, operator and the state transport utility can result in the most efficient sizing of the storage tanks and minimize any additional expenditure for modifications.

9.2.3 Institutionalized Procurement of HFCEV Buses and Hydrogen Refueling Infrastructure

Taking cue from the procurement of renewable energy through a central institution like SECI, a similar special purpose entity can be constituted for the procurement of the HFC buses and associated hydrogen Refueling infrastructure. This special purpose entity can address the challenges of nation-wide policies coming from various ministries for the various states with different demands and financial constraints.

The special purpose entity would have the responsibility and objectives of coordinating between the various ministries including the Ministry of Petroleum and Natural Gas, Department of Heavy Industries, and state-owned transport corporation. The entity would also be responsible for developing procurement standards, coordinating in disbursing central funds to state corporations, and facilitating the use of green hydrogen for HFC buses.

To take advantage of economy of scale, the special purpose entity can also procure e-buses at a large scale and distribute them to various agencies. This can also help financing institutions (if involved) secure timely payments and thus, lower the cost of financing.

9.2.4 Financing HFCEV Bus Procurement

To address some of financing challenges, apart from the state/ central government entities playing the role of an aggregator and doing bulk procurement of HFC buses on behalf of the financially weak state transport utilities, joint leasing options can also be explored, wherein the capital cost of the HFC-buses is not borne by the state transport utility, but by a lender-OEM consortium. Similar models have been used in the United States and Costa Rica, for e-bus procurement. Climate fund with special low interest rates for low emission buses may also be tapped – similar to the Green Climate Fund's financing of e-bus procurement in Armenia.

9.2.5 Investment in Hydrogen Refueling Infrastructure

Hydrogen Refueling infrastructure is expected to contribute considerably to the CAPEX of HFC fleet adoption, the cost would primarily depend on the type of hydrogen (green, blue, or grey), proximity of the hydrogen production plants to the Refueling stations, storage and Refueling technology, total number of HFC bus deployment withing the transport utilities fleet, and the range and storage capacity of hydrogen on-board the buses. In-addition the cost of setting up the Refueling stations (location cost, civil works, etc.) must also be factored into the total cost calculations. A detailed system-level cost estimation is warranted to evaluate the viability and investment required for the implementation of the hydrogen Refueling infrastructure.

The procurement of hydrogen can also be directed through an institutionalized mechanism. Existing PSU's which have shown interest in developing green hydrogen capabilities like IOCL, HPCL and BPCL can use their existing infrastructure and distribution models with the necessary upgrades to cater to generation, distribution, and sale of hydrogen through such special purpose entity

This can also enable the standardization of bidding processes and documentation required for generators to produce and sell hydrogen. Financing hydrogen generation projects also would be easier for lenders and banking institutions as there would be a centralized/institutionalized off-taker for the generated hydrogen fuel. An institutionalized approach for the generation of green hydrogen can reduce offtake risks and provide some payment security, enabling the development of green hydrogen production facilities in India.

9.3 Challenges and Barriers in Public Sector HFCEV Bus Procurement

As of this writing, there are no HFC buses deployed commercially with state transport authorities in India, which limits our knowledge of the challenges related to procurement. We instead use our observations from e-bus procurement tenders and processes as a reference point for HFC bus procurement and setting up related Hydrogen Refueling Infrastructure (HRI).

9.3.1 Structuring fair and balanced tender documents/contracts for procurement

A balanced tender with a structured contract should enable an optimal and feasible Per kilometer (PK) price for the transport authorities and provide the HFC bus operator with contracted revenues to operate the buses as per the agreement. Per kilometer price is the rate that is charged by the contractor for operating the bus per km over the contract period. Factors like operational routes, daily average kilometers, vehicle utilization, hydrogen fuel utilization, refueling infrastructure costs would influence the PK rates for HFC buses. Learnings from the e-bus procurement models must be applied here to avoid unsatisfactory tender outcomes such as undesirable bid prices.

Familiarity with Hydrogen Fuel Cell Technology on the part of STUs is low. From past tenders that were announced for the procurement of e-buses, which unfortunately were not successful in most parts of the country, it is necessary that the contracts for the HFC buses take a more structured and decisive approach. Adding in the requirement for the Refueling infrastructure, would further complicate the contract for HFC bus operations. To address these barriers, extensive consultations are required between the various stakeholders including the state road transport corporations, HFC bus operators and manufacturers, refueling infrastructure developers and other relevant authorities before a tender is floated.

9.3.2 Lack of alignment of procurement tender specifications with bus operational requirements

A common challenge that e-bus operators faced was the lack of details of the routes or existing fleet operations shared in the tender documents and even during the pre-bid consultations. This made it difficult for the bidders to understand the operational requirements and enter into service level agreements with the transit agencies. This information gap is largely attributed to the limited understanding of the transit agencies about e-bus operations and lack of their preparedness prior to issuing tenders.

