The City College of New York

# Sustainability in Infrastructure

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## Topic: Feasibility of hydrogen powered BRT in Guwahati

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# Abstract

This paper examines the feasibility of using hydrogen energy on Bus Rapid Transit (BRT) systems, focusing on its advantages, challenges, and current state of the technology. Guwahati was chosen as the location to first examine the need and potential of a BRT system in the city and second, study the feasibility of using hydrogen energy to power its buses.

The paper begins with three introductory sections. The first one introduces the city of Guwahati to its readers highlighting some of the key issues as it pertains to its population growth, public transportation and infrastructure development. This sets the base to argue for the need of a dedicated BRT system for the city. The second introductory section talks about hydrogen energy in general, highlighting the different types and technologies used for production. The third introductory section briefly introduces the present status of hydrogen energy adoption and development in India and highlights some of the salient features of the National Hydrogen Energy strategic master-plan.

The methods and analysis section of the paper delves into the concept of Total Cost of Ownership (TCO) and how it relates to the information presented on this paper. This is followed by a comparative analysis of three different kinds of vehicle drive-trains, namely - Battery Electric Vehicles (BEVs), Fuel Cell Electric Vehicles (FCEVs) and Internal Combustion Engine (ICE) vehicles. These drive-trains are considered in the context of heavy-duty short-range and long-range segments. It evaluates the sensitivities of each system measured against a number of metrics to determine the eventual winner, if any. The different scenarios considered as it pertains to timelines are 2020, 2030 and 2050. BEVs are found to hold a competitive advantage over both FCEVs and ICE vehicles in the short-range segment by 2050. However, the competition between FCEVs and BEVs is more nuanced in the long-range segment during the same time period.

The discussion section breaks down the importance of India's collaboration with the Gulf Cooperation Council (GCC) countries with regard to the research and development of a green hydrogen economy in the country. It highlights some of the key nuances of this collaboration as it pertains to signed Memorandums of Understanding (MoUs) on bilateral project undertakings. This section also sheds light on the National Hydrogen Mission (NHM) of India while delving into the details of this mission's number game in dollar amounts and also the key stakeholders involved.

This is followed by a deeper dive into the city of Guwahati as it pertains to its need for a BRT system over a Metro Rail Transit (MRT) system. Furthermore, the paper assesses the potential for renewable energy production in the state of Assam and how this is connected to the feasibility of homegrown green hydrogen production facilities in Guwahati itself. It is found that Assam has substantial potential for solar and hydro power generation. The economy and current state of transport

infrastructure of the city are also briefly discussed to provide the reader with some context to better understand the urgent need for state of the art, planned public transportation in the city.

Finally, the conclusion highlights the key takeaways from this study. Firstly, it is expected that BEVs will be quite competitive as long as daily utilization rates are below 500 km and they run on well-defined routes that allow for longer charging periods. This includes waste disposal, commuter bus routes, and service vehicles. Secondly, FCEV trucks may hold a slight advantage for routes exceeding 500 km, but their competitiveness relies on significant cost reductions across a plethora of technologies and on achieving substantially low costs of hydrogen transportation. The goal should be to achieve net emissions reductions as soon as possible. The process of achieving that can be accelerated by making it easier to access renewable or low-carbon sources of electricity generation and significantly reducing electricity grid emissions. And lastly, Compressed Natural Gas (CNG) can serve as a potential transitional option, but it is necessary to exercise caution when making investments and establishing infrastructure for CNG. The overarching sentiment of this assessment hints towards the fact that both BEVs and FCEVs have roles to play in achieving cleaner heavy-duty transportation with low GHG emissions. However, it is important to prioritize electrification through BEVs and only resort to FCEVs for segments within heavy-duty transport where BEVs are not viable.

# Introduction

## Guwahati

Guwahati is the capital of the state of Assam, located in Northeast India. It is a riverine city whose economy is primarily driven by agriculture, trade, commerce, and services. It is the largest city in North-East India and is an important commercial and educational hub in the region, serving as the gateway to South-East Asia.

As of 2023, the metro area population of Guwahati stands at 1,176,000 which is a 1.8% increase from 2022. Over the last 20 years, the city has undergone significant growth and development, particularly in terms of infrastructure and urbanization while its population has been constantly increasing at an average rate of 1.65% per year. The Guwahati Metropolitan Area has expanded to include neighboring towns and cities, leading to an increase in the population density and overall population of the area.

The rapid population growth of Guwahati has led to a significant strain on the city's transportation infrastructure. The city's narrow roads, coupled with the lack of dedicated bicycle lanes and pedestrian infrastructure, have made it difficult to accommodate the growing number of vehicles on the roads. As a result, traffic congestion has become a significant problem, leading to longer travel times and reduced productivity for commuters. The city's public transportation system has also struggled to keep up with the demand. Overcrowding of public transport, particularly buses, has led to an uncomfortable and inconvenient commuting experience for many residents. Additionally, the city's lack of a dedicated metro system has further exacerbated the problem. Another very important fact to note is that the entire state of Assam and most of Northeast India belongs to seismic zone V. This is the topmost bracket of seismic zones and indicates the potential for severe intensity impact in case of earthquakes, which themselves are rather frequent in the region. Assam experiences an average of 71 earthquakes per year which roughly translates to 5 every month or one every 5 days. This information is important to understand the constraints for infrastructure development in the state. Everything needs to be approved for severe earthquakes (>6.5 on the Richter scale) and that makes the development process expensive while the permit approval process becomes increasingly strenuous and tedious.

To address the challenges associated with transportation and traffic congestion, the government of Assam has taken some steps over the last 15 years. An example of this is the Guwahati Masterplan 2025 which was drafted in 2008 by the Guwahati Metropolitan Development Authority (GMDA). However, a lot of the ideas from that master-plan failed to undergo implementation for a plethora of reasons but mostly related to land acquisition issues and financial constraints. Some of the ideas which did get implemented include the construction of new highways, bridges, and flyovers, which have helped to ease traffic flow in some areas of the city. These were coupled with greenifying efforts which included building more parks and recreational spaces and planting trees along avenues. There was a detailed plan on the 2025 master-plan for the implementation of both a BRT system with dedicated bus lanes and a light rail system. The latter was eventually scrapped because the GMDA had concerns about ridership levels. They thought it would not be profitable enough and the estimated cost of construction did not justify the price tag. However, the BRT system did not get implemented either and land acquisition issues were cited for the non development of dedicated bus lanes. The GMDA is currently in the process of developing the next 15 year master-plan to be released in 2025 and according to the CEO of the organization, it is extremely likely that the topic of BRT would once again be included in it.

The city's population continues to grow, putting additional pressure on transportation infrastructure, and congestion remains a significant challenge. The government has acknowledged the need for further investment and infrastructure development to tackle these issues and improve the quality of life of Guwahati's residents.

