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Hydrogen Buses: An Analysis with a Focus on India's Hydrogen Roadmap

TESI DI LAUREA MAGISTRALE IN MOBILITY ENGINEERING

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Abstract

Growing human activity has resulted in a significant increase in worldwide energy consumption; because the primary sources of energy are still fossil fuels, this industry is associated with the development of toxic by-products that contribute to environmental degradation and climate change. Fuel Cell Systems (FCS) are progressively achieving maturity, driven by a small number of specialized markets and several decades of application research, to the point where many stakeholders are questioning the interest and intensity of its deployment in the transportation sector in general. Carbon-free transportation is envisioned using Fuel Cell Electric Vehicles (FCEV) fuelled by hydrogen derived from renewable energy. This paper seeks to provide light on the topic from the standpoint of road transportation in India. It concentrates on the description of the fuel cell vehicle (FCV) to comprehend its advantages, supply chain of hydrogen and present courses of progress in the sector. India pledged to increasing the percentage of non-fossil fuel sources in power production capacity to 40% and reducing the economy's emissions intensity by 33-35% compared to 2005 levels [1]. However, there is a spatial and temporal disparity between hydrogen production and demand. As a result, hydrogen storage and transportation continue to be major problems for sustainable mobility with FCEVs all over the world, particularly in India.

Key-words: fuel cell bus, hydrogen, renewable energy, India, hydrogen chain.

Abstract in italiano

La crescita dell'attività umana ha comportato un aumento significativo del consumo energetico mondiale; poiché le fonti primarie di energia sono ancora i combustibili fossili, la produzione di energia è associata allo sviluppo di sottoprodotti tossici che contribuiscono al degrado ambientale e al cambiamento climatico. I sistemi a celle a combustibile (FCS), ad oggi spinti da un piccolo numero di mercati specializzati ma da diversi decenni di ricerca applicativa, stanno progressivamente raggiungendo la maturità necessaria a incrementare interesse e diffusione nel settore dei trasporti. In particolare, la decarbonizzazione di questo settore è prevista anche utilizzando veicoli elettrici a celle a combustibile (FCEV) alimentati da idrogeno derivato da energia rinnovabile.

All'interno di questo panorama internazionale, questo lavoro di tesi, si concentra sulla descrizione del veicolo a celle a combustibile (FCV) per comprenderne i vantaggi, la catena di approvvigionamento dell'idrogeno e presentare i progressi nel settore con un approfondimento sul trasporto su strada in India. L'India, infatti, si è impegnata ad aumentare al 40% la percentuale di produzione di energia da fonti non fossili e a ridurre del 33-35% l'intensità delle emissioni rispetto ai livelli del 2005 [1]. Tuttavia, in tutto il mondo e in particolare in India, esiste una disparità spaziale e temporale tra la produzione e la domanda di idrogeno. Di conseguenza, oltre alla produzione, anche stoccaggio e trasporto dell'idrogeno continuano a essere i principali problemi per la mobilità sostenibile con FCEV.

Parole chiave: autobus a celle a combustibile, idrogeno, energie rinnovabili, India, filiera dell'idrogeno.

Contents

1 Introduction

Mobility is undergoing significant sociological and technical developments (car-sharing, car-pooling, selective traffic limits in city centres, etc.). For almost a century, gasoline has been the hegemonic energy resource of road vehicles because it has a high energy density (a high value of heat combustion approximately 44 MJ/kg) [2], is easy to transmit (recharging time 5 minutes) and is cheap to store (plastic tanks made to match the passenger compartment). This extended lifespan has enabled the internal combustion engine to be optimized, a power converter whose efficiency, mass, and volume power densities have substantially grown over time, allowing for significant vehicle volume growth while maximizing comfort, safety, and social status standards. This expansion has escalated the use of this mode of transportation to the point where it is causing particularly serious public health issues in large cities. In 2012, the World Health Organization (WHO, Geneva, Switzerland) designated diesel exhaust as a definite carcinogen based on solid scientific evidence [3,4].

These challenges are addressed by electric vehicles (EVs), the first as a direct result of electric drivetrains and the lack of fossil fuel burning, and the second in tandem with the growing presence of renewables in the electricity mix [5]. The concept of sector coupling (SC) was developed to maximize the benefits of wind and solar energy's stochastic character for industrial, mobility, and residential applications [6]. EVs require a specific charging infrastructure to either recharge batteries or refill hydrogen tanks, like how ICEVs require a specific refuelling infrastructure. The availability of these infrastructures is one of the key challenges to EV commercialization success, and without EVs on the road, the incentives to construct a network are limited. BEVs and FCEVs, on the other hand, are not equally affected by this problem.

Electric operation is appropriate in a confined economy and geographical region due to the electric machine's silence as well as its high efficiency (>90 to 95 percent throughout a wide power range) and power reversibility associated with Li-Ion batteries' good charge–discharge efficiency (>90 to 95 percent) [7]. By recovering braking energy in the urban cycle, this efficient two-way power minimizes overall trip consumption (individual vehicle on commuting trips, local buses, delivery trucks, etc.). On the other hand, significant energy storage is required for intense usage (taxis, car-sharing, deliveries) and lengthy road travels (interurban transportation). This results in a large increase in battery mass, since the latter stores the chemistry reactants required for future electrochemical conversion on its electrodes. The first is the rise in no-load mass conveyed, which has a negative influence on the traction chain's ownership cost, consumption, and power. The energy consumption of a road vehicle is roughly proportionate to its mass when determining the acceptable speed range. It is predicted to be between 100 and 120 Wh per km per ton for a passenger urban car, and it rises when speed rises over 90 km per hr. [6]. As a result, a 1.5-ton car can go 6.1 kilometres on 1 kWh of mechanical energy [6]. The second barrier is the increase in recharging time (and thus the vehicle's availability time, limiting the possibility of intensive use) and/or the requirement for extremely high recharging powers, which affects the electricity network's stability as well as the cost of the related infrastructure. As a result, the cost of employing a battery electric vehicle (BEV) solution has increased. On-road recharging solutions that use an overhead contact line with catenary suspension (tested on a 2 X 5 km section of German motorway near Frankfurt) or energy transmission by magnetic induction (100-meter prototype road built by QUALCOMM and VEDECOM in Versailles, France) allow for a reduction in on-board capacity at the cost of a significant increase in infrastructure complexity and a reduction in charging efficiency [8]. As a result, it is widely acknowledged that, in the medium term (a few decades), present and developing battery technologies will struggle to fulfil this market sector [9].

While the employment of a fuel cell system (FCS) to carry out the bulk of the electrochemical conversion is a lever to break the vicious loop of Autonomy - Mass power - Consumption [10]. It does so while keeping the appeal of electric traction. This solution is to store reactants in a tank designed to efficiently hold the maximum mass and volume densities while allowing for quick recharging at the end of usage (min). The hydrogen tank is not a crucial component of the vehicle, and its capacity may be raised to enhance its size, weight, and autonomy. This means that the on-board mass growth is relatively limited, minimizing the influence on traction power. Energy recharging is quick since it simply takes transferring dihydrogen from a big, fixed tank to replenish the fuel tank [2]. This is a critical feature for intense usage (intercity trucks, taxis, vehicle sharing, and so on) as well as a motivator for incorporating FCS into mobility items.

1.1. Literature Review

The deployment of battery-electric buses and hydrogen fuel cell buses in the public transportation sector plays an important role in reducing transportation exhaust gas emissions [11]. Both technologies' adoption has risen in the last decade, influenced by national energy policy, and pushed more by environmental concerns than by commercial reasons. Many cities are rapidly committing to electrifying their bus fleets with government financing subsidies [12].

Several research [13-16] anticipate that the adoption of zero-emission buses will be successful. One article attempts to model the number of zero-emission buses (ZEB) in European Union (EU) member countries over two-time frames: 2025 and 2030, as well as to forecast the number of clean cars over both time ranges [13]. According to one analysis, when the indirect costs of human health and climate change are considered, the economic sustainability of buses will reach parity with those of fossil fuel equivalents by 2030 [14].

Since the beginning of the century, there has been a growing interest in hydrogen-powered buses. Santarelli et al. [17] conducted one of the first studies on fuel cell buses already in 2003. The emissions and economics of FCBs were assessed in this study. However, the capital costs used in this study were projected costs, which are below currently experienced costs of FCBs [18]. First studies on the social aspects of hydrogen FCBs have focused on general acceptance of hydrogen use as a fuel [16][19] as well as on the corresponding willingness to pay [20][21]. Later, these studies were expanded by looking at the perspectives of FCB implementers and users, demonstrating that there is no "showstopper" that would preclude future generations from using FCBs [16]. Doyle et al. [22] investigated suitability of FCB and BEB from the operator's perspective in different case studies, indicating the environmental and societal benefits of alternative buses in reduction of local pollutants and energy security concerns. In early studies, focus was at first on modification of diesel buses [23] as well as on non-hybridized FCBs in combination with hydrogen produced by steam reforming [24]. At the same time, a research highlights that by 2050, most European countries will most likely be unable to replace traditional diesel buses with replacement buses [25]. As a result, the launch of buses will be determined by technological improvements.

However, there are several roadblocks in the way of widespread adoption of electric and hydrogen buses now. Most of the technical challenges faced by electric buses are related to battery technology. The comparatively poor energy density of batteries is a key obstacle, which is directly tied to a price issue on buses [13]. As a result of recent advancements in battery technology, electric buses now have a greater chance of becoming a viable public transportation option. Furthermore, an attempt has been made to compare the socioeconomic, environmental, and technological circumstances that affect the ability of buses, trams, and trolleybuses to operate [26]. Coleman et al. [27] examine the value chain of green hydrogen for

FCBs, taking into account various hydrogen delivery options, using field data from the 6 MW power-to-gas plant Energiepark Mainz" and the bus demonstration project"H2-Bus""Rhein-Main." Bonilla and Merino [28] did an economic analysis of FCB in 2010, using optimistic capital cost assumptions and carbon credits and subsidies. Cockroft and Owen [29] conducted a cost-benefit study of FCBs in the Perth bus fleet in comparison to diesel and CNG buses, assuming that buses are manufactured under conditions of economies of scale and fully functioning fuel infrastructure. Correa et al. [30] undertook a comparative energy and environmental analysis of several urban buses with an emphasis on Argentina, Brazil, and Chile. Meishner and Sauer [31] analysed the technical and economic aspects of various electric bus designs based on demonstration projects in European cities, but they did not include FCBs. Olabi et al. [32] published a detailed review article on fuel cell applications in the automotive industry. They reviewed the obstacles of using fuel cells in the transportation sector, considering various modes of transportation.

However, there are various renewable bus technologies to select from, making it difficult to determine which is ideal. As a result, one study [33] established a multicriteria assessment (MCA) method to enable studies of the sustainability of public bus technologies. To commercialize electric buses, considerable infrastructure construction must be made. Several studies [34][35] demonstrate a detailed review of infrastructure.

The results achieved by a 12 m-long electric bus with the opportunity charging model surpassed the others, even though the charging time spent on-route normally suggests more vehicles [36]. Unlike battery buses, line configuration is not a cost-cutting strategy for hydrogen bus operations. The present H2 bus fleet is adequate to cover the planned daily mileage [37]. However, for hydrogen mobility, supply infrastructure and associated fuel prices are critical. Its development is associated with substantial investment costs and legal obligations (BImSchG, BetrSichV), which may be a barrier for transportation businesses conducting an initial small-scale testing of the technology.