A review of tender documents of e-bus procurements showed that apart from stipulating the daily running kilometers for e-bus operation, there is hardly any information given regarding the route(s), the serving depot (s) or service level benchmarks. This results in high risk-perception amongst the bidders that often translates to higher price quotations in bids for risk hedging. There have been several instances till now where tenders had to be cancelled due to submission of limited number of bids or high price quotations.

9.3.3 Bundled or Unbundled Hydrogen Refueling Infrastructure (HRI)

The hydrogen supply infrastructure could depend on a variety of factors including the availability of feedstock, like renewable energy, policy support and various stakeholder involvement. The generation of hydrogen can be accomplished through the distributed on-site generation or through a centralized production facility. The ownership of these generation stations and distribution infrastructure as well as the business models for economic viability also needs to be delineated and assigned prior to floating the tender for the HFC buses.

9.3.4 Financing and Payment Security in HFC bus Procurement

Public bus transport in India is characterized with lower Earnings Per Kilo meter (EPKM) than the Costs Per kilo meter (CPKM) in a vast majority of cases. This will make financing institutions wary about funding HFC bus procurement which is currently a costly proposition. Any prospective lender, currently contemplating entry strategies for the HFC bus ecosystem, is cautious of the technological nascency of HFC buses, credit unworthiness of the state transport utilities, the resulting lack of payment securities in place, and the escrow mechanism within the GCC model.

A possible reason for lenders' discomfort regarding HFC bus procurement by state transport utilities in India could be similar to the challenges faced by e-bus procurement, i.e.: the escrow mechanism being propagated within the GCC model. Although escrow account-based payment mechanism is intended to secure the payment, the operator and the lender find that they effectively do not have any control over the escrow account; rather, the control lies solely with the state transport utility. Thus, the objective gets defeated. Further, the only asset in possession of the lender (within the concession period) would be the depreciating assets such as HFC buses and some refueling infrastructure. Thus, a major barrier that needs to be addressed is how can a lender secure its capital in case of default or dispute. Since there is no clear answer to that at the moment, the confidence of potential lenders to step into lending for HFC bus procurement is naturally expected to be quite low.

9.3.5 Innovative Solutions for HFCEV Bus Procurement

Best practices in e-bus and HFC bus procurement from across the world show that the key to an effective transition is innovative partnerships. A majority of bus operations in India are by private operators who do not have access to basic resources such as land for parking and charging/Refueling, or even access to incentives. Such operators will have to rely on partnerships with other players to leverage their expertise and reduce overall risks. While a well-executed GCC model can mitigate risks for both the HFC bus operators/service providers as well as the for the state transport authority, the success lies in its implementation. Economies of scale can be achieved when multiple players come together, reducing overhead costs, and subsequently reducing the TCO.

Oil companies, who are realigning themselves with the shift in fuel consumption, have begun to explore options of collaborating with hydrogen infrastructure players and technology providers to transition from their core business to a more sustainable hydrogen as a fuel. A key to reducing the TCO is to identify high-impact factors and leverage them for maximum benefits. Even financial institutions like banks and insurance companies can help rejig the cash flow model by collaborating with energy providers and reducing the burden on the agency, whether it is public or private.

Infrastructure costs for hydrogen generation, transport, storage, and Refueling stations can be optimized by collaboration with state transport authorities and HFC bus operators/service providers. State transport authorities can partner with hydrogen infrastructure providers can open new avenues of business by allowing other users (private, commercial HFC vehicle operators) to utilize any excess capacity within the system. Such solutions aid in the transition of a variety of services, such as school buses, overnight tourist buses and office commute buses which operate on pre-determined routes and have fixed kilometers travelled per day.

A key to viable HFC bus operations is reducing risks. This can be achieved by separating components and ensuring that multiple technically compatible players are brought to the fore. Identifying risk factors and ensuring that they are financed and handled by competent stakeholders (for instance, HFC bus technology, green hydrogen generation dispensing stations, annual maintenance, etc.) can lead to an efficient business model for HFC buses in the country

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Section 7.0 GHG emissions life cycle analysis (LCA) of buses powered by alternative energy sources