## Hydrogen energy

Hydrogen energy is in its early stages of development, but holds significant potential in facilitating the transition from hydrocarbons to renewable energy sources. Despite being the most abundant element on Earth, it is not readily available for use as a means for energy. That being said, it is possible to obtain hydrogen energy through variegated processes which make the case for commercial feasibility. Based on the method used, hydrogen energy is broadly categorized into five different colors - Grey, Blue, Green, Red and Turquoise. The reason why colors specifically are used to differentiate between the various methods is unknown. Some of the various methods include steam methane reforming (SMR), partial oxidation, and coal gasification, which utilize hydrocarbons like natural gas, oil, and coal - these would classify as grey hydrogen and they contribute to exacerbating the greenhouse effect by virtue of greenhouse gas (GHG) emissions. Hydrogen can also be produced from renewable feeder energy sources such as hydropower, solar, and wind through methods like electrolysis, photolysis, and other thermo-chemical processes - these, on the other hand, would classify as green hydrogen. Currently, the global demand for hydrogen stands at 70 million metric tons per year, with over 76 percent being produced from natural gas, 23 percent from coal, and the remaining portion from water electrolysis **[1](Lambert, 2020).**

Hydrogen has one of the highest specific energy densities from among all sources of energy (including fossil fuels). The only known exception is nuclear energy which has a specific energy density higher than that of hydrogen. This translates to approximately 34 kWh of usable energy per kg for hydrogen, versus diesel which holds less than half that amount (~13 kWh) **[2](ThrustDrive).** In simpler terms, this means that 1kg of hydrogen which is used in a fuel cell to power an electric motor, contains almost the same amount of energy as a gallon of diesel. Renewable energy sources in general, have some of the lowest specific energy densities, Among them, Concentrated Solar Power (CSP) is somewhat of an outlier and its specific energy density stands at around 5-8 kWh/kg.

However, at room temp (~293 K) and standard atmospheric pressure (1 atm), hydrogen is a gas and its molecules are loosely packed. Additionally, hydrogen has the lowest atomic weight of any element. As a result, its molecules are very small. Hence, despite having a substantially high specific energy density, hydrogen has a low mass per unit volume. Furthermore, since hydrogen is a highly reactive gas, it needs to be stored under high pressure or at very low temperatures in order to increase its density.

## Hydrogen energy in India

Hydrogen is in the early stages of integration into India's energy sector, with active involvement from both government and non-government funding agencies in research and development projects. These projects focus on various aspects of hydrogen, including production, storage, utilization, power generation, and transportation applications. In 2003, the National Hydrogen Energy Board was established, followed by the formulation of the National Hydrogen Energy strategic masterplan by the Ministry of New and Renewable Energy (MNRE) in 2006, which prioritizes green energy initiatives in transport and power generation **[3](Priya, 2021).** India is also participating in a national innovation challenge for developing clean hydrogen technologies. This is being done with an aim to advance the global hydrogen market and overcome logistical and technological barriers associated with large-scale production, distribution, storage, and utilization of hydrogen. India targets about three-fourths of its hydrogen production by 2050 to be from renewable energy sources **[3](Priya, 2021).**

Research and development efforts in India would focus on the efficiency improvement of water-splitting reactions and the discovery of new materials, catalysts, and electrodes which would enable the acceleration of these processes. Fuel cell technology is a prominent area of research, with over 100 research groups dedicated to its advancement. Numerous foreign and local companies are presently engaged in hydrogen-related activities in India. Some of these including Praxair (USA), Linde (a global member of the Hydrogen Council), Inox (an Indo-US joint venture), Air Liquide (France), SAGIM (France), Air Products (USA), Fuel Cell Energy (USA), H2Scan (USA), ITM Power (UK), Heliocentris (Germany), Aditya Birla (India), Bhoruka Gases Ltd (India), Gujarat Alkalies and Chemicals Limited (India), Gujarat Heavy Chemicals Ltd (India), Air Science Technologies, and Sukan Engineering Private Limited (India) **[3](Priya, 2021).**

# Methods and Analysis

## Total Cost of Ownership Assessment

This section examines the long-term evaluation of the economic viability of different drive-trains and fuels in the heavy-duty transport sector using a Total Cost of Ownership (TCO) model. It provides a comprehensive measure of the lifetime costs of acquiring and operating a transport vehicle per kilometer **[4](Hall, Spencer et al, 2020).** The TCO formula considers discounted fixed and variable costs over the vehicle's lifetime, divided by discounted kilometers traveled. Going forward, Battery Electric Vehicles would be abbreviated and referred to as BEVs, Fuel Cell Electric Vehicles as FCEVs and Internal Combustion Engine vehicles as ICEs.

The term "Discount rate" is important to understand in the context of this paper and will aid in interpreting the following graphs. This rate is used to translate future costs in terms of present value. It encompasses factors such as capital costs, time preference rates, and risk aversion. A higher discount rate suggests increased risk and reduces the current value of future cash flows, while a lower discount rate increases the current value. In this scenario, a higher discount rate emphasizes upfront costs in the TCO evaluation, diminishing the significance of future costs. Here, it is important to note that the cost structure of battery electric vehicles (BEVs) is primarily weighted towards upfront capital costs. On the other hand, the cost structure for internal combustion engine (ICE) vehicles are primarily weighted towards lifetime fuel costs. As a result, discount rates tend to disadvantage BEVs. Thus, to eliminate any biases, this study adopts a uniform discount rate of 15% across the heavy-duty vehicle segment, regardless of drive-train and fuel types **[4](Hall, Spencer et al, 2020).**

## Drive-trains in the heavy-duty transport sector

The process by which a vehicle's drivetrain converts the energy from fuel into mechanical or motive energy is crucial in determining the overall cost and environmental effects of the drivetrain. However, it's also essential to take into account the efficiency of the production, storage, and distribution processes of the fuel. This is particularly critical for hydrogen fuel cell electric vehicles since there are significant conversion losses in the upstream fuel production processes.

Figure 1 illustrates the complete conversion efficiency of an FCEV and a pure electric vehicle in the value chain. The process for both vehicles begins with the input of electricity, which is assumed to be 100 units. The source of hydrogen for the FCEV is assumed to be electrolytic hydrogen, which is the most likely source of low-carbon hydrogen competitive in India. The conversion efficiency of the electrolysis process is about 70%, resulting in a loss of 30 units of energy input. The transmission, distribution, and storage (TDS) phase causes an additional loss of 26%. In contrast, the electrolysis stage is skipped in a BEV, and only around 5% of losses occur in the TDS phase. After that, minor losses occur when AC current is converted to DC current for charging the battery, as well as in the battery charging process. The FCEV, however, has zero losses in these stages. For the FCEV, the next step involves converting hydrogen into electricity to power the vehicle's electric motor, resulting in a further loss of 50%. In terms of conversion loss, the FCEV incurs a 50% loss in the conversion of hydrogen into electricity to power the vehicle's electric motor **[4](Hall, Spencer et al, 2020).** This phase is skipped in the case of a BEV. In the end, both drive-trains experience slight losses in the conversion of DC current to AC current and the conversion of electrical energy to mechanical energy in the electric motor, with losses of approximately 5% and 10%, respectively.