1.2. Electric Vehicle Bloom

One of the most important aims in the battle against climate change is to increase the number of electric car sales. Vehicle-related greenhouse gas emissions were the greatest source of U.S. greenhouse gas emissions in 2019, accounting for around 29% of total U.S. greenhouse gas emissions [38]. In 2021, electric car sales in Europe increased by 72 percent. In 2030, electric vehicle sales are predicted to account for 29.5 percent of all new vehicle sales [39]. However, if we don't look at the other side of the manufacture of electric cars and their components, this might be a one-sided narrative. This raises the question of whether electric vehicles are truly green.

1.3. Environmental Impact

Lithium-ion batteries have less dangerous metals than traditional batteries that may include toxic metals like lead or cadmium [40] and are thus classified non-hazardous waste. The majority of lithium-ion battery ingredients, such as iron, copper, nickel, and cobalt, are regarded acceptable for landfills and incinerators [41,42]. While lithium mining and production are both safe for landfills, the physical mining of lithium and the creation of lithium-ion are both extremely labour demanding, with the bulk of it not being recycled, resulting in high environmental costs. Furthermore, as lithium-ion battery manufacturing rises, demand for the precious metals required to create lithium-ion rises, potentially posing environmental issues due to the waste generated [43]. Lithium extraction is a resource-intensive process that utilizes a lot of water in particular. One metric ton of lithium is predicted to need 500,000 gallons of water to mine [44]. Chile is the world's biggest producer of lithium [45], and the lithium mines are located in rural locations with a diversified ecology. About 65 percent of the water in Chile's Salar de Atacama, one of the world's driest regions, is utilized to mine lithium, forcing many local farmers and community people to find water elsewhere. Locals frequently have disagreements with the nearby lithium miners. Many reports have surfaced of dead animals and destroyed crops in the areas surrounding many of these mines. There have been reports of dead fish and huge animals drifting down several of the rivers near the Tibetan mines in Tagong, a tiny town in China's Garzê Tibetan Autonomous Prefecture. Researchers discovered that this might have been caused by leaking evaporation pools that have been sitting for months, if not years [46].

1.4. The Scarcity of Relevant Natural Resources

The availability of natural resources, which are required for the construction of electric vehicles, is the most critical aspect that will determine the success of the transition from traditional to alternative fuel vehicles [47]. The worldwide market for electric vehicles, on the other hand, is predicted to worsen the scramble for limited natural resources at the price of natural reserves, environmental norms, and human rights [48]. Shortages in the minerals supply chain are a significant risk that could halt the technology boom sooner than expected, putting multiple countries with strong traditional automotive industries, such as Germany, at a competitive disadvantage by potentially losing many jobs during a prolonged supply crisis. This is particularly true if the global automobile industry's transition away from diesel and gasoline vehicles is less diverse and hence irreversible. A new global economic downturn, as well as natural calamities, are both plausible scenarios that would have a direct influence on demand for minerals, metals, and rare earths. Tesla had to postpone the debut of several of its most recent automobile models several times due to unanticipated supply bottlenecks created by different business partners [49]. As a result, supply dependencies can result in immediate and severe financial losses, which automakers must be prepared for.

Figure 1.2 : Salar de Uyuni, the world's largest salt flat mined for lithium [64]

Figure 1.1 : Lithium salt being carried by workers from Bolivia's salt flats. [64]

Several nations with the world's biggest mineral resources and rare earth reserves, such as the Democratic Republic of Congo, China, and Bolivia, are non-democratic, hybrid governments with authoritarian features. These nations may control supply and consequently influence market pricing due to their near-monopoly position in specific mineral, metal, and rare earth segments. Companies in the extractive and commodities trading industries frequently take advantage of these market arrangements and seek out government partnerships to help them grow their businesses. If supply is curtailed, it will have a direct impact on import-dependent nations like Germany, the United Kingdom, and France. China's rare earths policy [50] and Indonesia's nickel export limitations [51] have both led to skyrocketing commodity prices in recent years, demonstrating how complicated things can get.

When you look at the market concentration of production-relevant natural resources, you'll see that just a few participants [52] (countries with important reserves, private and state mining firms, and so on) dominate the various market categories. The Democratic Republic of Congo accounts for 65 percent of world cobalt supply, China accounts for 65 percent of graphite production, and Indonesia accounts for more than half of nickel supply [58]. Another key metal, manganese, is mostly mined in six nations (South Africa is by far the greatest producer, followed by China, Australia, Gabon, Brazil, and India), which account for about 90% of the global market [58]. In the case of lithium, only four nations (Argentina, Australia, Chile, and China) produce over 80% of the global supply [58]. Other notable lithium producers are China and Zimbabwe. The fact that lithium production is still dominated by a few major multinational companies, particularly from Argentina, Australia, Canada, Chile, China, and the United States, exacerbates the problem on the extractive side. As demand grows, more competitors enter the market, potentially resulting in increased competition. However, because smaller mining businesses are less well-known [53], they may take advantage of commercial possibilities where general regulation is lax.

Overall, supply bottlenecks are a serious and long-term threat, since worldwide demand [54] for a variety of minerals, metals, and rare earths is growing faster than mineral extraction production [55]. More crucially, the availability of adequate amounts of certain of these minerals and metals to meet future market demands is a hot topic of debate [56].

Figure 1.3 : Microbial mat floating in Salar de Llamara. [59]

Figure 1.4 : An aerial view of Evaporation pool in Salar de Tara. [59]

Governments and the global automotive industry need to tap a variety of mineral, metal, and rare earths supply sources to ensure a sustainable supply chain and reduce reliance on corrupt regimes and bad reputed private industries, but consciousness of this need is growing steadily, if at all, at least at the political level, like that outlined in the European Union's Raw Materials Initiative. [57]

1.5. Hindrance in Recycling

There are presently three primary ways for recycling lithium-ion batteries, which are:

- **Pyrometallurgical recovery**
- **Hydrometallurgical metals reclamation**
- **Direct recycling are all examples of pyrometallurgical recovery.**

Even though recycling is a possibility, the cost of obtaining the ores is still higher [59]. With the increased demand for lithium-ion batteries, a more effective recycling program is critical, and several firms are racing to discover the effectual techniques. One of the most important complications is that recycling is not a design goal when the batteries are made [60].

The Faraday Challenge, a £246 million UK government initiative for battery development, is financing research at the University of Birmingham to look into new techniques to recycle lithium-ion batteries [61]. According to Australian research, just 2% of the country's 3,300 tons of lithium-ion trash is recycled [62]. Metals from the electrodes and ionic fluids from the electrolyte can escape into the environment if unwanted MP3 players and laptops wind up in trash. Using robots' technology developed for nuclear power plants, a group of researchers led by the Birmingham Energy Institute is attempting to securely remove and disassemble potentially explosive lithium-ion cells from electric vehicles. Several fires have occurred at recycling operations where lithium-ion batteries were poorly kept or disguised as lead-acid batteries and processed through a crusher [63].

Lithium cathodes decay with time, thus they can't just be thrown into fresh batteries, although some efforts are underway to use old vehicle batteries for energy storage applications where energy density is less critical. "The trouble with recycling any type of battery using electrochemistry is that you never know where it is in its life cycle," explains Stephen Voller, CEO, and founder of ZapGo [64]. Another roadblock, according to Dr. Gavin Harper of the Faraday Institution's lithium recycling project, is manufacturers' understandable secrecy about what goes into their batteries, making appropriate recycling more difficult. Recovered cells are now shredded, resulting in a metal slurry that may be separated using pyrometallurgical methods. This approach wastes a significant amount of lithium. Alternative processes are being investigated by researchers, including biological recycling, which uses bacteria to process the minerals, and hydrometallurgical procedures, which employ chemical solutions in a similar fashion to how lithium is collected from brine in the first place [65]. Harper's goal is to develop a method for securely shepherding lithium-ion batteries through their entire lifespan, ensuring that we aren't pulling additional resources from the earth unnecessarily or allowing toxins from old batteries to cause harm. Because batteries have had such a significant environmental and societal impact, there is a deliberate need to ensure their safekeeping.

2 Fuel Cell Technology

Chemical potential energy (energy retained in molecular bonds) is converted to electrical energy in a fuel cell. Hydrogen gas (H2) and oxygen gas (O2) are used as fuel in a PEM (Proton Exchange Membrane) cell. Water, electricity, and heat are the by-products of the process in the cell [65]. Internal combustion engines, coal-fired power plants, and nuclear power plants all emit toxic by-products, so this is a significant improvement.

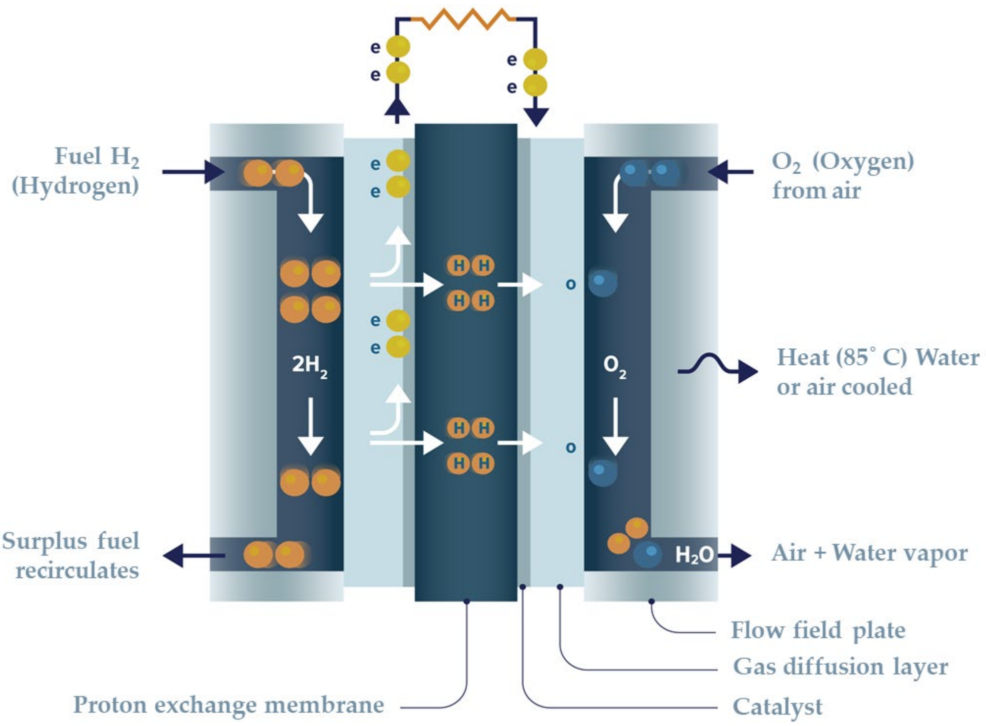

Figure 2.1 : Operating principle of the fuel cell stack [66]

Fuel cells, unlike other batteries, require a continual supply of fuel and oxygen (typically from the air) to keep the chemical reaction continuing. But chemical energy in a battery is usually derived from metals and their ions or oxides that are already present in the battery, except for flow batteries. If fuel and oxygen are available, fuel cells can create power continuously. There are many different types of fuel cells, but they all have an anode, a cathode, and an electrolyte that permits ions to travel between the two sides of the fuel cell. A catalyst at the anode induces oxidation reactions in the fuel, which produce ions (typically positively charged hydrogen ions) and electrons. The electrolyte transports the ions from the anode to the cathode. At the same time, electrons travel through an external circuit from the anode to the cathode, providing direct current power. Another catalyst at the cathode induces the reaction of ions, electrons, and oxygen, resulting in the formation of water and perhaps other compounds. The type of electrolyte used in fuel cells is categorized, as well as the starting time, which ranges from 1 second for proton-exchange membrane fuel cells (PEM fuel cells) to 10 minutes for Solid Oxide Fuel Cells (SOFC)[66].