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List of Acronymns

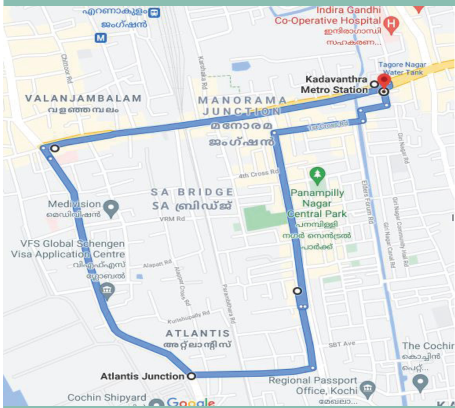
ESS	Energy Storage System
FCE	Fuel Cell Engine
HFC	Hydrogen Fuel Cell
HFCEV	Hydrogen Fuel Cell Electric Vehicle
H2	Hydrogen
KSRTC	Kerala State Road Transport Corporation
LEV	Low Emission Vehicle
ZEV	Zero Emission Vehicles
OEM	Original Equipment Manufacturer
BEV	Battery Electric Vehicle
CNG	Compressed Natural Gas
LNG	Liquified Natural Gas
LCA	Life Cycle Analysis
TCO	Total Cost of Ownership
VGF	Viability Gap Funding
CCUS	Carbon Capture Utilization and Storage
NDC	Nationally Determined Contributions
IEA	International Energy Agency
GW	Giga Watts
GoI	Government of India
RE	Renewable Energy
JNNSM	Jawaharlal Nehru National Solar Mission
MNRE	Ministry of New and Renewable Energy
PESO	Petroleum and Explosives Safety Organization
LiON	Lithium Ion Batteries
NHM	National Hydrogen Mission
NITI Aayog	
IOCL	Indian Oil Corporation
PEM	Proton Exchange Membrane
SMR	Steam Methane Reformation
PLF	Plant Load Factor
WACC	Weighted Average Cost of Capital
AEM	Anion Exchange Membrane
BPCL	Bharat Petroleum Corporation Limited
PSA	Pressure Swing Absorbers
HRI	Hydrogen Refueling Infrastructure
H2LCM	Hydrogen Hub Location and Capacity Optimization Model
ANERT	Agency for Non-Conventional Energy and Rural Technology
KSEBL	Kerala State Electricity Board Limited
CEPZ	Cochin Export Processing Zone
PV	Photo Voltaic
RPO	Renewable Purchase Obligations
MU	Million Units (of power)

SECI	Solar Energy Corporation of India
INR	Indian Rupees
VRE	Variable Renewable Energy
PPA	Power Purchase Agreement
HRS	Hydrogen Refueling Station
HT/EHT	High Tension
KSERC	Kerala State Electricity Regulatory Commission
CERC	Central Electricity Regulatory Commission
IPP	Independent Power Producers
CIAL	Cochin International Airport Limited
REC	Renewable Energy Certificate
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
US DOE	United States Department of Energy
LCOH	Levelized Cost of Hydrogen
HDSAM	Hydrogen Delivery Scenario Analysis Model
STU	State Transport Undertakings
O-D	Origin Destination Pairs
KURTC	Kochi Urban Road Transport Corporation

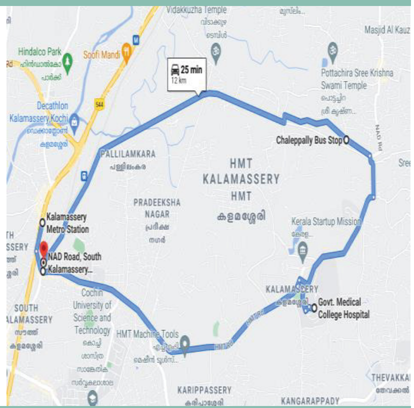
APPENDIX A1

SCENARIO B: Intra-City 9-meter HFC Fleet - Kochi Metro Feeder Routes

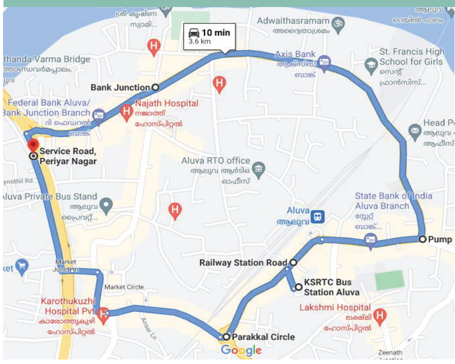
Route 1:
Kadavanthara Metro to Ravipuram



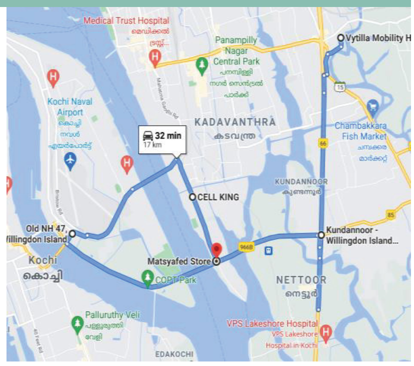
Route 2:
Kalamassery Metro to Govt. medical college