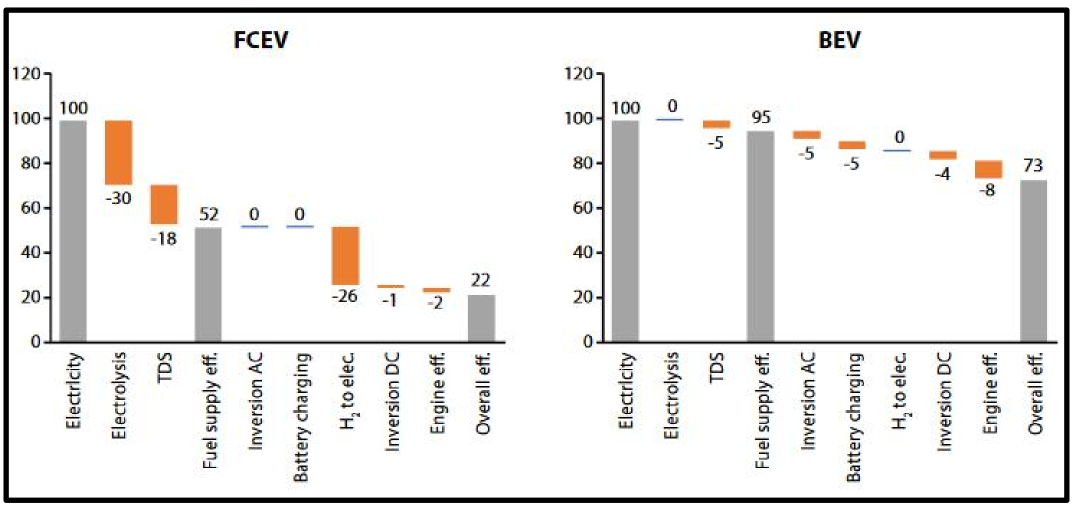



***Fig 1: Value chain conversion efficiency of FCEV (left) versus BEV (right)***
***Source: TERI analysis, TDS = Transmission, distribution and storage***

As a result of the value chain requiring multiple energy conversions, only 22% of the input electricity is converted into mechanical energy to power an FCEV. Conversely, a BEV can convert 73% of the input electricity into mechanical energy since it skips several energy conversions that cause losses to accumulate in an FCEV **[4](Hall, Spencer et al, 2020).** Comparatively, the conversion efficiency of an internal combustion engine (ICE) vehicle is roughly 33%, which is similar to the full value chain conversion efficiency of FCEVs once upstream conversion losses in fuel production and refining processes are considered **[4](Hall, Spencer et al, 2020).**

The accumulated conversion losses have various negative impacts. Firstly, they affect the economic competitiveness of FCEVs since more input electricity is required to produce the same mechanical energy output. Secondly, if the growth of zero-carbon electricity supply is constrained, direct electrification should be prioritized wherever technically possible and economically attractive to make the use of electricity as efficient as possible. Finally, if the input electricity is not 100% zero carbon, the cumulative conversion losses of FCEVs mean that CO2 emissions per kilometer will be proportionally higher when upstream emissions are accounted for.

In order to make a comparison, an electric city bus equipped with air conditioning is assessed alongside a high-end diesel bus and a low-end diesel bus, both of which also have air conditioning and modern technologies.

## Short Distance Heavy Duty Sector

According to the modeling results based on 2020 cost assumptions, the electric bus demonstrates cost competitiveness in terms of total cost of ownership (TCO) when compared to both the high-end and low-end diesel buses. This holds true when considering the baseline assumptions for electricity tariff, discount rate, and kilometers traveled annually **[4](Hall, Spencer et al, 2020).** That being said, there are a few scenarios in which the electric bus becomes less competitive than the diesel bus, at least in the current context. The annual utilization factor is the primary reason behind this. For example, if the bus travels less than approximately 55,000 kilometers per year, it loses its cost competitiveness compared to the low-end diesel bus. Similarly, if electricity tariffs surpass $0.10/kWh, the electric bus loses its competitive advantage against the low-end diesel bus **[4](Hall, Spencer et al, 2020).** Additionally, if the discount rate is higher than 16%, electric buses lose their economic viability in comparison to Internal Combustion Engine (ICE) buses at current costs. These factors help to explain why the deployment of electric buses has not been as widespread as initially expected, despite successes in other countries and numerous studies indicating the competitiveness of Battery Electric Vehicles (BEVs) against ICE buses.

Nevertheless, the main point remains valid: with projected battery cost reductions of more than 50% by 2030, electric city buses are anticipated to be cost-competitive with ICE variants by 2030 - this is true even in worst-case scenarios.

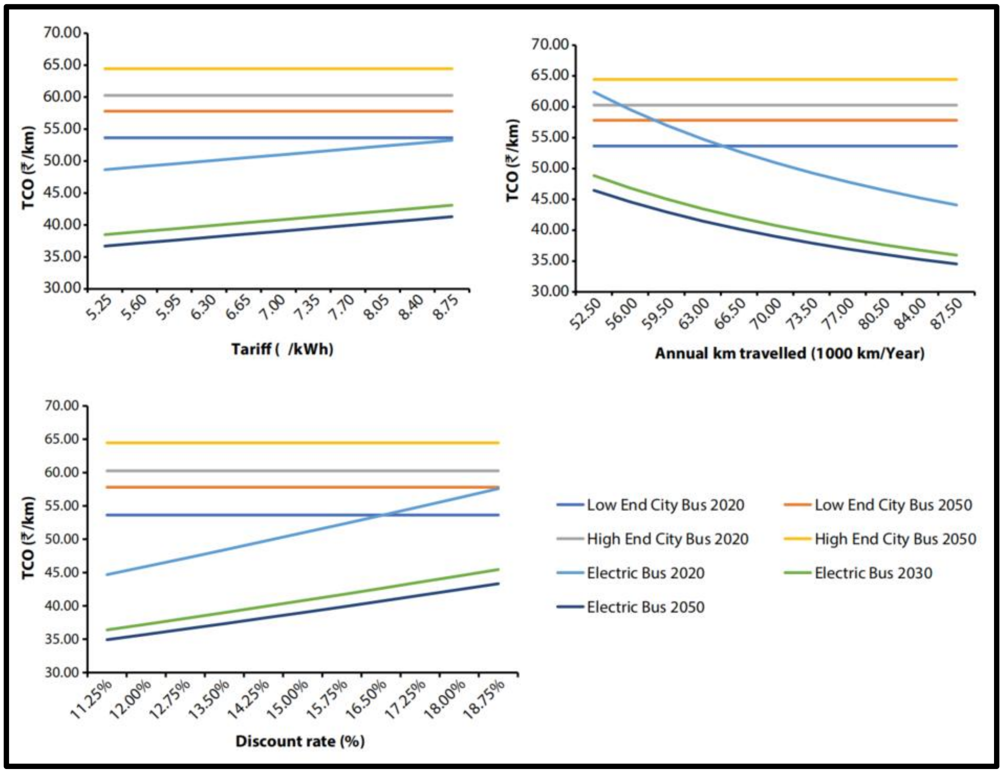



***Fig 2: Sensitivity of BEV and ICE city buses to electricity tariff, annual KM, and discount rate***
***Source: TERI analysis***

Figure 3 provides a comparative analysis of BEV and FCEV buses, highlighting the sensitivity of FCEV Total Cost of Ownership (TCO) to three parameters: fuel price, discount rate, and vehicle capital costs. The comparison is made against EV buses, where all assumptions are held constant at the baseline level. The data for the BEV bus is presented for the 2020 and 2050 models, while data for the FCEV buses is provided for 2020, 2030, and 2050 **[4](Hall, Spencer et al, 2020).**

The findings suggest that FCEV buses are unlikely to be competitive with BEV buses in the long term. If we assume all other factors to remain unchanged, FCEV buses could potentially have a slightly lower TCO than EV buses by 2050 if their fuel costs are 25% lower than the baseline forecast **[4](Hall, Spencer et al, 2020).** However, it's important to note that the assumed baseline already incorporates significant cost reductions for fuel expenses due to anticipated declines in electrolyser costs. Thus, achieving a retail-level delivered cost of $1.65/kg by 2050 seems improbable, especially considering the additional costs associated with transportation and storage, although it might be feasible at the wholesale level. Similarly, FCEVs might pose a competitive challenge to BEV buses if capital costs are 20-22% lower than the baseline forecast **[4](Hall, Spencer et al, 2020).**When considering this scenario, it is imperative to keep note of the aggressive cost declines already observed in capital costs for fuel cell and hydrogen tank storage components in the baseline for this study.