2.1. Types of Fuel Cell Technology

The kind of electrolyte used in fuel cells is the most important distinction. This categorization affects the type of electrochemical processes that occur in the cell, the type of catalysts required, the operating temperature range, the fuel required, and other criteria. These properties have an impact on the applications that these cells are best suited for[67]. Below table explains the many types of fuel cells.

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	<120°C	<1 kW - 100 kW	40 – 60%	Backup power. Portable power. Distributed generation. Transportation. Specialty vehicles.	Solid electrolyte reduces corrosion. Less electrolyte management problems. Low temperature. Quick start-up and load following.	Expensive catalysts. Sensitive to fuel impurities.
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1 - 100 kW	60%	Military. Space. Backup power. Transportation.	Wider range of stable materials. Lower cost components. Low temperature. Quick start-up.	Sensitive to CO2 in fuel and air. Electrolyte management (aqueous) and Electrolyte conductivity (polymer).
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150 - 200°C	5 - 400 kW	40%	Distributed generation.	Suitable for CHP. Increased tolerance to fuel impurities.	Expensive catalysts. Long start-up time. Sulphur sensitivity.
Molten Carbonate (MCFC)	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	600 - 700°C	300 kW - 3 MW	50%	Electric utility. Distributed generation.	High efficiency. Fuel flexibility. Suitable for CHP. Hybrid/gas turbine cycle.	High temperature corrosion. Breakdown of cell components. Long start-up time. Low power density.
Solid Oxide (SOFC)	Yttria stabilized zirconia	500 - 1000°C	1 kW - 2 MW	60%	Electric utility. Auxiliary power. Distributed generation.	High efficiency. Fuel flexibility. Solid electrolyte. Suitable for CHP. Hybrid/gas turbine cycle.	High temperature corrosion. Breakdown of cell components. Long start-up time. Limited number of shutdowns.

Table 2.1 : Comparison between different Fuel cells [67].

There are various varieties of fuel cells under research right now, each with its own set of benefits, drawbacks, and prospective uses. Polymer electrolyte membrane (PEM) fuel cells, also known as proton exchange membrane fuel cells, have a high-power density and are lighter and smaller than conventional fuel cells[68]. A solid polymer electrolyte and porous carbon electrodes with a platinum or platinum alloy catalyst are used in PEM fuel cells. It runs at 80°C (176°F), which is a comparatively low temperature[68]. They are most commonly employed in transportation and certain stationary applications. Vehicle applications, including as automobiles, buses, and heavy-duty vehicles, are particularly well suited to PEM fuel cells.

The majority of fuel cells run on hydrogen, which may be delivered directly into the system or created within the system by reforming hydrogen-rich fuels like methanol, ethanol, and hydrocarbon fuels[69]. Pure methanol, which is commonly combined with water and delivered directly to the fuel cell anode, is used in direct methanol fuel cells (DMFCs). Because methanol has a greater energy density than hydrogen—though not as high as gasoline or diesel fuel—direct methanol fuel cells avoid many of the fuel storage issues that plague other fuel cell systems. Because it is a liquid, like gasoline, methanol is also easier to transport and deliver to the public utilizing our present infrastructure. DMFCs are frequently used to power portable fuel cell applications like mobile phones and laptop computers.

Alkaline Fuel Cells (AFCs) were one of the earliest fuel cell technologies to be invented, and they were the first form of fuel cell widely employed in the United States space program to create electrical energy and water on-board spacecraft [70]. One of the most significant challenges for this fuel cell type is that it is prone to carbon dioxide poisoning (CO_2). These issues are addressed by alkaline membrane fuel cells (AMFCs), which are less susceptible to CO_2 poisoning than liquid-electrolyte AFCs. However, CO_2 influences performance, and AMFC performance and durability fall below PEMFCs. AMFCs are being studied for applications ranging from a few watts to a few kilowatts [70]. AMFCs encounter a series of limitations, including carbon dioxide tolerance, membrane conductivity and durability, higher temperature operation, water management, power density, and anode electrocatalysis.

The electrolyte of Phosphoric Acid Fuel Cells (PAFCs) is liquid phosphoric acid, which is housed in a Teflon-bonded silicon carbide matrix, while the electrodes are porous carbon electrodes with a platinum catalyst [71]. The PAFC considers modern fuel cells to be "first generation." It is one of the most developed cell kinds, as well as the first to be commercialized. Although PAFCs are primarily used for stationary power production, they have also been utilized to power big vehicles such as city buses. When utilized for co-generation of electricity and heat, PAFCs are more than

85% efficient, but when used to generate electricity alone, they are less efficient (37–42%) [71] and PAFCs are also expensive.

For electrical utility, industrial, and military uses, Molten Carbonate Fuel Cells (MCFCs) are currently being developed for natural gas and coal-based power plants. MCFCs are high-temperature fuel cells that employ a molten carbonate salt combination floating in a porous, chemically inert ceramic lithium aluminium oxide matrix as an electrolyte. Another reason MCFCs are less expensive than phosphoric acid fuel cells are their increased efficiency. When combined with a turbine, molten carbonate fuel cells may achieve efficiencies of up to 65 percent, which is significantly greater than the 37 percent to 42 percent efficiencies of a phosphoric acid fuel cell system [72]. The major disadvantage of current MCFC technology is its short lifespan. The high temperatures in these cells, combined with the corrosive electrolyte, accelerate component damage and corrosion, resulting in shorter cell life.

The electrolyte of Solid Oxide Fuel Cells (SOFCs) is a hard, non-porous ceramic composition. Overall fuel consumption efficiency might reach 85 percent in systems that capture and utilize the system's waste heat (cogeneration) [73]. SOFCs operate at extremely high temperatures, up to 1,000 degrees Celsius (1,830 degrees Fahrenheit) [73]. There are drawbacks to operating at high temperatures. Material durability is also a concern due to the high working temperatures. The primary technological difficulty facing this technology is the development of low-cost materials with good durability at cell operating temperatures. Scientists are actively looking at the possibility of building lower-temperature SOFCs that operate at or below 700°C, have fewer durability issues, and are less expensive.

Conventional fuel cells, create electricity from hydrogen and oxygen while also generating heat and water as by-products. Reversible fuel cell systems, on the other hand, divide water into oxygen and hydrogen fuel using energy from solar, wind, or other sources. This process is known as electrolysis. Reversible fuel cells can produce electricity when required, but they may also store extra energy in the form of hydrogen during periods of high-power output from other technologies (such as when strong winds result in an excess of available wind power). This energy storage potential might be a crucial enabler for renewable energy systems that are intermittent.

2.2. The Hydrogen Economy

International energy estimates predict that hydrogen will have a bright future as an energy carrier. When created in a sustainable manner, hydrogen has several advantages: Ecology, Energy, Innovation high-tech development, Economy, and Autonomy. In terms of tackling environmental issues, fuel cell and hydrogen (FCH) technologies hold considerable potential for transportation applications. As part of a future low-carbon economy, the European Union is committed to improving its transportation infrastructure. The European Council's Strategic Energy Technologies Plan (SET) acknowledges that FCH technologies play a crucial role in this shift. This is consistent with the European Commission's (EC) Communication "Energy for a Changing World - An Energy Policy for Europe," the Lisbon Strategy's goals, and the European Strategic Transport Technology Plan [76]. Fuel cells, as an efficient conversion technology, and hydrogen, as a clean energy carrier, offer enormous potential to help Europe overcome its energy concerns. They will enable the use of renewable energy technology in transportation.

2.2.1. Hydrogen Chain

The European Commission is especially determined to make Europe deliver on its ambitious climate promise of achieving carbon neutrality by 2050 [75]. In its main report related to "The Introduction of Green Hydrogen Technology", it aspires to increase clean output since this incredibly adaptable energy sector has a wide range of possible uses in modern society, from industry to residences to transportation [78]. The current surge in interest in hydrogen as a fuel source demonstrates the advantages of hydrogen in the energy ecosystem. Hydrogen production, storage, distribution, and utilization are all possible paths to a hydrogen economy.

2.2.1.1. Production

The initial stage of the hydrogen value chain is its production, which has previously identified many pathways, processes, and associated technologies. The distinction between large-scale centralized and small-scale decentralized production is very crucial. The current worldwide demand for hydrogen is 70 million metric tons per year, or roughly 330 Mtoe in energy terms. The majority of it is produced from fossil fuels (76 percent from natural gas, almost 23% from coal, and the balance from water electrolysis), which consumes 2% of global coal and 6% of global natural gas [74]. All of this adds up to CO_2 emissions of roughly 830 million tons each year. The majority of CO_2 generated is not caught; only around 130 million tons are captured and used in fertilizer production. The scenario will alter as non-fossil fuel-based hydrogen generation increases, and as more renewables are deployed, the trend will be towards green hydrogen production.

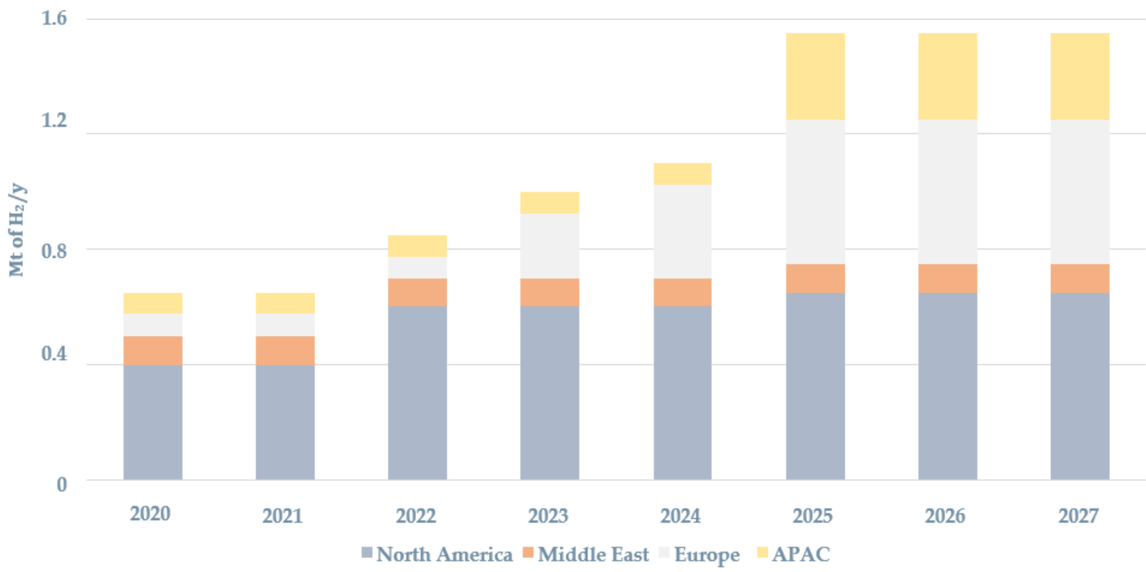

Figure 2.2 : Medium-term 'blue' hydrogen production capacity by region. [77]

2.2.1.2. Storage and Distribution

The second step begins with storage and concludes with final delivery. This stage contains activities that are generally divided into sub-processes; for example, a sub-process could include subterranean gas storage, liquefaction, compression, storage and distribution in gas networks, road, and sea transport, or refuelling.