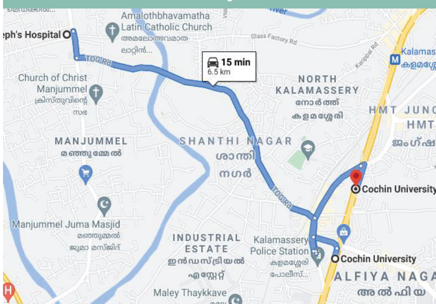
Route 3:
Aluva Metro to Railway station



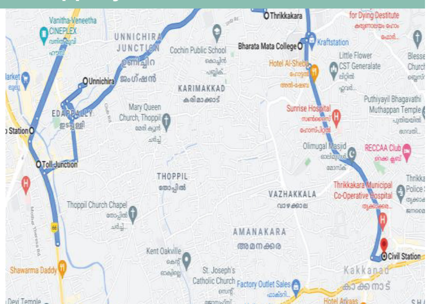
Route 4:
Vytilla Metro to Theavara



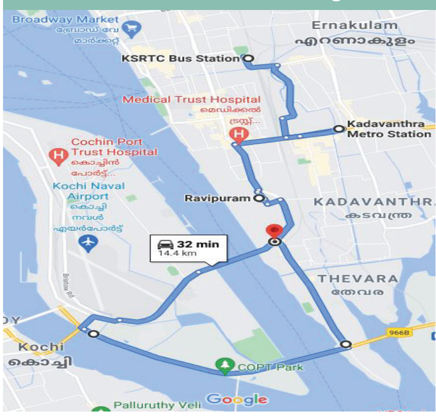
Route 5:
CUSAT Metro to Manjumel



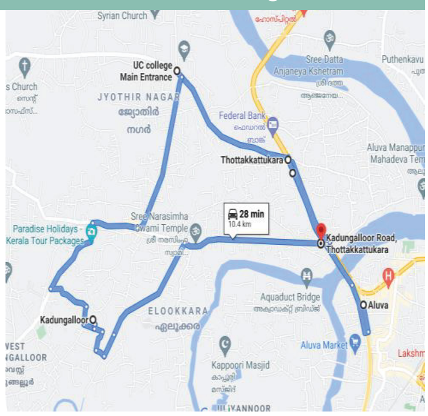
Route 6:
Edappally Metro to Civil station



Route 7:
KSRTC bus station to SH college

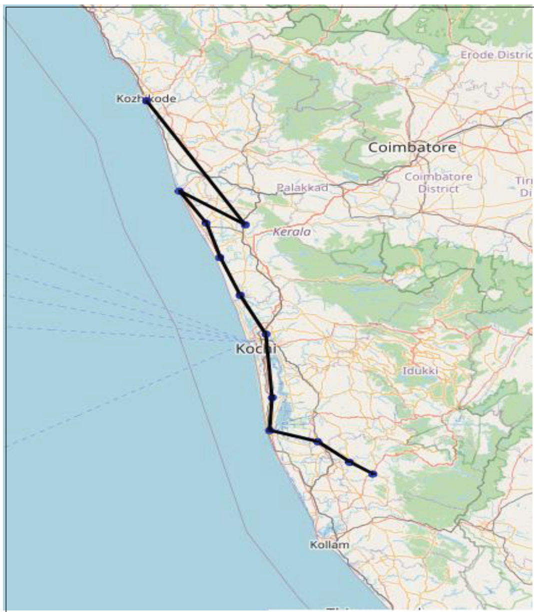


Route 8:
Aluva Metro to UC college



APPENDIX A2

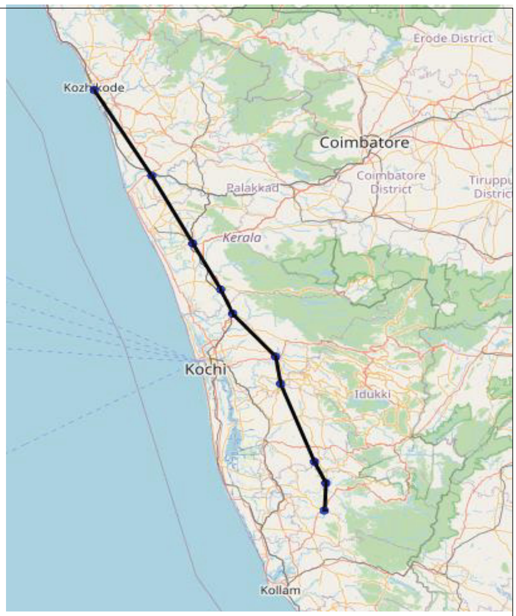
SCENARIO A: Inter-City 12/13-meter Long-Haul HFC fleet routes



Route -1:

Kozhikode> Thiroor> Ponnani> Guruvayoor> Thriprayar> Kodungalloor> Ernakulam> Cherthala> Alappuzha> Changanassery> Aranmula> Pathanamthitta.