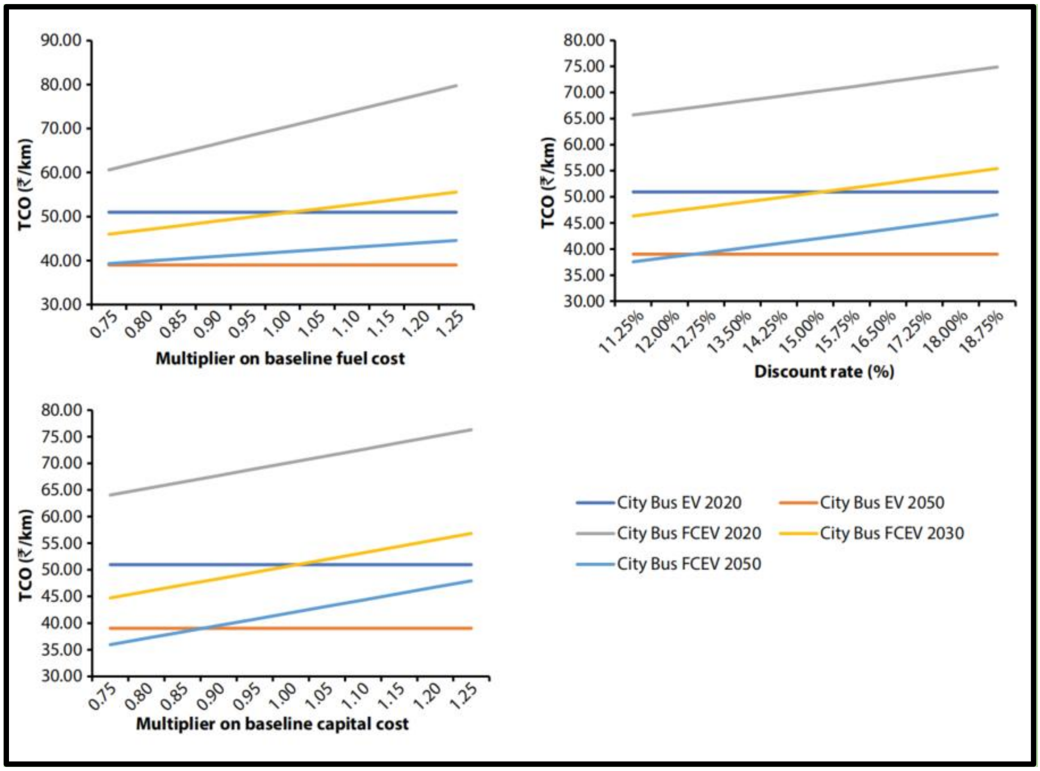



***Fig 3: Sensitivity of FCEV and BEV city buses to fuel cost discount rate, and capital cost***
***Source: TERI analysis***

## Long Distance Heavy Duty Sector (trucks and buses)

Additionally, a distinct evaluation was conducted to compare the costs and emissions of different drive-trains for long-haul trucks, considering whether the distance traveled affected the perceived feasibility of Fuel Cell Electric Vehicles (FCEVs) versus Battery Electric Vehicles (BEVs). In this analysis, a slightly different metric, Total Cost of Ownership/Tonne Kilometer (TCO/TKM), was employed **[4](Hall, Spencer et al, 2020).** TKM is calculated by evaluating the product of the vehicle's payload and the distance covered. Here, the assumed payload was considered, and for BEV trucks, the battery weight was deducted **[4](Hall, Spencer et al, 2020).** The battery weight is determined within the model, taking into account the ideal target range and advancements in energy density of the battery. The baseline assumption for the distance traveled is 800 km, but certain variations to this distance are explored in the sensitivity analysis.

The modeled vehicle corresponds to a heavy-duty truck weighing approximately 25 tonnes, engaged in long-distance interstate travel during the initial five years of its lifespan before transitioning to reduced annual mileage. Much like the BEV variant, the size of the fuel cell and hydrogen tank is calculated based on the assumed target range and weight of the vehicle.

Figure 4 illustrates the results of truck modeling, presenting the total cost of ownership (TCO) and carbon intensity per tonne-kilometer (TKM) rather than per kilometer (KM). In 2020, Compressed

Natural Gas (CNG) trucks are the most cost-efficient option on the basis of TKM. This is due to the significantly lower cost of compressed natural gas (CNG) per unit of energy compared to diesel. This cost advantage is partly attributed to the favorable taxation of CNG as compared to diesel. Electric trucks, on the other hand, have a substantially higher estimated TCO/TKM in 2020 compared to internal combustion engine (ICE) trucks **[4](Hall, Spencer et al, 2020).** This is primarily due to the significant weight penalty imposed by the battery, resulting in a reduction in payload capacity.

However, as battery costs decrease and battery energy density improves according to forecasts, by 2030, long distance BEVs are projected to be on par with their counterparts in the ICE segment in terms of TCO/TKM. By 2050, BEVs may even emerge as the more cost-effective option. Nevertheless, the model estimates that fuel cell electric vehicles (FCEVs) hold a slight advantage over BEVs in the long distance segment due to the absence of a weight penalty.

In terms of emissions intensity, the choice of fuel has limited impact as CO2 intensity is primarily determined by the fundamental conversion efficiencies of the different technologies. In the short term, CNG trucks are the most CO2-efficient option, as the weight penalty of batteries increases the gCO2/TKM of BEV trucks **[4](Hall, Spencer et al, 2020).** Additionally, the grid CO2 intensity in 2020, at around 700 gCO2/kWh, remains relatively high. The CO2 intensity of FCEVs is even higher, surpassing that of diesel trucks by an order of magnitude, due to conversion losses in the FCEV value chain.