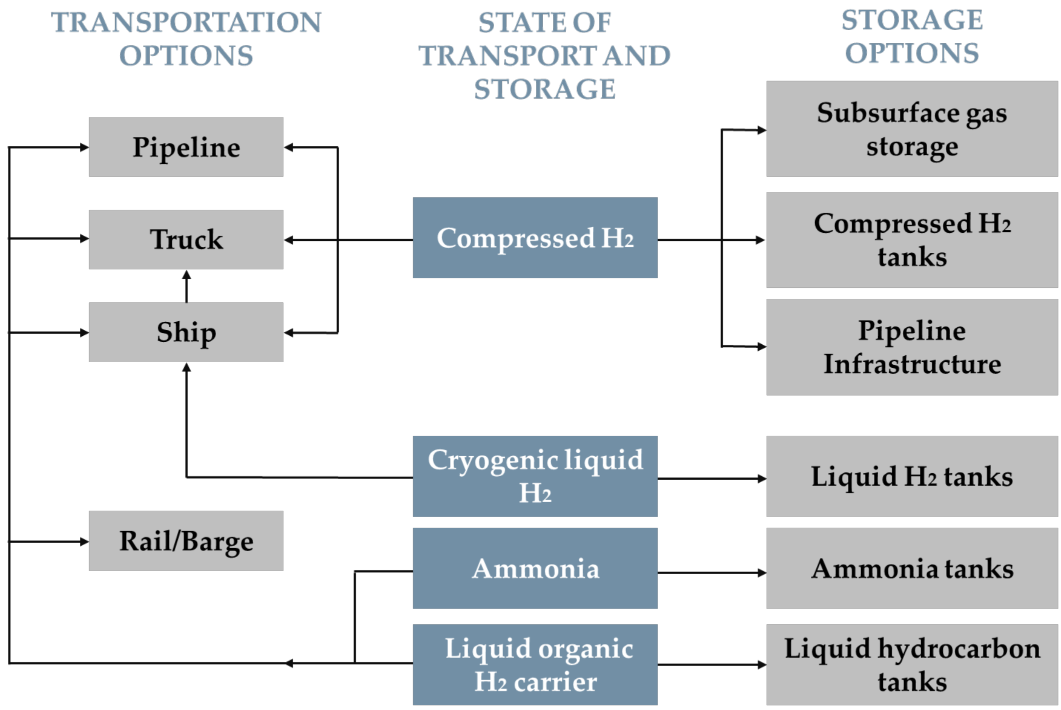

Figure 2.3 : Main options for H2 storage and transport. [77]

Naturally, each of these has its own set of risks and safety problems connected with operating at extremely low temperatures and/or extremely high pressures, necessitating the use of thicker tanks to ensure adequate insulation levels. Likely combinations of hydrogen fuelling processes could be Road distribution in the form of liquefied/compressed gas, followed by a liquid-to-liquid refuelling process, liquid-to-gaseous cryogenic storage systems, or gas - to - gas at various scales, Ship distribution in the form of liquefied hydrogen, including delivery for end-use in oil pipelines and road transport, Gaseous hydrogen distribution via pipeline systems, and also in the existing natural gas infrastructure, hydrogen is blended with natural gas.

2.2.1.3. End-use

The hydrogen value chain is addressed to the primary end-use applications in the mobility/transport and industrial sectors in the third stage.

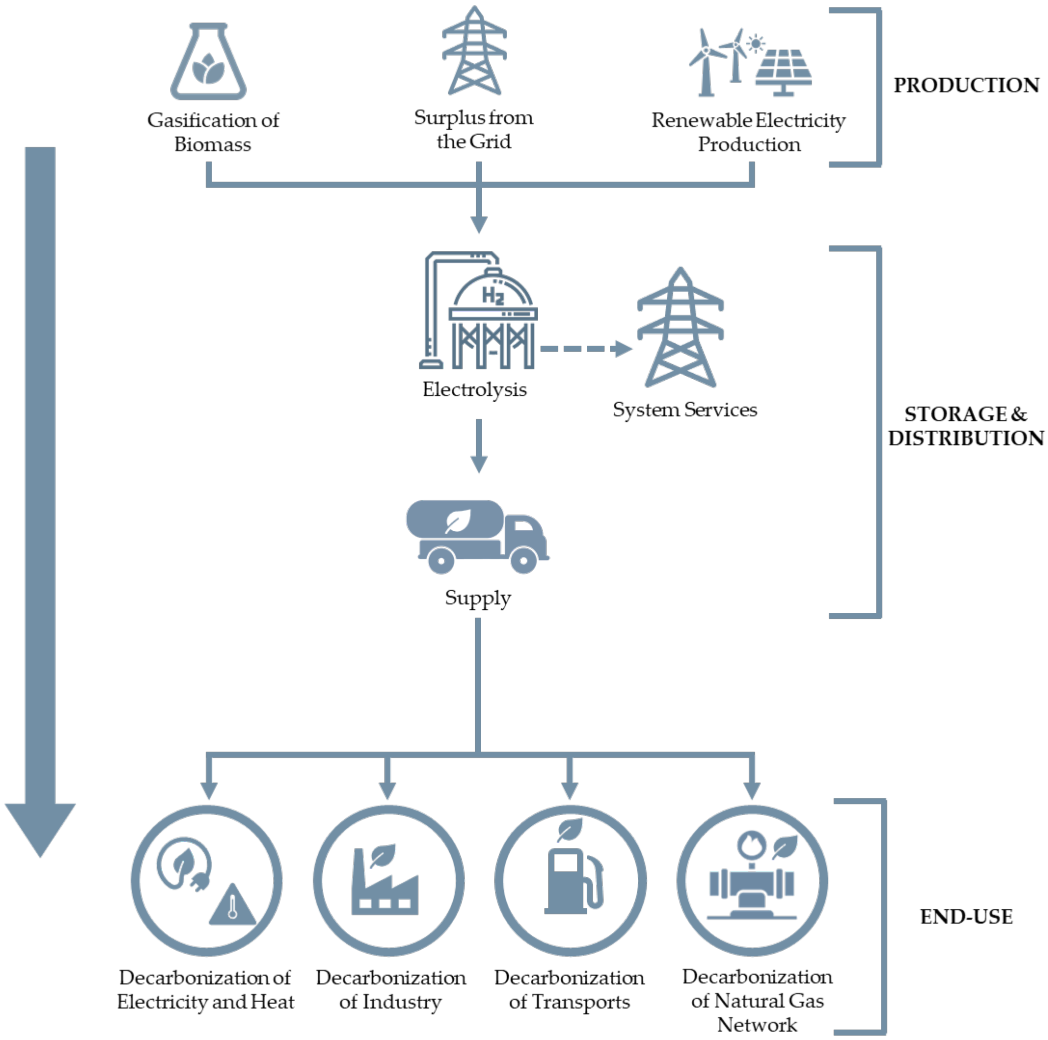

Figure 2.4 : General flowchart of hydrogen chain [78].

Hydrogen will be in a unique position to contribute to worldwide environmental goals, particularly in industries where considerable emissions reductions are required. The major hydrogen demand will be related to three broad categories: transportation, industrial uses, and home heating. Hydrogen and natural gas combinations can be used to generate heat and electricity in home and industrial stationary applications.

2.3. Recent Breakthroughs in Fuel Cell Technology

2.3.1. Resolving the Overheating Issue

The long-standing problem of overheating, one of the most significant technical barriers in using medium- and heavy-duty fuel cells in transportation vehicles such as trucks and buses, has been solved by a new high-temperature polymer fuel cell that operates at 80 - 160 degrees Celsius and has a higher-rated power density than current-generation fuel cells [79]. The Advanced Research Projects Agency-Energy (ARPA-E) of the Department of Energy (DOE) funded a study, which intended to create new high-temperature polymer electrolyte fuel cells for transportation applications. This study also contributes to the DOE's Energy Efficiency & Renewable Energy Hydrogen and Fuel Cell Technologies Office's (EERE-HFTO) "L'innovator" program [79], which aims to accelerate the commercialization of innovative hydrogen and fuel cell technologies developed at national labs in order to enable a strong domestic hydrogen and fuel cell industry and supply base. Because modern fuel cells operate at 60-80 degrees Celsius [79], they require big radiators and air intakes to keep it cool. Los Alamos National Laboratory scientists created a novel polymer fuel cell that can function at greater temperatures to tackle this problem. Phosphoric acid is used as an electrolyte at the electrode in traditional high-temperature polymer electrolyte membrane fuel cells. The Los Alamos team created a polymer electrolyte with a phosphonate polymer and a perfluoro sulfonic acid in this study. The researchers discovered that a proton from the perfluoro sulfonic acid passes to the phosphonate polymer in this composite electrolyte structure, greatly increasing proton conductivity. The researchers were able to attain a roughly 800 milliwatts per square centimetres rated power density of the fuel cell at 160° C using the composite polymer electrolyte, which is a 60% increase over phosphoric acid-based fuel cells [79].

2.3.2. Fuel Cell with Increased Lifespan and Reduced cost

University of Waterloo published a paper which suggests a future decrease in the cost of fuel cell vehicles (FCVs), which could potentially shift transportation systems towards using more of them [80]. FCVs are now heavily subsidized by countries like Japan and China, although they still cost around twice the maximum amount as their gasoline or diesel counterparts. This recent technical breakthrough led to the invention of a replacement electric cell with a ten-fold longer lifespan than conventional fuel cells. "With our design strategy, the cost might be equivalent to or even lower than gasoline engines," says Xianguo Li, head of the Waterloo Electric Cell and Green Energy Lab. This phenomenon may help facilitate a sustainable increase within the usage of this new technology among price-sensitive customers.

Traditional catalysts are usually expensive metals like platinum, but university researchers have identified a low-cost catalyst for hydrogen powered fuel cells. Their research reveals that compounds costing a fraction of this price of platinum may additionally function. The innovative materials are 60 percent as effective as platinum-related compounds at around one-fifth the value in line with the researchers [80]. Lower prices are passed on to the patron due to these price reductions. in line with Reuters, electric cell manufacturers like Toyota lowered costs by restricting the quantity of platinum utilized in fuel cells. By limiting each car to 30 grams of platinum each, Toyota saves US $300 per fuel stack [80]. Although platinum is that the optimum catalyst, it's "too scarce and too expensive to utilize at" a giant scale. These more cost-effective catalysts will provide FCVs greater flexibility in reacting to promote demands within the future. Ballard has unveiled the world's first PEM FC product supported non-precious metal catalysts, which is manufactured in partnership with Nisshinbo Holdings. This new cell design uses 80% less platinum [80] and is more tolerant to air contaminants, like sulphur oxides (SOx), than Pt based catalysts.

2.3.3. Economic Production of Hydrogen

Researchers from China's University of Science and Technology have created a more cost-effective catalyst for producing hydrogen from water electrolysis. Currently, 95% of all hydrogen is reformed from fossil fuel, producing greenhouse gas as a by-product [80]. On the opposite hand, electrolysis, the reaction of splitting water into hydrogen and oxygen, only requires electricity. To genuinely minimize emissions, hydrogen manufacturing must evolve removed from fossil fuel reforming for electric cell vehicles. This scientific breakthrough is particularly significant for China, where the 17.1% of renewable power that's lost is also utilized to form hydrogen [80]. Having a cheap catalyst increases the motivation for companies to speculate during this solution, which accelerates its adoption. These advancements, however, can't be applied immediately, they hold the potential to develop new facets of the cell industry, they'll still take years to implement. However, we hope to work out evidence of those findings within the field within the following few years.

2.3.4. Cathode and Anode Layer Design for improved performance

It is known that cathode catalyst performance may be improved by alloying metals like cobalt and nickel with platinum. However, these metals don't seem to be stable within the cell environment: they will leach out during operation, resulting in performance losses. This problem will overcome with a completely unique catalyst layer design that achieves higher performance with greater durability than conventional catalyst layers. This high performing design leads to a 5x durability improvement compared to a more conventional design using the identical alloy catalyst [81].

Fuel cells can fail when not enough fuel reaches the anode catalyst. If a fuel clog occurs in one cell's anode flow field, the impacted cells are unable to supply enough current using conventional electrochemical processes. These cells are driven to pass current by the opposite cells within the stack, leading to cell reversal or negative cell voltage. this may cause anode materials to corrode quickly, resulting in the cell's eventual failure. Researchers have developed a proprietary catalyst treatment/anode catalyst layer design that greatly mitigates this degradation, while reducing system control requirements and hence reducing material and manufacturing costs. they need anode designs which will tolerate many hours during this situation, compared to only seconds to minutes of tolerance without proprietary treatments [81].