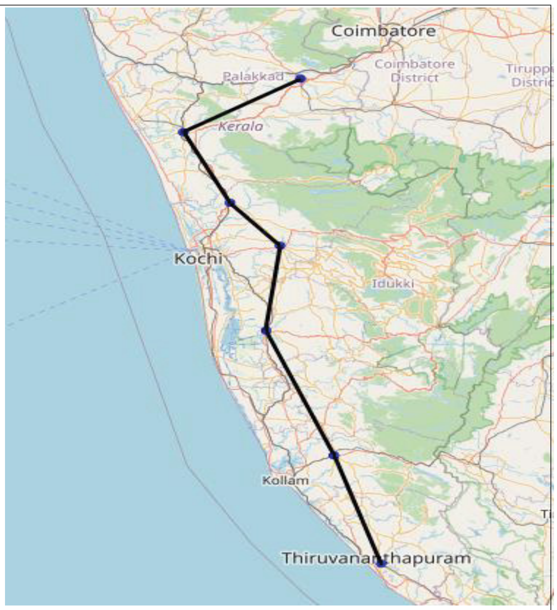
394 Kms



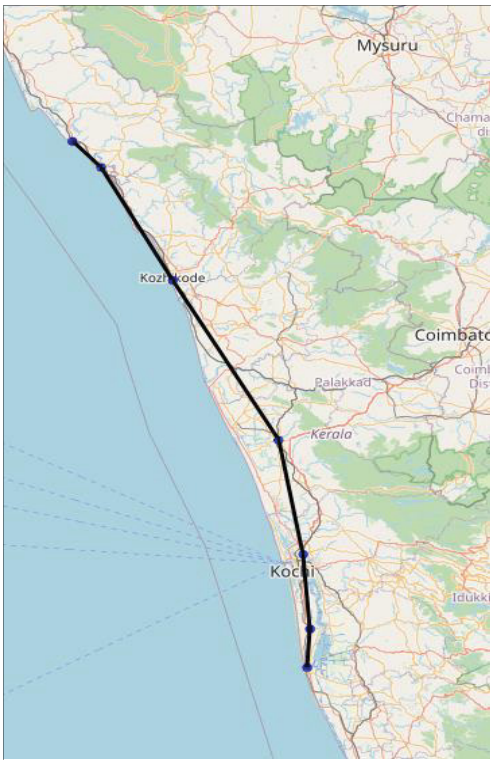
Route-2:

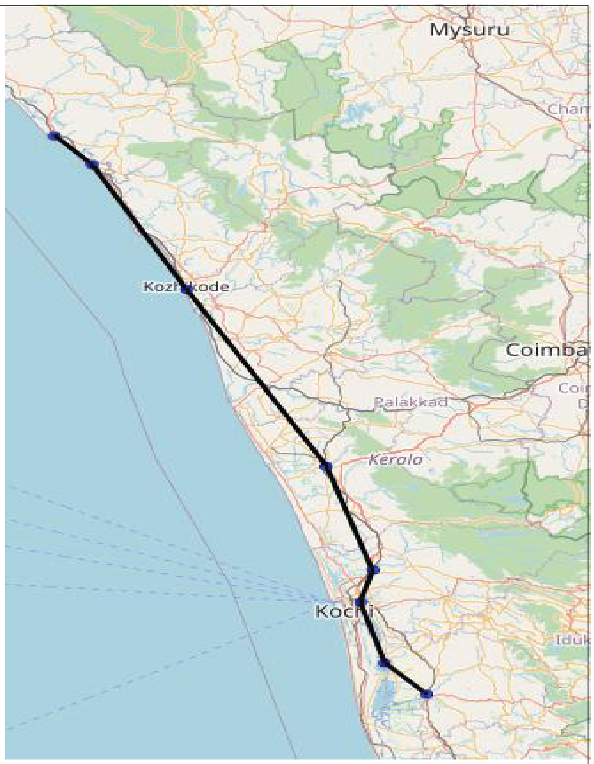
Pathanamthitta> Manimala> Koothattukulam> Moovathupuzha> Angamaly> Chalakudy> Thrissur> Kuttipuram> Kozhikode.

310 Kms



Route-3:	**Route-4:**
TVM> Kollam> Alappuzha> Ernakulam> Thrissur> Palakkad.	TVM> Kottarakkara> Kottayam> Moovathupuzha> Angamaly> Thrissur> Palakkad.
353 Kms.	346 Kms





Route-5:

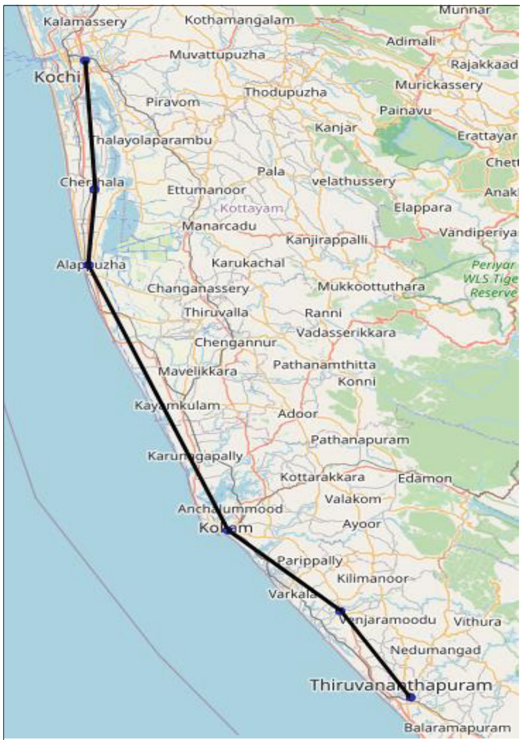
Alappuzha> Cherthala> Ernakulam> Thrissur> Kozhikode> Thalassery> Kannur.

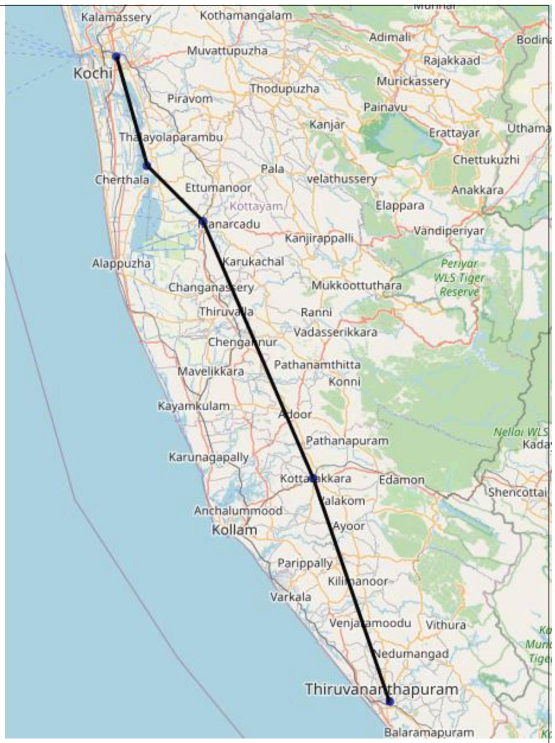
345 Kms

Route-6:

Kottayam> Vaikom> Vytilla> Aluva> Thrissur> Kozhikode> Thalassery> Kannur.

354 Kms





Route-7:

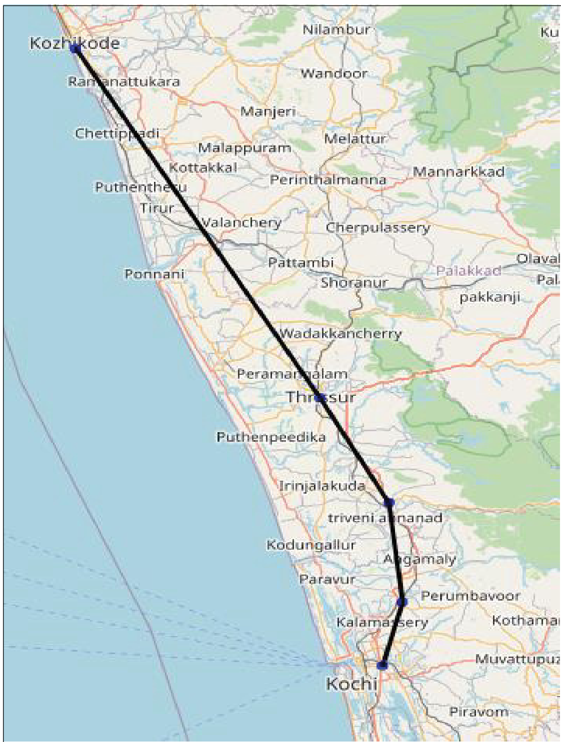
Vytilla Mobility Hub> Cherthala> Alappuzha> Kollam> Attingal> TVM.

205 Kms

Route-8:

TVM> Kottarakkara> Kottayam> Vaikom> Vytilla Mobility Hub.