The expected reductions in grid CO2 intensity and improvements in battery energy density by 2030 will make BEV trucks more environmentally friendly than CNG trucks. In contrast, FCEV trucks will only have a CO2 intensity similar to diesel trucks by 2050, when the power grid has become decarbonized. This highlights the main problem with FCEVs in terms of mitigating climate change: for heavy-duty segments, the electricity production's carbon intensity must be lower than 250 gCO2/kWh for FCEV trucks to reduce emissions compared to diesel trucks **[4](Hall, Spencer et al, 2020).**

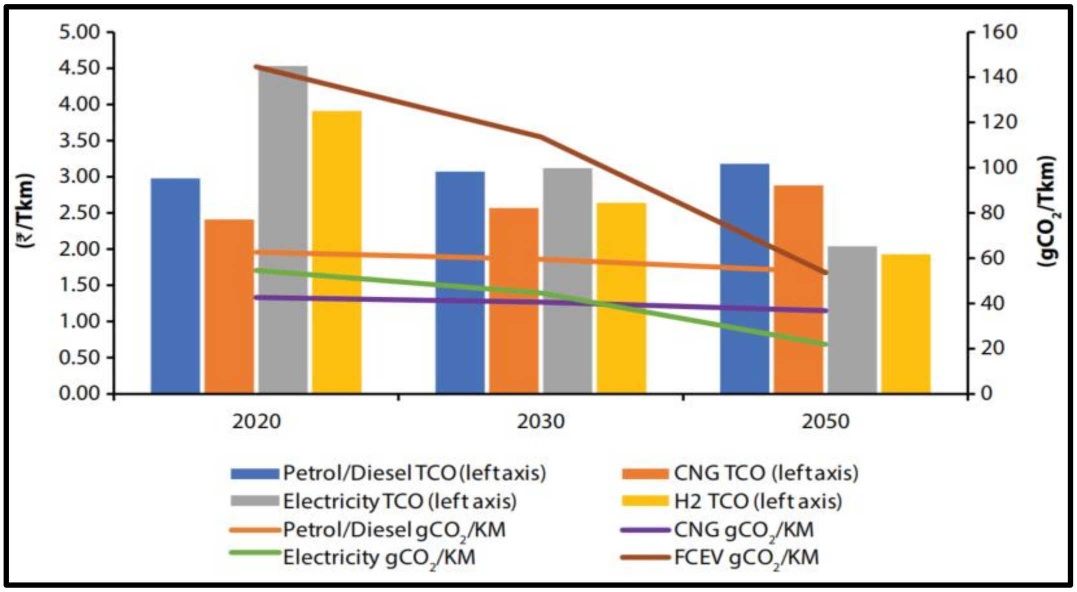



***Fig 4: Modeled results for TCO/TKM and carbon intensity (gCO2/TKM)***
***Source: TERI analysis***

Figure 5 illustrates the primary factors that can impact Battery Electric Vehicles (BEVs) in comparison to Fuel Cell Electric Vehicles (FCEVs). Out of these factors, only two have the potential to influence the conclusions drawn in the previous figure for the year 2050. If the target range of BEVs is hypothetically reduced to less than 500 km, it would lead to a decrease in the required battery size and associated weight penalty. This suggests that BEVs would be competitive with FCEVs for short-distance heavy-duty transportation. Similarly, if the fuel price for FCEVs exceeds the projected value by just 15% ($2.5/kg instead of $2.2/kg), BEV trucks would demonstrate a lower Total Cost of Ownership per Ton-Kilometer (TCO/TKM) **[4](Hall, Spencer et al, 2020).** Achieving this scenario is feasible, considering the ambitious cost reductions needed to achieve a target of $2.2/kg for delivered hydrogen, which includes transportation and storage costs.

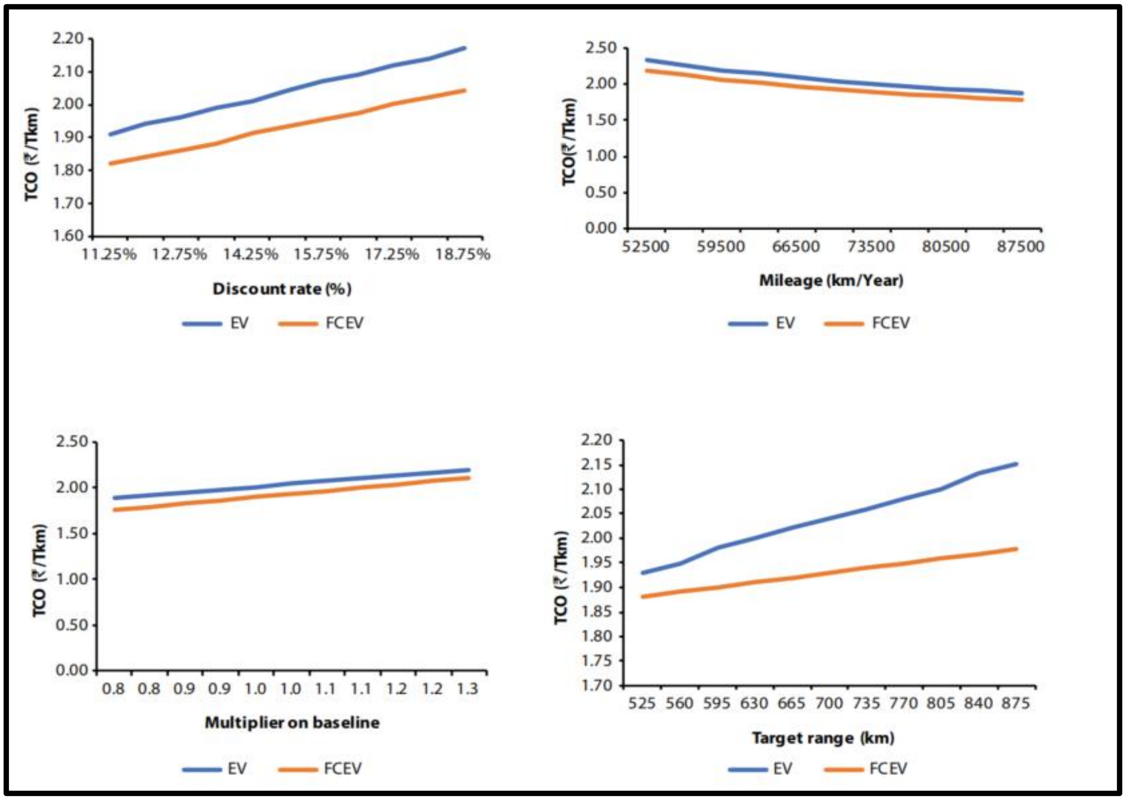



***Fig 5: Key sensitivities of FCEV vs BEV trucks***
***Source: TERI analysis***

# Discussion

## Breakdown of the Gulf Cooperation Council (GCC)

The Gulf Cooperation Council (GCC) countries include Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and the United Arab Emirates (UAE) **[3](Priya, 2021).** These countries are abundant in hydrocarbon resources and currently consume approximately 7 percent of grey hydrogen derived from natural gas. Among them, Qatar ranks as the largest consumer, followed by Saudi Arabia, and Kuwait **[3](Priya, 2021)**. Recently, Saudi Arabia, the UAE and Oman have expressed interest in utilizing hydrogen domestically as part of their decarbonization efforts and also view it as a potential export commodity. Energy security and economic diversification are additional factors motivating their interest in hydrogen.

Moreover, the GCC countries are at the forefront of driving down costs in renewable energy and shaping the energy transition both within the region and beyond **[3](Priya, 2021).** An analysis by the International Renewable Energy Agency (IRENA) suggests that the accelerated deployment of renewable sources of energy in the GCC region could potentially result in a reduction of about 136 million tons of $CO_2$ emissions **[3](Priya, 2021).** These countries view renewable energy as a sector that can generate employment opportunities, particularly for their young populations facing unemployment challenges. This positive spillover effect may also benefit the expatriate population.