3 Fuel Cell Bus

One of the strongest techniques for commercializing fuel cells for automobiles and moving to a hydrogen economy is to employ buses in public transportation [82]. The use of buses as fuel cell platforms has a number of benefits that have been recognized. Buses in the public transportation system have well-defined duty cycles, centralized fuelling and repair infrastructure, and specialized maintenance employees [83].

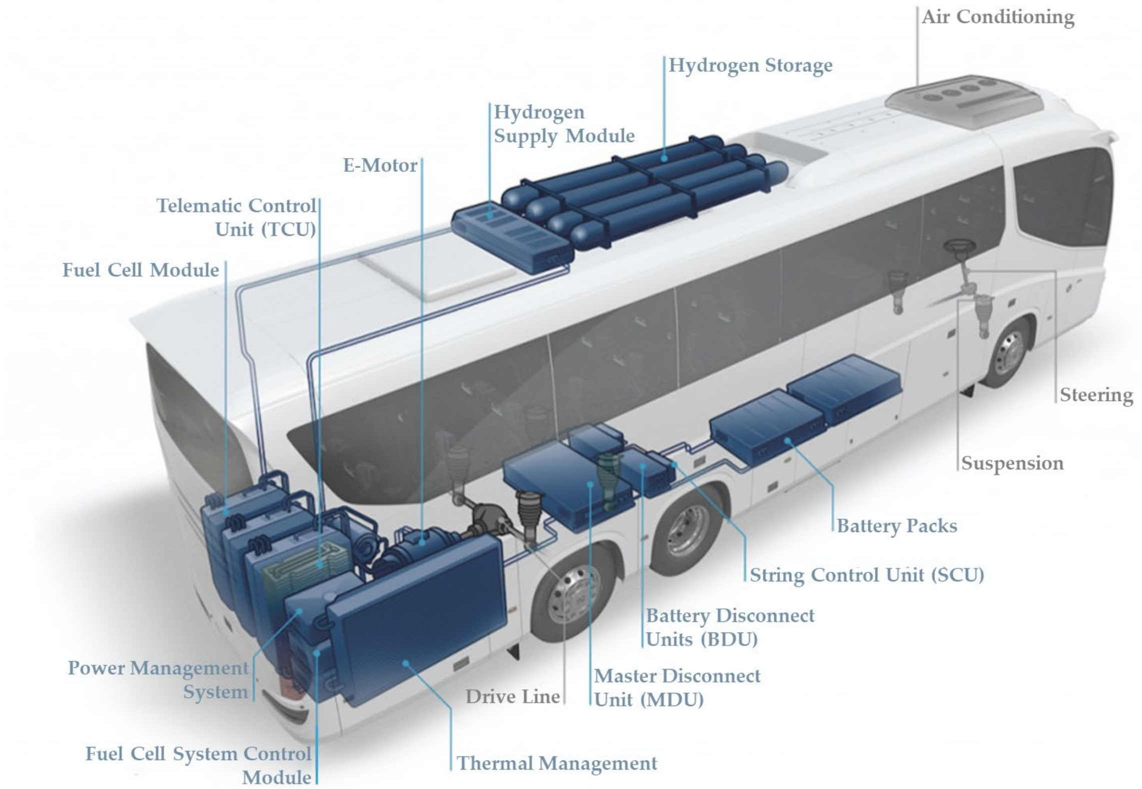

Figure 3.1 : General structure of Fuel Cell buses. [93]

PEM fuel cells are used to power nearly all current buses. In transportation applications, PEM fuel cells appear to have advantages. Almost all utilize compressed hydrogen as a fuel, which is normally kept in high-pressure tanks on the vehicle's roof. This allows the hydrogen to be synthesized outside of the vehicle, lowering the cost, weight, and complexity of the vehicle. This storage system also employs compressed natural gas technology, which is well-known in the transportation business. Roof mounting looks to provide certain benefits as well as hydrogen atoms are smaller than other fuels, storage methods for hydrogen are more likely to leak. If a leak occurs, the hydrogen may evaporate swiftly into the atmosphere thanks to the roof installation. Furthermore, in the case of a traffic incident, the roof of the bus is unlikely to be destroyed, aiding in the preservation of the tanks' integrity.

A fuel cell electric bus is an electric bus that comprises both a hydrogen fuel cell and batteries/capacitors. In such a hybrid architecture, the fuel cell supplies all of the energy for the vehicle's operation, but the batteries/capacitors can deliver peak power to the motors to meet rapid acceleration and gradients. By combining a fuel cell and a battery, the size of each can be tailored for a specific route. The fuel cell power module onboard the bus generates electric energy via an electro-chemical reaction that produces only water and heat as by-products, resulting in no local emissions. Electric energy is employed to produce direct electric traction and to charge the batteries. The by-product heat is stored on the brake resistors and used to keep the passengers warm while significantly increasing energy efficiency. The batteries also serve as a repository for regenerated braking energy. The hydrogen stored on board provides all of the energy required for the bus to operate.

Hydrogen has a higher energy density than electrical storage systems such as batteries, allowing for a greater range than systems in which batteries are employed as energy stores. Today, refuelling the bus takes approximately 7 minutes for an average fill, with improvements being researched to allow for less than 5 minutes [102]. Other than a centralized Hydrogen Refuelling Station (HRS) at the bus depot, a fuel cell electric bus requires no additional city infrastructure work or permissions. Because the fuel cell emits only water, the bus will always be zero emission. While the majority of industrial hydrogen utilized in the world today is derived from fossil fuels (mostly natural gas), the majority of hydrogen filling stations are based on hydrogen for low and zero carbon sources. Hydrogen can be created using a variety of ultra-low carbon methods, including as renewable power, biomass, and other hydrocarbons, as well as carbon capture and storage. The fuel cell bus, when powered by hydrogen produced by any of these routes, provides a truly zero-carbon answer to public transportation. The fuel cell electric bus is an all-electric zero-emission solution that operates similarly to a diesel bus and is therefore advertised as the closest like-for-like zero-emission option to replace diesel.

3.1. EVOBUS

EVOBUS, a division of Daimler-Benz AG, has created three generations of fuel cell buses. Mercedes-Benz debuted the NEBUS (New Electric Bus) in 1997 as the first version. In Norway and Germany, it gathered almost 540 driving hours. The ZEBUS (Zero Emission Bus) was created in 1999 in collaboration with Sun Line Transit. It was on operation in Palm Desert, California for 13 months, accumulating over 15,000 miles. The Citaro, the most recent bus, is now being tested in Europe. In 1997, the Citaro was debuted as a diesel-powered urban transit bus. It has a low floor and three doors, with a capacity of around 60 passengers [84].

Figure 3.2 : Mercedes Citaro F-Cell [84]

The updated fuel cell versions include a 200-kW fuel cell, which the business claims can match the performance of a diesel engine. The buses run on compressed hydrogen fuel stored in a roof-mounted storage module. Under the CUTE initiative, the Citaro will be supplied to nine European towns. Three additional Citaro buses are being run in Iceland as part of the Ecological City Transport System (ECTOS) initiative, and three more are on their way to Perth, Australia, as part of their Sustainable Transport Energy Program (STEP). For two years, the automobiles will be examined and assessed [85].

Figure 3.3 : Mercedes Benz eCitaro (Source: Daimler). [94]

The Mercedes eCitaro with fuel cell range extender were tested for the first time in Hamburg. Between 2021 and 2025, Hamburger Hochbahn, a public transportation operator, have proposed to shop for 530 electric buses and highlighting hydrogen use. The operator began to field testing of the new vehicle in its articulated variant in 2021. [94]

3.2. VAN HOOL

Van Hool has been involved fuel cell buses for over a decade. within the mid-1990s, Van Hool participated within the development of an 18-meter, articulated bus powered by an alkaline fuel cell. The fuel cell produced roughly 78 kW and was augmented by batteries [86]. Van Hool's fuel cell bus made its debut in Dallas in 2005. For the first time, the foremost sophisticated hydrogen-powered bus was shown to the American public. The commercial vehicles team developed and built a hydrogen-powered bus for the American market in less than two years after obtaining the commission. Three buses for AC Transit and one for SunLine Transit, both from California, were ordered.

Figure 3.4 : Van Hool Fuel cell bus for AC Transit [95]

The European fuel cell bus was launched on May 14, 2007. it is the world's first completely functional hybrid bus (hydrogen-electric) that recycles braking energy. As a result, it utilizes a fraction of the energy employed by earlier fuel cell buses. It also has the same passenger capacity (up to 104), performs similarly, and has the identical range (up to 350 km) as a contemporary diesel bus. Van Hool designed a 13.2-meter-long vehicle with three axles to try and do this [86]. Van Hool manufactured 30 hydrogen buses for Cologne and 10 for Wuppertal (Germany) in 2018, the largest order for hydrogen buses in Europe. This was a

Figure 3.5 : Van Hool A330 Fuel cell bus [95]

reward for Van Hool's ongoing dedication to innovative technology and environmentally friendly solutions.

3.3. NEW FLYER

Foothill Transit has awarded NFI Group Inc.'s subsidiary New Flyer of America Inc. ("New Flyer") a new contract for 20 zero-emission, hydrogen fuel cell-electric Xcelsior CHARGE H2TM forty-foot heavy-duty transit buses. NFI Group Inc. is a leading independent bus and coach manufacturer and a frontrunner in electric mass mobility solutions. Foothill Transit is situated in West Covina, California, and operates one amongst the country's biggest fleets of electric buses, offering approximately 14 million rides within the San Gabriel and Pomona Valleys annually. Foothill Transportation was the first bus-only public transit system in North America to get the American Public Transportation Association's Platinum Level for substantial sustainability achievements, and it absolutely was the first within the country to place battery-electric buses on the road. The Xcelsior CHARGE H2TM is a battery-electric vehicle that uses compressed hydrogen as an energy source and range extender. It will be refuelled in 6-20 minutes. The Xcelsior CHARGE H2TM, based on New Flyer's proven Xcelsior platform, may save 85 to 135 plenty of greenhouse emission per annum in tailpipe emissions compared to a diesel bus [87].

These buses, which may go up to 350 miles on one refuelling, cut greenhouse emission emissions while simultaneously providing increased range, quick fill times, and no performance degradation from start to complete. NFI could be a pioneer in zero-emission transportation, with electric vehicles in additional than 80 cities across five countries (or on order). NFI has the largest range of zero-emission battery and fuel cell-electric buses and coaches, with over 40 million EV service kilometres under its belt [87].

Figure 3.6 : New Flyer Xcelsior CHARGE H2 [87]

3.4. TOYOTA

The e.City Gold battery electric city bus and also the H2.City Gold fuel cell electric bus are co-branded by Toyota and CaetanoBus, a Portuguese bus manufacturer. Toyota's fuel cell technology, including fuel cell stacks, hydrogen tanks, and other important components, has been integrated into CaetanoBus' hydrogen city buses from 2019 [88]. Toyota Caetano Portugal (TCAP) became a right away stakeholder in CaetanoBus in December 2020 to help the company's rapid expansion from its core bus business towards the development and distribution of zero-emission buses. With increased sales of its zero-emission buses across Europe over the last year, the Portuguese bus firm has strengthened its worldwide footprint.