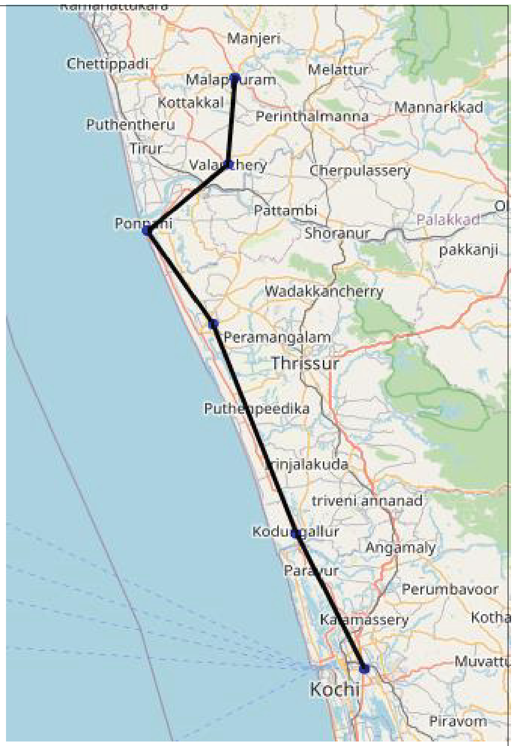
209 Kms



Route-9:

VytillaMob. Hub>Aluva>Chalakudy> Thrissur> Kozhikode.

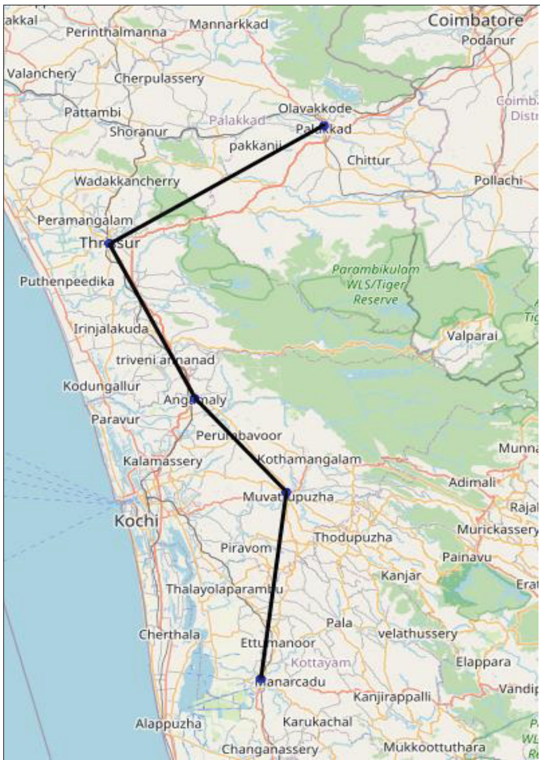
197 Kms

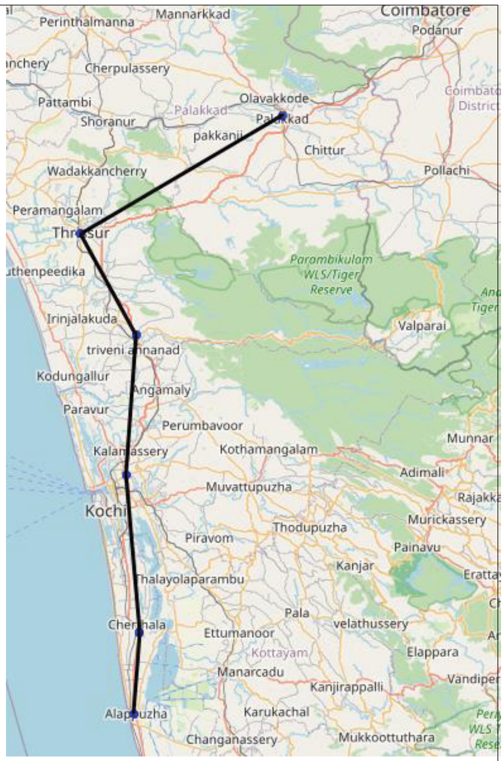


Route-10:

Malappuram> Valanchery> Ponnani> Guruvayoor> Kodungaloor> Vytilla Mobility Hub.

158 Kms





Route-11:

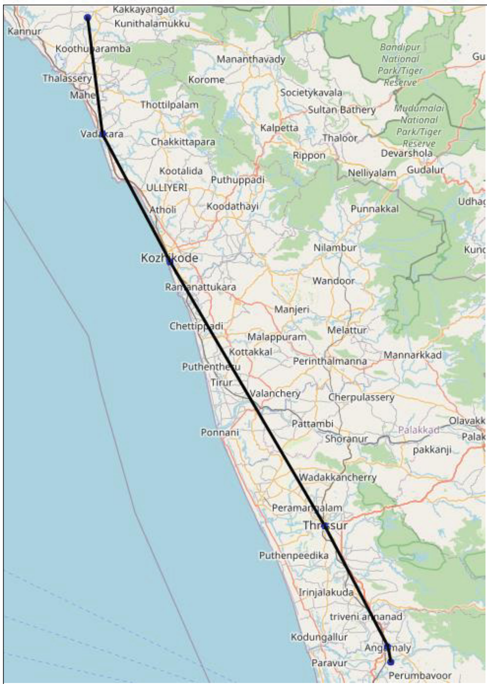
Kottayam> Moovathupuzha> Angamaly> Thrissur> Palakkad.