Achieving their renewable energy targets would also lead to a projected 17 percent reduction in power sector water withdrawal and a 12 percent reduction in water consumption **[5] (Energy, 2020).** This is significant for the region's water-scarce environment.

Additionally, several facilitating factors make renewable energy investment favorable for the GCC countries. They have the potential to leverage their existing industrial capacity and available capital for infrastructure investments and become some of the world's largest hydrogen producers and exporters. The GCC countries have ample low-cost land and water resources, as well as abundant solar and wind resources, which are essential for green hydrogen production **[5] (Energy, 2020).** Moreover, their geographical proximity to emerging and future markets for cleaner fuels presents strategic advantages.

## The case for H2 in India - framework and mission

***GCC and India cooperation***

India and the Gulf Cooperation Council (GCC) countries share a substantial energy partnership which includes sharing of knowledge and technology. In the 2017-18 fiscal year, India obtained approximately 53 percent of its oil imports from the Persian Gulf, with the UAE and Saudi Arabia ranking as India's third and fourth largest trading partners respectively **[3](Priya, 2021)**. Recognizing their inherent compatibility, India and the GCC have significant potential for expanding their cooperation in cleaner fuel alternatives, specifically hydrogen**.** India has entered into Memorandums of Understanding (MoUs) on renewable energy with most GCC nations. Acme Solar Holdings Ltd, a prominent Indian solar platform, has ambitious plans to invest $2.5 billion in the production of green ammonia and green hydrogen in Duqm, Oman **[6](ACME Group, 2021).** Additionally, they have signed an MoU with the Oman Company (OC) for the infrastructure development of a Special Economic Zone (SEZ). The SEZ will hold, among other things, a manufacturing facility which aims to supply Europe, America, and a lot of southeast Asia with green ammonia, boasting a daily production capacity of 2,200 metric tonnes (mt).

Additionally, India is actively exploring potential avenues for collaboration on hydrogen with Bahrain. After a diplomatic meeting in New Delhi, the two countries joined hands to further strengthen their involvement in the renewable energy capacity-building sector through the development of infrastructure and prioritizing enhanced cooperation between their respective governments and private sectors, particularly in the fields of solar, wind, and clean hydrogen. India inked an agreement with Saudi Arabia in 2019, to cooperate on renewable energy technologies which included the likes of hydrogen **[3](Priya, 2021).** Both nations are currently conducting joint research on green hydrogen energy. Saudi companies like Alfanar and Aljomaih have already invested in India's wind and solar energy projects and may potentially participate in collaborative efforts for the production of Green Hydrogen **[3](Priya, 2021)**.

### *National Hydrogen Mission*

The Indian Prime Minister announced the launch of the National Hydrogen Mission (NHM) in August 2021 with the objective of reducing emissions and promoting renewable energy sources. The overarching aim of the mission is to increase the production and use of Green Hydrogen while setting up global standards in technology, policy, and regulation in the country **[7] (Govt. of India, 2023)**.

The mission's budget amounts to $2.4 billion in total. This includes $2.1 billion for the Strategic Interventions for Green Hydrogen Transition programme (SIGHT) program, $178 million for pilot projects, $48.6 million for research and development, and $47.15 million for other mission components.

The SIGHT program will offer incentives for electrolyzer manufacturing and green hydrogen production, positioning India as a leading nation in public funding for green hydrogen. These incentives are expected to attract manufacturers to establish production facilities in India, leading to economies of scale and cost reductions in electrolyzer technologies.

The mission is anticipated to deliver various advantages, including the establishment of export capabilities for green hydrogen and its by-products, the reduction of carbon emissions in industrial, mobility, and energy sectors, decreased reliance on imported fossil fuels and raw materials, the growth of domestic manufacturing capabilities, job creation, and advancements in cutting-edge technologies **[7] (Govt. of India, 2023)**. India's objective is to achieve a minimum green hydrogen production capacity of at least 4.5 million metric tonnes (MMT) annually, coupled with a boost in renewable energy capacity of around 125 gigawatts (GW) **[8] (Sagar, 2023)**. These targets for 2030 are estimated to attract investments exceeding $9 billion and create over $600,000 jobs. By 2030, it is expected that the mission will help prevent approximately 50 million metric tonnes (MMT) of CO2 emissions per year.

The mission's objective is to make India energy-independent by 2047, with green hydrogen playing a crucial role as a substitute for petroleum and fossil-based products. In 2020, India's hydrogen demand reached 6 million tonnes (MT) annually **[7](Govt. Of India, 2023)**. Projections indicate that hydrogen costs will decrease by 50 percent by 2030. Furthermore, India's hydrogen demand is expected to rise fivefold to 28 MT by 2050, with 80 percent of the demand being green hydrogen. This ambitious mission will be driven by Public-Private Partnerships involving prominent private entities and governments at both the federal and state levels. Among the private entities is one of India's largest conglomerates by market cap, Reliance Industries Limited (RIL). RIL has set a target to become a net-zero carbon company by 2035 and plans to invest approximately ₹750 billion in Renewable Energy within the next three years **[7](Govt. Of India, 2023)**. Among public sector participants, Indian Oil is leading the green hydrogen revolution by intending to establish India's first green hydrogen unit at a refinery located in Mathura, a city in Northern India **[7](Govt. Of India, 2023)**.

The National Thermal Power Corporation (NTPC), a public sector entity, has initiated a tender to establish a unique hydrogen refueling station in Leh, a city in Kashmir. This station will be powered entirely by renewables through a standalone 1.25 MW solar grid system. Furthermore, two other hydrogen refueling stations are already up and running—one at the Indian Oil R&D Centre in Faridabad and the other at the National Institute of Solar Energy (NISE) in Gurugram **[9] (Kumar, 2023)**.

Moreover, the Government of India has supported projects to develop and showcase various hydrogen-powered vehicles over the last 5 years or so. These include 6 fuel cell buses by Tata Motors Limited, 50 hydrogen-enriched CNG (H-CNG) buses in Delhi by the Indian Oil Corporation Limited in collaboration with the Delhi government, and 2 hydrogen-fueled internal combustion engine buses by the Indian Institute of Technology (IIT) Delhi in collaboration with Mahindra & Mahindra **[10](Gupta, 2021).** In addition, indigenously developed green hydrogen-powered city buses were unveiled in Pune in August 2022 and in Hyderabad in February 2023. The ones in Pune were developed by the Council of Scientific and Industrial Research (CSIR) in collaboration with KPIT Limited, while the ones in Hyderabad were developed by Olectra Greentech Limited (OGL) in collaboration with Reliance.

India is a front-runner when it comes to low-cost renewable electricity. This, coupled with declining electrolyser prices, gives the country a sizeable advantage in this sector. This, in turn, positions green hydrogen to be not only cost-effective compared to fossil-fuel-based hydrogen but also competitive with international green hydrogen production **[7] (Govt. of India, 2023)**. This observation is supported by a research paper published by the Rocky Mountain Institute.