Figure 3.7 : H2.City Gold fuel cell electric buses [88]

CaetanoBus' engineering skills and cutting-edge technology of its zero-emission products are being increasingly recognized in the competitive European bus industry. The CaetanoBus H2.City Gold is a hydrogen-powered electric bus that uses Toyota's fuel cell technology. The city bus has a 400-kilometer range and can be refuelled in less than 9 minutes [88]. This vehicle demonstrates the complementing technology and engineering skills of both businesses. It's the first stage in a co-branding campaign that also includes the 100 percent electric e.City Gold bus. A revision to the car badging to feature both "Caetano" and "Toyota" emblems is at the core of the co-branding, recognizing Toyota's great visual familiarity among European buyers.

Figure 3.8 : Toyota Sora [89]

The Toyota Sora is a transit bus developed in collaboration with Hino Motors that features an electric motor driven by Toyota's hydrogen fuel cells. Components from the Toyota Mirai, a mid-size fuel cell vehicle, are used in the bus. Sora refers to the water cycle and is an acronym of the phrases Sky, Ocean, River, and Air. The Sora is powered by two sets of 155 horsepower polymer electrolyte fuel cells. The bus also has a power system that may be utilized as an emergency power source, supplying up to 235 kWh of electricity at a maximum output of 9 kW to external customers [89]. The bus has a radar and a collision warning system, as well as an extra solution to avoid a collision when turning right, which notifies the driver of incoming cars or pedestrians. Passengers can also use the Emergency Driving Stop System to bring the car to a halt in an emergency, such as when the driver passes out. Toyota buses can communicate with other vehicles to provide information about traffic, pedestrians, and light changes. In 2017, the Sora made its public premiere at the Tokyo Motor Show. In 2018, it was released in Japan. More than 100 buses have been added to the public transportation network, mostly in Tokyo, in preparation for the 2020 Olympic and Paralympic Games [88].

3.5. SOLARIS

The fuel cell bus was included to the Polish manufacturer's zero-emission bus portfolio in 2020. The eighth generation of Ballard's fuel cell module, which was unveiled at Busworld 2019, is at the core of the vehicle. In mid-2019, Solaris unveiled their hydrogen Urbino 12 at the UITP conference in Stockholm [89]. A year and a trade show that saw fuel cell solutions in the spotlight, with many projects implemented under the H2 banner. The first order for the Solaris Urbino 12 hydrogen came from Italy. SASA Bolzano (Bozen's public transportation operator) made a 12-unit order under the European Union's JIVE initiative [89]. The deal is worth 12.8 million euros and covers eight years of servicing and maintenance. The Solaris Urbino hydrogen is built in the same way as its battery-electric sibling, with stainless steel accents and roof-mounted hydrogen tanks. The traction system has remained the same. The bus bought by SASA will be equipped with 30 kWh of Solaris High Power batteries, which are designed for rapid charging due to their high maximum charging power. The batteries are charged using power generated by fuel cells as well as energy recovered from the braking system. There's also a plug-in socket that lets the bus charge its batteries while it's stopped. It has a pair of electric portal axle ZF 125kw motors coupled with 70kW hydrogen fuel cell and lithium-ion traction batteries. It consists of 5 composite hydrogen tanks of 312 litres [90].

Figure 3.9 : Solaris Urbino 12 hydrogen [89]

Regionalverkehr Köln GmbH (RVK) of the Cologne area has just placed an order with Solaris Bus & Coach for 15 fuel cell buses to be delivered by 2022. The buses will be acquired under the EU's JIVE 2 initiative, which will be sponsored by the "Fuel Cells and Hydrogen Joint Undertaking" (FCH JU) [91]. Solaris Bus & Coach have signed hydrogen bus contracts with Sweden, Hungary, Poland, Netherlands and furthermore countries under several hydrogen programs [92].

4 A Global vision on Fuel Cell

4.1. Fuel Cell Projects in Europe

FCEBs (zero-emission buses) are becoming a larger part of public transportation in several European nations, with more than 30 governments declaring hydrogen strategies. The European Union's 2050 emissions reduction plan sets targets and a schedule for being climate-neutral by 2050 [96]. For example, Transport for London has declared that starting in September 2021, it would solely by zero-emission buses, moving the fleet's carbon neutrality date ahead to 2034 [96].

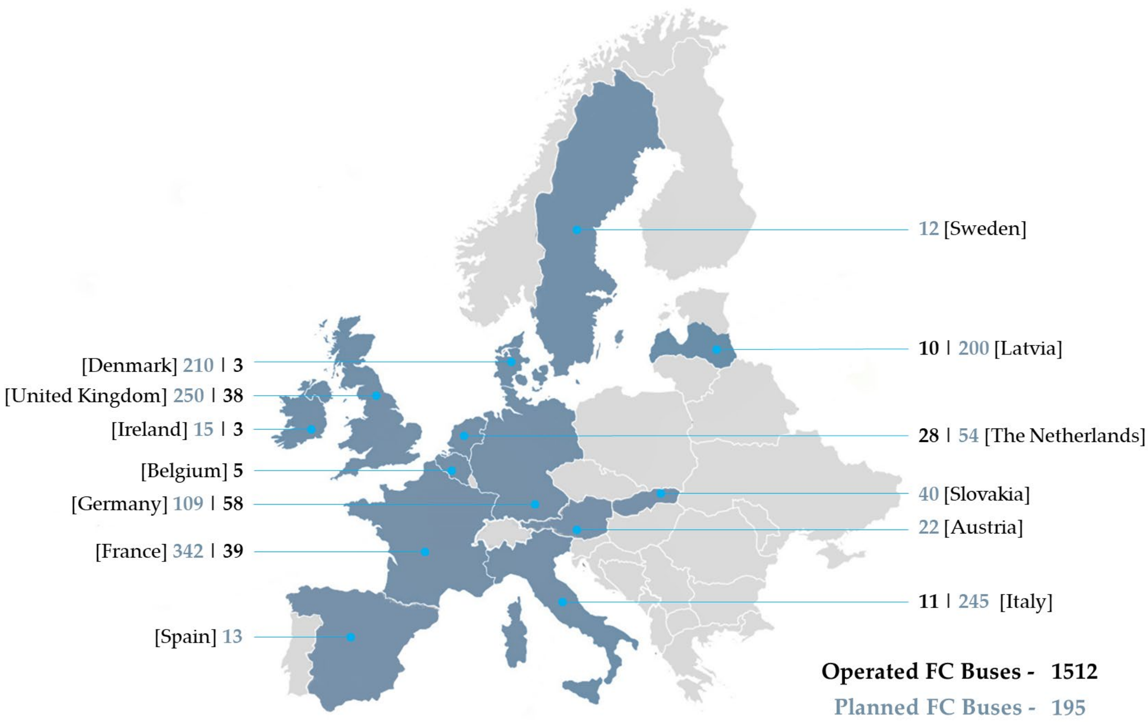

Figure 4.1 : Fuel cell buses planned and operated in Europe under all projects [96 - 106]

4.1.1. CHIC

The Clean Hydrogen in European Cities (CHIC) project was a flagship zero-emission bus initiative that deployed a fleet of fuel cell electric buses and hydrogen refuelling stations in cities throughout Europe and one in Canada. The project began in 2010 and concluded in December 2016 [97]. The study successfully demonstrated that fuel cell buses may provide communities with a viable option for decarbonizing their public transportation fleets, improving air quality, and lowering noise levels. The vehicles can operate with the same flexibility as a diesel bus while maintaining public transportation productivity.

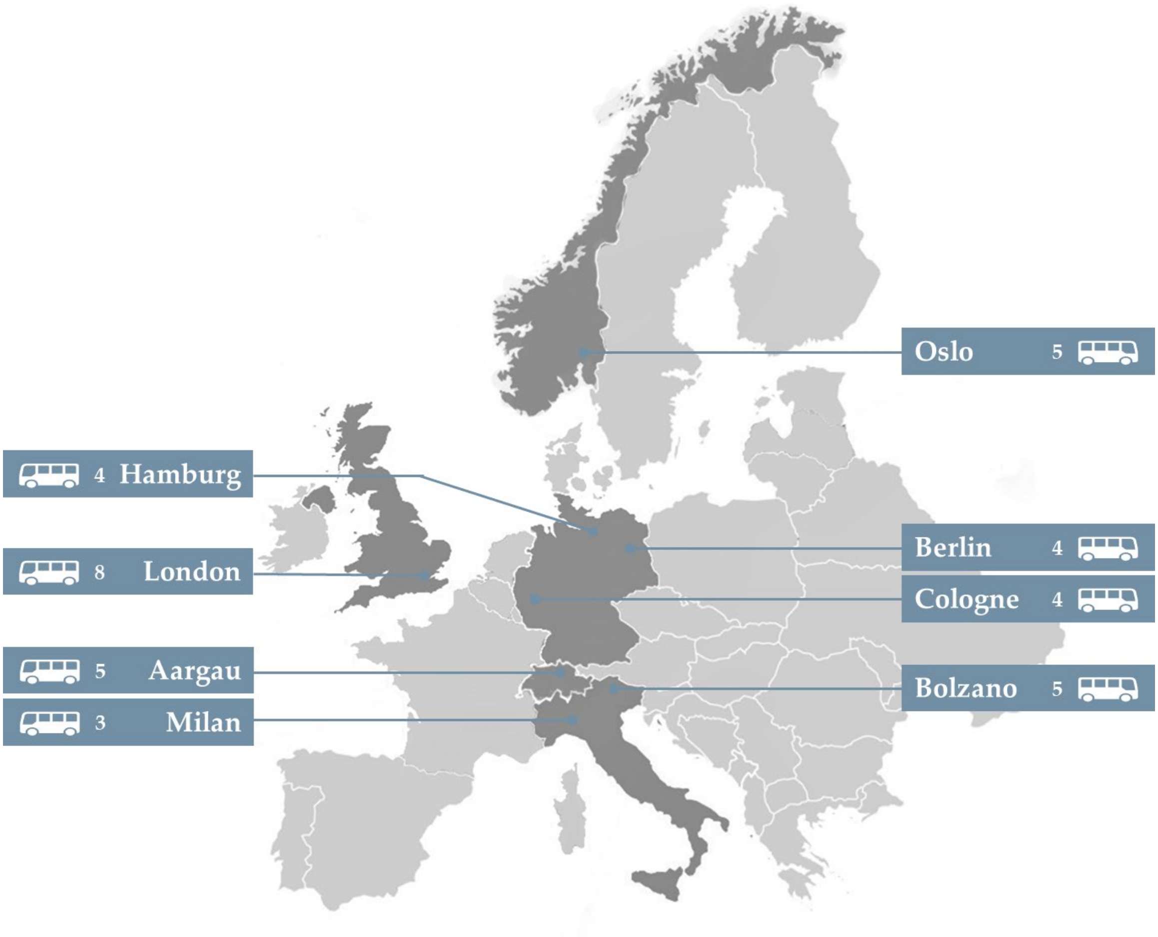

Figure 4.2 : H_2 FC buses deployments within the CHIC project in Europe

The overall project budget was €81.8 million, with the Fuel Cells and Hydrogen Joint Undertaking contributing €25.88 million (FCH JU). There are 26 FCH JU-funded fuel cell electric buses operating in the canton of Aargau (CH – 5 buses), Bolzano (IT – 5 buses), London (UK – 8 buses), Milan (IT – 3 buses), and Oslo (NO – 5 buses). Cologne (DE – 4 buses) and Hamburg (DE – 4 buses) ran 8 more fuel cell buses through separate schemes. Between 2010 (Winter Olympics Games) and

March 2014, Whistler (CA) saw the deployment of 20 fuel cell buses. Between 2006 and December 2014, four hydrogen internal combustion engine (ICE) buses operated in Berlin (DE). During the course of the project, 54 fuel cell buses were demonstrated. [97]. The variety of climates and city sizes allowed the vehicles to be tested in a variety of conditions.