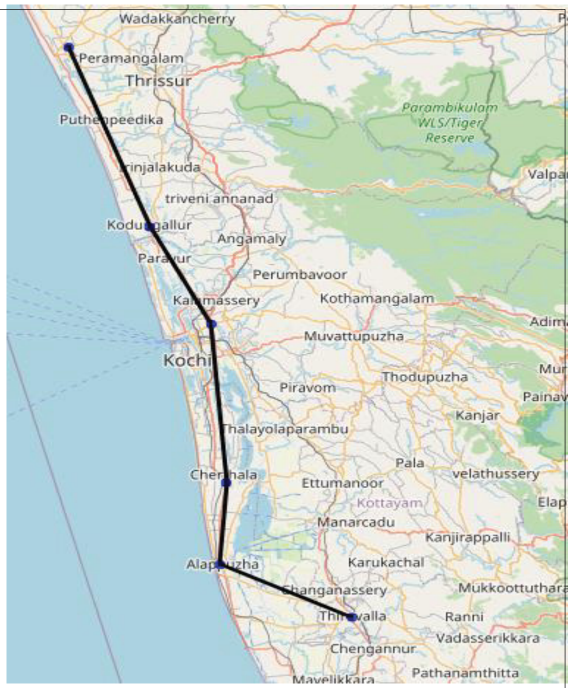
201 Kms

Route-12:

Alappuzha> Cherthala> Ernakulam> Chalakudy> Thrissur> Palakkad.

202 Kms





Route-13:

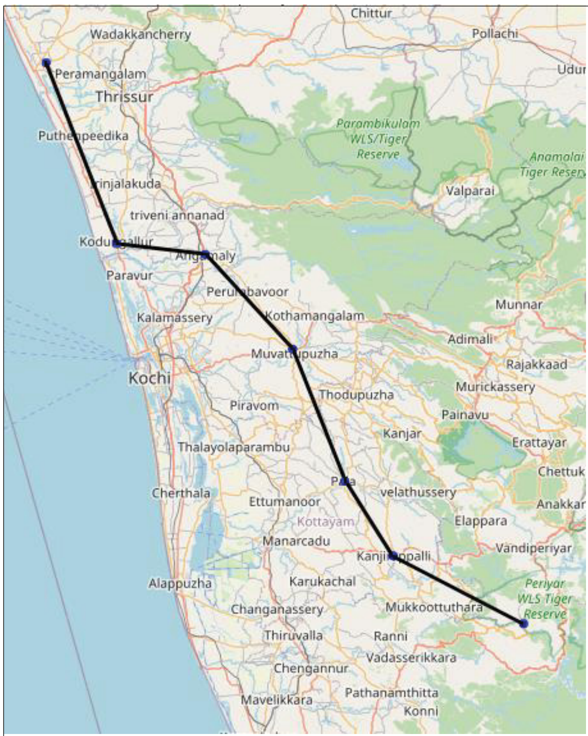
Kannur Airport> Kozhikode> Thrissur> Angamaly> Kochi Airport.

258 Kms

Route-14:

Guruvayoor> Kodungaloor> Ernakulam> Cherthala> Alappuzha> Thiruvalla.

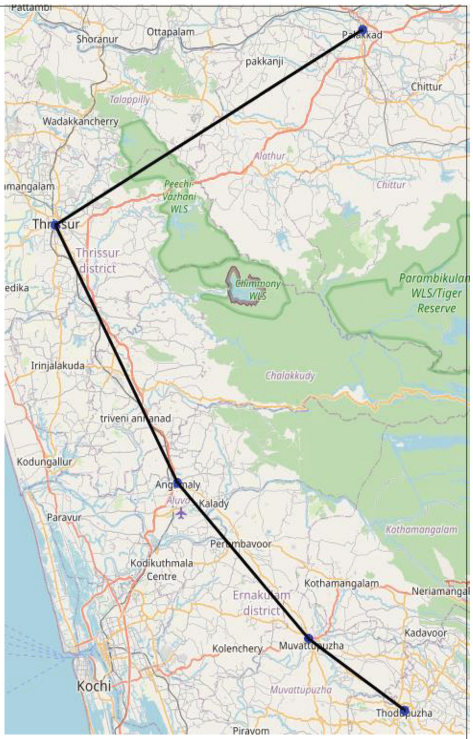
178 Kms



Route-15:

Guruvayoor> Kodungaloor> Angamaly> Moovathupuzha> Pala> Kanjirapally> Sabarimala.

218 Kms



Route-16:

Thodupuzha> Moovathupuzha> Angamaly> Thrissur> Palakkad.

167 Kms


H_2
H_2