## Why BRT (and not MRT) in Guwahati?

To alleviate traffic caused by passenger vehicles, the two most widely used public transportation systems throughout the world are Bus Rapid Transit (BRT) and Metro Rail Transit (MRT). In the context of Guwahati, a BRT is (at least on paper) a better option than an MRT for a plethora of reasons, some of which were already highlighted in the introduction section.

Guwahati has an area of approximately 84 square miles and the total number of registered vehicles in the metropolitan area stands at 1.2 million, as per the latest data. In contrast, New York City has an area of about 306 square miles with the total number of registered vehicles being 1.9 million (2022). Thus, Guwahati is almost 3.5 times smaller than NYC while the latter only has 0.6 times more cars than the former. This makes a strong enough case for a dedicated BRT system, especially given that the city will most likely never get a metro or light rail system.

Firstly, the construction cost of a metro is significantly higher than that of a BRT system. The cost of constructing a MRT in Guwahati would be approximately $2.6 billion. Whereas, the cost of building a dedicated BRT system would be around $182 million. This cost difference is significant and cannot be ignored. Secondly, BRT is more flexible than a MRT as it can be designed and implemented to suit the specific needs of a city. Guwahati is a rapidly developing city with a diverse population and varying transportation needs. A BRT system can be more easily integrated with existing road networks and can be modified or expanded as per the changing requirements of the city. In contrast, a metro system has a fixed route and cannot be modified easily, making it less suitable for a dynamic and evolving city like Guwahati. These needs are exacerbated by the fact that the city is situated in a valley and contains numerous hilly regions within its metropolitan area.

Furthermore, a BRT system is operationally more efficient than a MRT. Buses can be added or removed from the system as per demand, and the frequency can be adjusted accordingly. This flexibility ensures that the system is optimized for efficiency and ensures that passengers have a shorter waiting time. In contrast, a metro system has high fixed costs, and the frequency of trains cannot be easily modified. This, in turn, can lead to longer waiting times for passengers during off-peak hours (as is the case with the NYC Subway and PANYNJ Path Trains).

Additionally, a BRT system is more environmentally friendly than a metro system. The construction of a metro system requires the excavation of large areas of land, which can lead to deforestation and soil erosion. In contrast, a BRT system can be built on existing roads with far smaller expansions required and thus, would entail a much smaller ecological footprint. This positive effect can be further enhanced with the use of buses powered initially by a mixture of CNG and BEV drive-trains before the adoption of a fully electric fleet. Thus, a BRT system can help Guwahati to reduce its carbon footprint and improve its air quality.

Lastly, BRT systems provide greater accessibility to public transportation for a larger section of society, especially for people living in the narrow hilly locales of the city. On the other hand, a metro system is typically designed to serve the central business districts and may not reach all parts of the city. The construction of a MRT can also result in the displacement of people living along the proposed route. In contrast, a BRT system can be designed to cater to the specific needs of different parts of the city, ensuring that people have access to public transportation irrespective of their location.

## Assessment of renewable energy potential in Assam

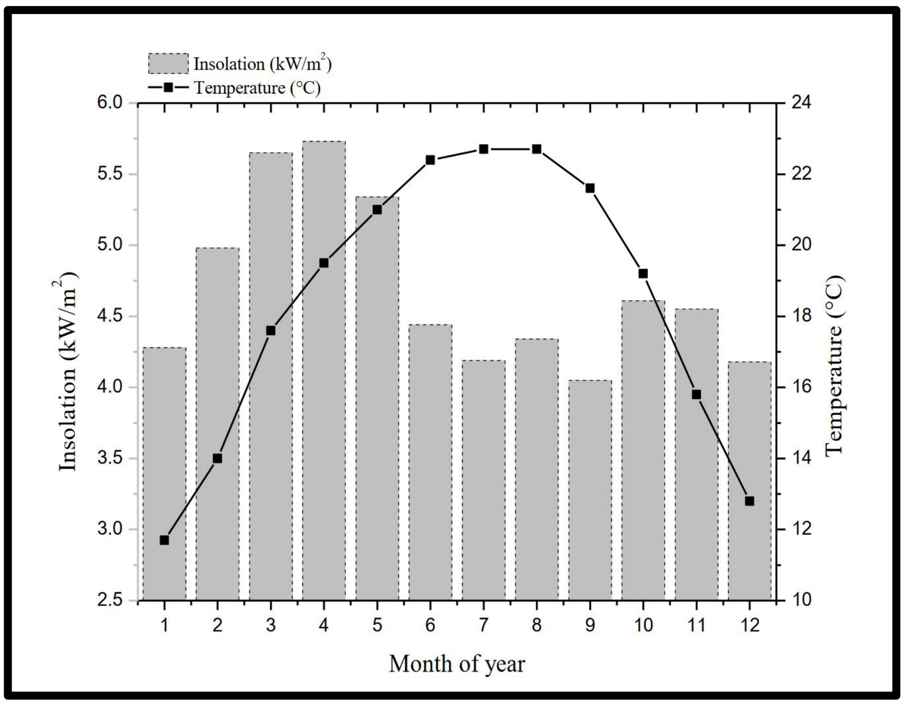
The state of Assam has a total area of 78,438 square kilometers and a population of over 31 million people. The has a significant potential for renewable energy development, specifically with ample opportunities for solar, and hydro power generation.

### *Solar energy*

Assam is located between 24.7 degrees and 28.4 degrees North latitude and 89.4 degrees and 96.0 degrees East longitude, placing it in a region characterized by abundant solar radiation.

The state receives an average daily solar radiation of approximately 4-5 kWh/m2, with peak solar radiation reaching around 5.5-6.0 kWh/m2 during the spring months. This is comparable to the average monthly solar irradiance of Seattle, Washington. This high solar radiation makes Assam highly suitable for solar energy generation. Moreover, the solar energy potential in Assam is estimated to be 13,760 MW, but the current installed capacity is only 300 MW **[11](Saharia, Talukdar, 2014)**.

The state government has set a target of installing 1000 MW of grid-connected solar power capacity. This goal is being pursued through a Memorandum of Understanding (MoU) between the Assam Power Distribution Company (APDC) and NLC India Limited, a central public sector undertaking under the Government of India. Additionally, several large-scale power projects are currently under development in the state, including a 70 MW project in Amguri and a 42 MW project in Jorhat, both located within Assam.




***Graph 1: Average solar insolation per month in Guwahati, Assam.*** **[11]**

***Wind energy***

Assam has a limited potential for wind energy due to its topography and low wind speeds. However, there are some areas in the state that have moderate wind speeds and could be suitable for small-scale wind power projects. The government is exploring opportunities for setting up wind power projects in the state.

***Biomass energy***

Assam has a significant potential for biomass energy generation, with a large amount of agricultural and forest waste generated in the state. The government is promoting the use of biomass-based power plants, and several projects are already operational in the state. The state also has a large number of small-scale biogas plants, which provide a source of clean energy for rural households.

***Hydro power***

Assam has a significant potential for hydro power generation, with several rivers and streams flowing through the state. The state has an estimated potential of around 4500 MW of hydro power. Several large hydro power projects are under development in the state including the 2000 MW Lower Subansiri project located near North Lakhimpur on the border of Arunachal Pradesh and Assam.