4.1.2. HIGH V.LO-CITY

The High V. LO-City project began in 2012 and continued through the end of 2019 [98]. The project intended to facilitate the deployment of hydrogen refuelling stations and fuel cell buses in three European cities: Antwerp (Belgium), Aberdeen (United Kingdom), Groningen (Netherlands), and San Remo (Italy). The 14 buses that have been deployed are a like-for-like substitute for traditional diesel buses and trolley buses [98]. They are used in four separate public transportation fleets in three different climate zones, with varying environmental and bus route circumstances.

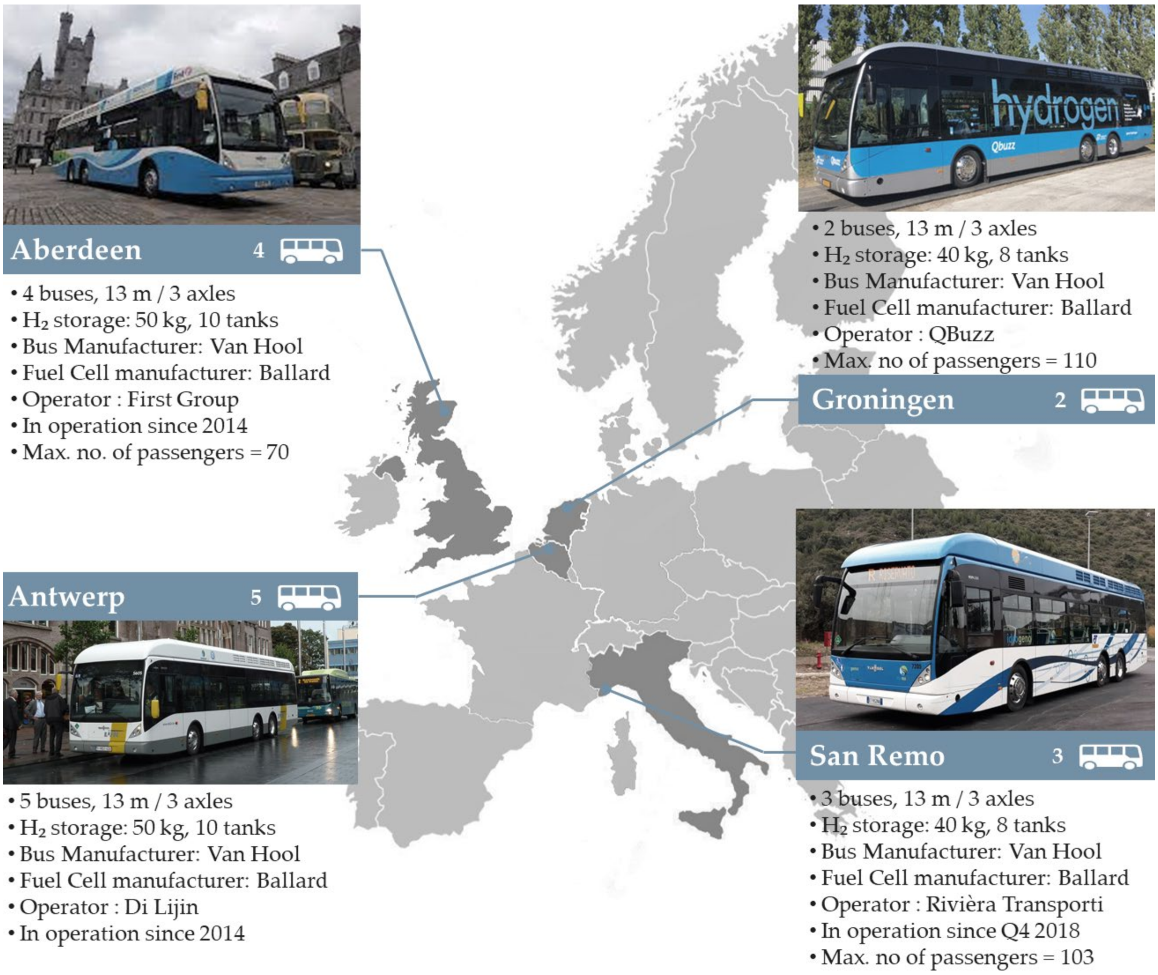

Figure 4.3 : H2 FC buses deployments within the High V. LO-City project in Europe

4.1.3. 3EMOTION

3Emotion stands for Environmentally friendly Efficient Electric Motion. The initiative runs from 2015 to 2022 and bridges the gap between current fuel cell bus demonstration programs and larger-scale implementation [100]. It describes the deployment of 21 new fuel cell buses, as well as the continued use of 8 current fuel cell buses with the necessary refuelling infrastructure, as part of a targeted expansion of the EU fuel cell bus demonstration [100]. The buses are stationed in five locations and are operated by seven public transportation companies from across Europe.

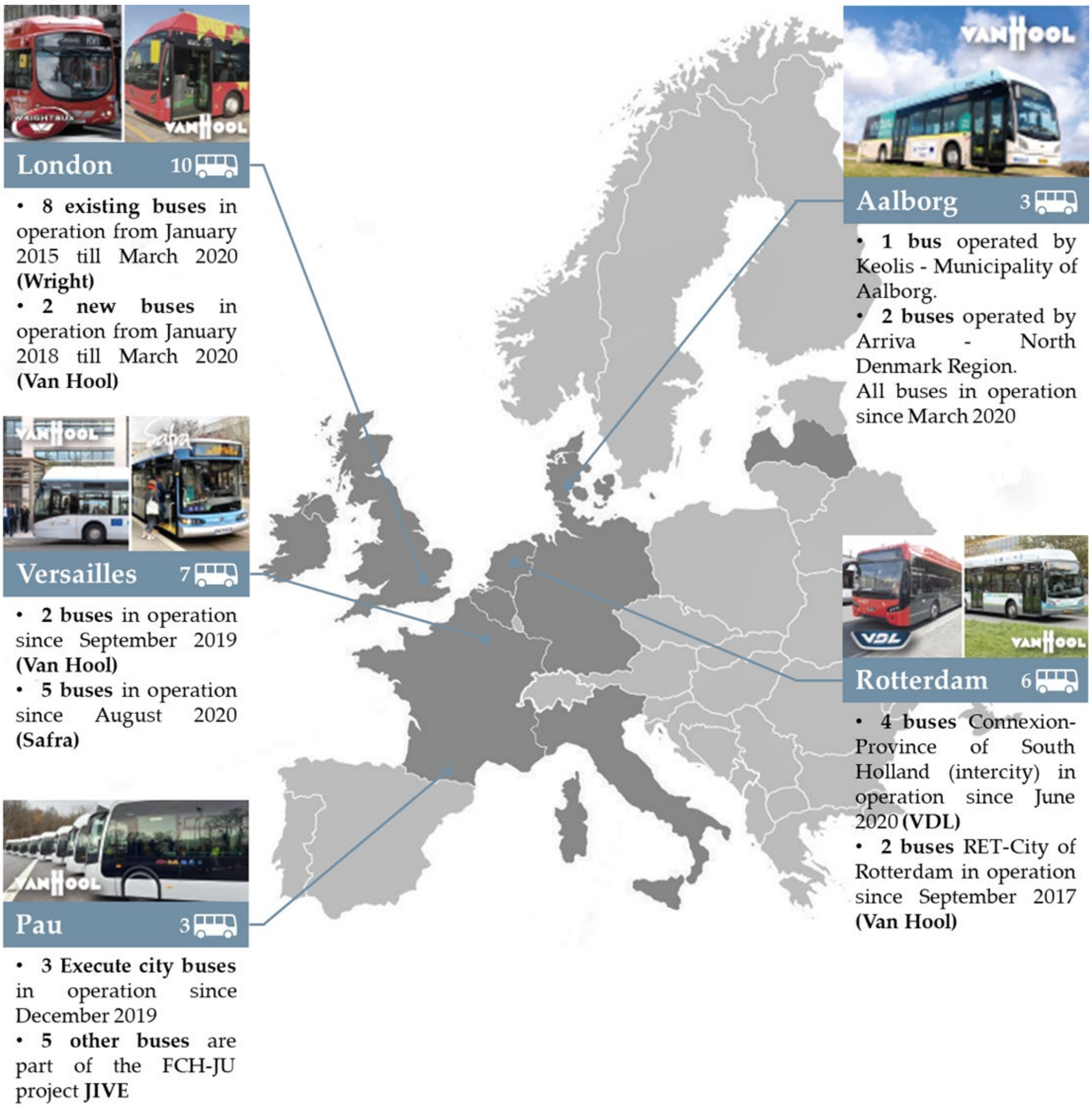

Figure 4.4 : 3Emotion sites in Europe [100]

Each of these sites has its own constraints for the buses, which distinguishes them all and spans the complete spectrum in which fuel cell buses can be a valuable replacement for fossil fuelled buses.

4.1.4. NEWBUSFUEL

Newbusfuel is a project supported by the Fuel Cells and Hydrogen Joint Undertaking that aimed to close the knowledge gap for the creation of large-scale hydrogen refuelling infrastructure for fuel cell buses.

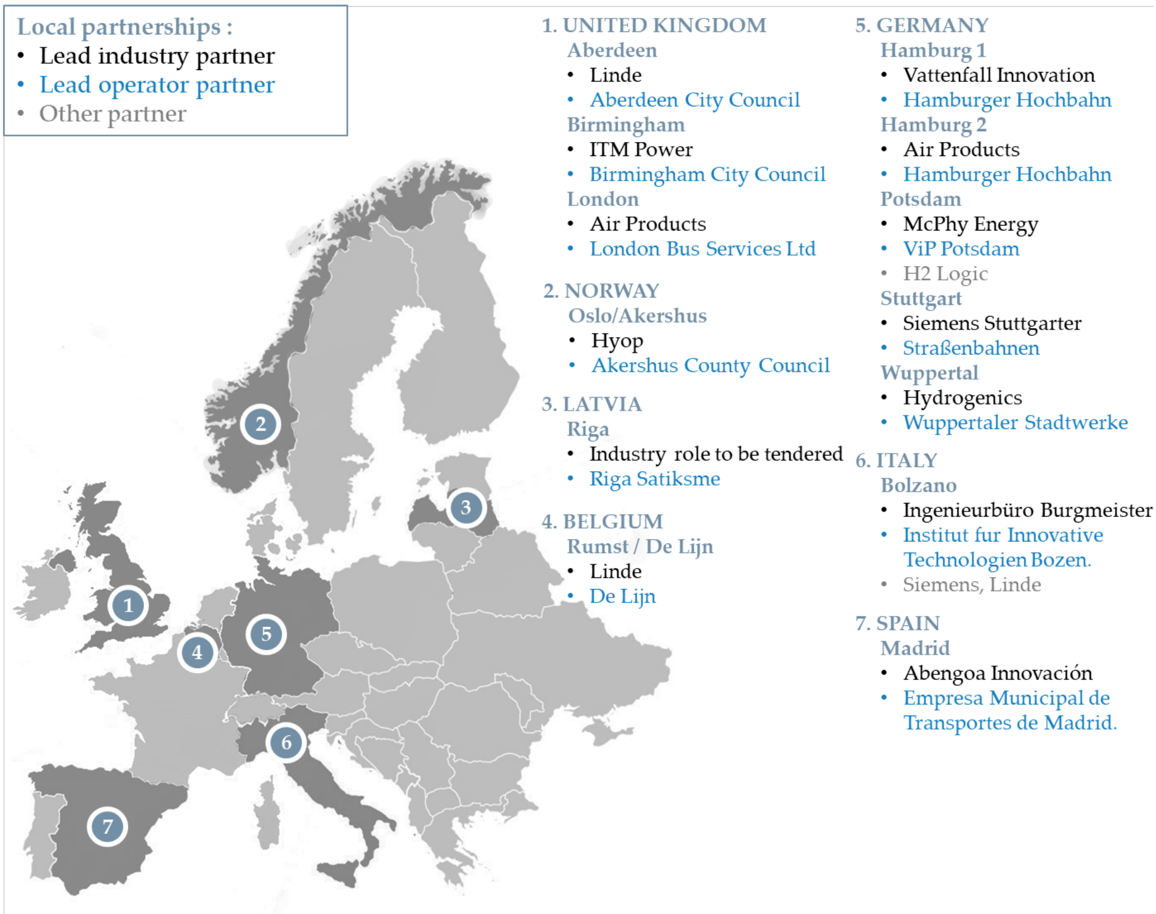

Figure 4.5 : Newbusfuel sites in Europe [101]

The project, which began in the summer of 2015, evaluated the central technological and engineering solutions required for the refuelling of a significant number of hydrogen fuel cell buses at a single bus depot. Large-scale bus depot refuelling creates substantial new issues that the hydrogen refuelling industry has yet to address:

- Scale – through puts more than 3,000kg/day are projected, which is far higher than the 1,200kg/day expected for current FCEV stations — the practicality of solutions of this sort is being questioned [101].