## Feasibility of Green Hydrogen in Guwahati

In the case of Guwahati, the feasibility of green hydrogen energy depends on several factors, such as the availability of renewable energy sources, the cost of production, and the demand for hydrogen.

The production of green hydrogen energy requires a significant amount of electricity from renewable energy sources such as solar, wind, and hydro-power. As discussed in the previous section, Guwahati has considerable potential for renewable energy due to its location in the northeast region of India, which receives rainfall and has a hilly terrain suitable for hydro-power generation. From the previous section, it is clear that the state of Assam also has an enormous ***potential*** for solar energy due to its location near the equator. The key word here is "potential" because it still has not been realized yet.

Furthermore, much like the rest of the country, the cost of producing green hydrogen is currently higher than that of conventional hydrogen produced from fossil fuels. However, the cost of renewable energy has been declining rapidly in recent years, and it is expected to continue to fall in the future. In addition, the cost of green hydrogen production can be reduced by improving the efficiency of electrolysis processes, increasing the scale of production, and using renewable energy sources with low capital costs. Thus, the eventual feasibility of green hydrogen energy in Guwahati depends on the cost competitiveness of green hydrogen compared to conventional hydrogen and other alternative fuels. This process is bound to be given a major push in the right direction with the onset of the National Hydrogen Mission.

The demand for hydrogen in Guwahati is currently limited, but it is expected to increase in the future due to the growth of industries such as transportation, power generation, and chemical production. The use of hydrogen in long distance transportation can reduce emissions and improve air quality, while hydrogen-based power generation can provide reliable and flexible electric supply. In addition, the use of hydrogen in chemical production can reduce the use of fossil fuels and contribute to a circular economy. However, the development of hydrogen infrastructure and the adoption of hydrogen technologies may face barriers such as high initial investment, lack of public awareness, and regulatory challenges.

## Economic breakdown of Guwahati

It is important to have an idea of the economy of Guwahati to understand its case for a continuing population increase with an ever growing influx of young people who move to the city from other parts of North-East India and beyond for education and employment. This is imperative to understand and empathize with the city’s urgent need for a BRT system with dedicated bus lanes.

- ***Industry***

  Guwahati has a diverse industrial base, including tea processing, pharmaceuticals, and electronics manufacturing. The city is home to several large industries, including Hindustan Unilever Limited, Indian Oil Corporation, and Numaligarh Refinery Limited. The tea industry is one of the major contributors to the city’s economy. The city also maintains a significant presence in the pharmaceutical industry, with several companies having manufacturing units in the city.

- ***Trade and Commerce***

  Guwahati is an important trade and commerce center in Northeast India, with a large number of wholesale markets, shopping malls, and retail stores. The city has several traditional markets, such as Fancy Bazaar and Pan Bazaar, which are known for their diverse range of products. The city's location on the banks of the Brahmaputra River also makes it a major transportation hub, with several river ports and inland waterway terminals.

- ***Tourism***

  Guwahati is a popular tourist destination, known for its cultural heritage, natural beauty, and wildlife sanctuaries. The city is home to several important religious sites, including the Kamakhya Temple, Umananda Temple, and Basistha Ashram. The city is also the gateway to several popular tourist destinations in the surrounding areas, such as Kaziranga National Park, Manas National Park, and Shillong.

- ***Services***

  The service sector is a significant contributor to Guwahati's economy, with several banks, insurance companies, and other financial institutions located in the city. The city is also home to several IT companies and call centers, which provide employment opportunities for the city's youth.

## Existing Transport Infrastructure in the Guwahati

- ***Road network***

  The road network in Guwahati is well-developed and serves as the primary mode of transport for both people and goods. The city is connected to other major cities in the region through the National Highway 27 (NH-27), which runs through the city. In addition to the NH-27, Guwahati is also connected to other parts of Assam through the State Highway 12 (SH-12) and State Highway 10 (SH-10). The city has a total of 802 km of roads, out of which 156 km are national highways, 169 km are state highways, and the remaining 477 km are city roads.

  The road network in Guwahati is subject to heavy traffic congestion during peak hours, which often leads to long travel times and delays. To alleviate this congestion, the city has implemented several measures, including the construction of flyovers and the widening of major roads.

- ***Railways***

  Guwahati is an important railway junction in the region and is served by the Northeast Frontier Railway (NFR). The city has two major railway stations, Guwahati Junction and Kamakhya Junction, which are connected to other parts of the country through a network of railway lines. The Guwahati Junction serves as the main railway station for the city and handles a large volume of passenger and freight traffic. There is no existing infrastructure for light gauge or broad gauge intra city rail.

- ***Air Transport***

  Guwahati is served by the Lokpriya Gopinath Bordoloi International Airport, which is located approximately 20 km from the city center. The airport is connected to other major cities in India, including Delhi, Mumbai, and Kolkata, through several domestic airlines. The airport also serves as an important gateway to other countries in the region, including Bhutan, Bangladesh, and Nepal.

- ***Public Transport***

  The public transport system in Guwahati is primarily dominated by buses, which are operated by the Assam State Transport Corporation (ASTC) and private operators. The city also has a network of auto-rickshaws and cycle-rickshaws, both electric and gas operated, which serve as popular modes of transport for short distances.

# Conclusion

The feasibility of hydrogen energy on Bus Rapid Transit (BRT) systems depends on various factors, such as the availability of hydrogen fueling infrastructure, cost-effectiveness, and environmental impact. The primary case for hydrogen fuel cell-powered buses is that they were found to have a longer range than their battery-electric counterparts. This allows them to operate for longer periods without the need for refueling. So, while this makes them an excellent option for long distance heavy duty transit like intercity buses that cover long distances or trucks with a substantial weight load, the studies cited on this paper have also provided enough compelling data to consolidate the fact that with electrification of the grid, BEVs will hold a definitive competitive advantage over both FCEVs and ICE vehicles in the heavy-duty short-range sector by 2050.

There is no doubt that in the context of heavy-duty vehicles, weight plays a crucial role. Fuel cell electric vehicles (FCEVs) offer similar high torque as battery electric vehicles (EVs), but at a lower weight. Lion Electric, a Canadian manufacturer of heavy-duty all-electric trucks, and Nikola, an American company developing heavy-duty trucks powered by hydrogen fuel cells, exemplify this. The Lion Electric truck, equipped with a 480 kWh battery pack and a range of 250 miles, weighs around 2 to 5 tons. In contrast, the Nikola One truck, featuring a 250 kWh battery pack and a range of 500-750 miles, weighs approximately 2.5 to 3 tons. Therefore, the FCEV Nikola One delivers more power while being lighter than the EV Lion 8.

As with the heavy-duty short-range sector, with the help of a thorough comparative analysis of the different drive-trains and their respective efficiencies, it is safe to conclude that the decarbonization of the heavy-duty long-distance vehicle segment will likely involve a combination of direct electrification (BEVs) and indirect electrification (FCEVs).

Finally, Guwahati urgently needs the implementation of a well planned BRT system with dedicated bus lanes. However, the buses either need to be a mixture of CNG or electric drive-trains or all electric drive-trains. If it is the former, then the CNG buses could be used as a bridge to electrify the entire fleet and will need to be phased out by 2035.

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