- **Availability** - A 100 percent available supply is required for public transportation networks that will rely only on hydrogen as a fuel source at bus depots.
- **Limited refuelling window** — buses will be refuelled in a limited night-time window, resulting in high H2 throughput.
- **Footprint** - the refuelling units must be smaller to fit into congested metropolitan bus depots.
- **The volume of hydrogen storage** - which can surpass 10 tonnes per depot, imposes significant regulatory and safety limits.
- **Cost** – comprehending how size influences costs and necessitating new company concepts that lead to competitive fuel.

4.1.5. HYTRANSIT

The FCH JU-supported HyTransit project began in 2013 and will continue through the end of 2018 [99]. The project's goal is to contribute to the commercialization of hydrogen buses in Europe by introducing a fleet of six hybrid fuel cell buses into daily fleet services, as well as a hydrogen production and refuelling infrastructure in Aberdeen (Scotland) [99]. The project's goal is to show that a fuel cell bus can meet the operational performance of a comparable diesel bus on challenging intercity UK routes while significantly outperforming its environmental performance.

4.1.6. JIVE

The JIVE (Joint Initiative for Hydrogen Vehicles across Europe) initiative aims to deploy 139 new zero-emission fuel cell buses and accompanying refuelling infrastructure across five European countries. JIVE will run for six years, began in January 2017, and co-funded by a 32 million euro grant from the FCH JU (Fuel Cells and Hydrogen Joint Undertaking) within the European Union's Horizon 2020 framework program for research and innovation. The project consortium consists of 22 members from seven different countries [102].

JIVE's specific objectives are:

- Reduce costs by 30% as compared to state-of-the-art.
- 50 percent of the cars must be operational for at least 36 months.
- Deploy the largest capacity hydrogen refuelling stations (HRS) in Europe and achieve near-perfect dependability.
- Demonstrate the technological readiness of FC buses and HRS and stimulate further advancement.

4.1.7. MEHRLIN

The MEHRLIN which stands for Models for Economic Hydrogen Refuelling Infrastructure, is a project of constructing seven hydrogen refuelling stations to serve bus fleets in cities throughout Europe, including the United Kingdom, the Netherlands, Italy, and Germany. MEHRLIN began in July 2017 and was completed by the end of 2020. MEHRLIN is supported by the European Commission's Connecting Europe Facility (€5.5M), which is handled by the Innovation and Networks Executive Agency [103]. MEHRLIN's overarching goal is to establish a financially viable demand-led business model for hydrogen refuelling stations in order to accelerate the deployment of hydrogen as an alternative fuel in the EU. The project entails testing huge hydrogen refuelling stations in seven different sites which includes, Birmingham, London, Rotterdam, Wuppertal, Hürth, Bolzano. The MEHRLIN project not only contributed to the expansion of Europe's hydrogen refuelling station network by building and operating these stations, but it also provided data on the technical and economic performance of refuelling stations under real-world conditions, such as high load and daily utilisation. MEHRLIN used this data to examine the financing case for HRS using a demand-led business model in order to facilitate the adoption of hydrogen as an alternative fuel in the EU.

4.1.8. JIVE 2

JIVE 2 (Joint Initiative for Hydrogen Vehicles Across Europe) aims to deploy 152 new zero-emission fuel cell buses and accompanying refuelling infrastructure in 14 European cities across France, Germany, Iceland, Norway, Sweden, the Netherlands, and the United Kingdom [104]. JIVE 2 will run for six years, beginning in January 2018, and will be co-funded by a 25 million euro grant from the FCH JU (Fuel Cells and Hydrogen Joint Undertaking) within the European Union's Horizon 2020 framework program for research and innovation. The project consortium consists of 23 members from nine different countries [104]. The JIVE2 project is a continuation of the JIVE initiative [104].

4.1.9. H2BUS EUROPE

On June 3, 2019, Everfuel, Wrightbus, Ballard Power Systems, Hexagon Composites, Nel Hydrogen, and Ryse Hydrogen, all leaders in the hydrogen fuel cell electric value chain, formed the H2Bus Consortium. The members have agreed to deploy 1,000 hydrogen fuel cell electric buses in European cities, along with supporting infrastructure, at commercially competitive pricing [105].

The first phase of the project, which includes 600 buses, is funded by the EU's Connecting Europe Facility, which is worth €40 million (CEF). The fund is used for the installation of 200 hydrogen fuel cell electric buses and accompanying infrastructure in Denmark, Latvia, and the United Kingdom by 2023 [105]. Over a 15-year span, fuel cell buses have travelled more than 12 million kilometres. During this time, they have reached an availability rate of more than 98 percent. The market has now been prepared for the following generation. Wrightbus collaborated with its suppliers, Ballard Power Solutions and Hexagon, to broaden its product portfolio for the European market. A 12-meter single-decker, double-decker, and articulated fuel cell electric bus will be included. This has been made possible by the scale and experience provided by earlier deployment projects, specifically the JIVE and JIVE2 programs. The JIVE programs are an essential prerequisite to the commercial deployment of hydrogen fuel cell electric buses. They had a significant catalytic effect in Europe, allowing fuel cell bus manufacturers to scale up manufacturing and begin providing volume-related offers. [105].

In addition, the consortium will provide an economical and dependable supply of green hydrogen directly to the operators' depot. Nel Hydrogen will provide electrolysers and hydrogen stations, while Hexagon will provide hydrogen trailers to complete the hydrogen value chain. Everfuel and Ryse Hydrogen will install and operate the entire hydrogen value chain, as well as provide dispensed hydrogen at bus terminals. Ryse Hydrogen is in charge of carrying out these operations in the United Kingdom, while Everfuel is in charge of carrying them out in the rest of Europe. On a per-kilometre basis, it is priced at parity with diesel - €5/kg to €7/kg depending on local conditions and bus fleet size [106]. Wrightbus will organize H2Bus maintenance to fit the needs of the customer. The maintenance package will cost 0.30€ per kilometre [106]. This initiative will ensure that each country maintains and manages a complete store of spare parts for these buses. This will include the standard as well as the drivetrain components. Wrightbus promises to deliver these components to the operators' depot on time. This initiative will also provide training to employees at the operator's depot. This will facilitate a smooth transition and qualify transit technicians to do maintenance on these hydrogen vehicles. Scale is required for the deployment of Fuel Cell Electric Buses (FCEBs). As a result, the H2Bus Consortium's initial rollout locations plan to install at least 200 FCEBs. This will be aided by centralized electrolytic hydrogen generation and a wide range of hydrogen dispensing options. Norway, Sweden, and Germany are currently on the list of potential roll-out locations.

4.2. Fuel Cell Technology Roadmap for China

Despite the lack of a national policy for hydrogen development, Chinese provincial governments and commercial firms have established hydrogen projects to assist the deployment of fuel cell vehicles (FCVs) and create renewable hydrogen [107]. China is already the world's greatest producer of hydrogen (mainly from unrestricted fossil fuels) and the world's third-largest market for FCVs.

		2015	2020	2025	2030
Market size (Units)		10	5 thousand	50 thousand	1million
Output density (kW/kg)		-	2	2.5	2.5
Passenger	Vehicle Rated output (kW)	35	70	90	120
	Fuel cell durability (hour)	3,000	5,000	6,000	8,000
	Cost per vehicle	-	300 thousand CNY and under	200 thousand CNY and under	180 thousand CNY and under
Commercial	Vehicle Rated output (kW)	35	70	120	170
	Fuel cell durability (hour)	3,000	10,000	20,000	30,000
	Cost per vehicle	-	1 million CNY under	1 million CNY under	600 thousand CNY under
Number of hydrogen stations		-	100	300	1,000
Objective		-	For Public Service use	For Public Service / private use	Personal, commercial (large)
Technical Method		• Fuel cell related materials • Fuel cell stack technology • System integration and control technology • Power system developmental research • Fuel cell vehicle design and system integration technology • Improvement of output density • Improved durability • Cost reduction • Hydrogen loading safety improvement			

Source: Created by MarkLines based on the SAE China's Technology Roadmap for Energy-Saving and New Energy Vehicle sand various media reports.

Table 4.1 : Market size of fuel cell vehicles, output, durability roadmap. [108]

The fast spread of renewable-based hydrogen might be aided by China's vast renewable power generation capability. Although hydrogen usage in industrial sectors appears to be increasing, the transportation sector, notably trucks and buses, may remain China's priority for hydrogen use [107].

4.2.1. China's Vision of FCV Development

With over 25 million tons (Mt), or nearly a quarter of the global amount, China is the largest producer of hydrogen today [107]. The majority of the volume comes from fossil fuels (60 percent from coal, and 25 percent from natural gas) China is looking at fostering lower-emission hydrogen production and consumption to assist fulfil energy demands and promote industrial development. China expects to increase its solar and wind power generating capacity from about 600 GW in 2020 to 1,200 GW by 2030[107]. According to research by the Hydrogen Council, electrolysis is already competitive with low-carbon production technologies in China at the present levelized cost of energy. In the lack of a national policy, Chinese firms have begun to invest in and produce electrolysers [107].

Figure 4.6 : Hydrogen Fuelling Stations Installed in China in 2019. [169]

Province	2022	2024	2025	2030
Shanghai	5-10		50	
Shanxi	13	20		
Hebei	20		50	100
Jiangsu	20			
Zhejiang	30			
Tianjin	10			
Chongqing	20		30	
Shandong			200	

Table 4.2 : Hydrogen Fuelling Stations Planned for 2022 – 2030. [169]

The global development of hydrogen fuel cell vehicles (FCV) aims to increase national or regional energy security, reduce carbon emissions, and mitigate climate change. In China, FCV development will also aid the country in resolving environmental pollution challenges caused by urban vehicle traffic, as well as increasing the country's auto industry's global competitiveness. China's FCV development goal is to deploy one million FCVs by 2030, and to achieve zero emissions by 2050 through the development of FCVs and electric cars in collaboration. The goal is to provide energy security through vehicles powered by diverse energy sources and emitting zero emissions in order to improve local urban air quality and prevent global climate change through a low-carbon energy system.

4.2.2. Made in China 2025

On May 8, 2015, the Chinese government released (2025)- "Made in China 2025," a 10-year plan by the Chinese Central Government to develop China's manufacturing industry completely. New-Energy Vehicles and Equipment is one of ten key sectors highlighted in the plan. The Strategy Advisory Committee issued the Energy Saving and New Energy Vehicle Technology Roadmap in October 2016 based on the New-Energy Vehicles and Equipment Plan stated in "Made in China 2025" [108]. This was jointly produced by the Society of Automotive Engineers of China (SAE-China), with Chapter 4 being the Hydrogen Fuel Cell Vehicle (FCV) Technology Roadmap.

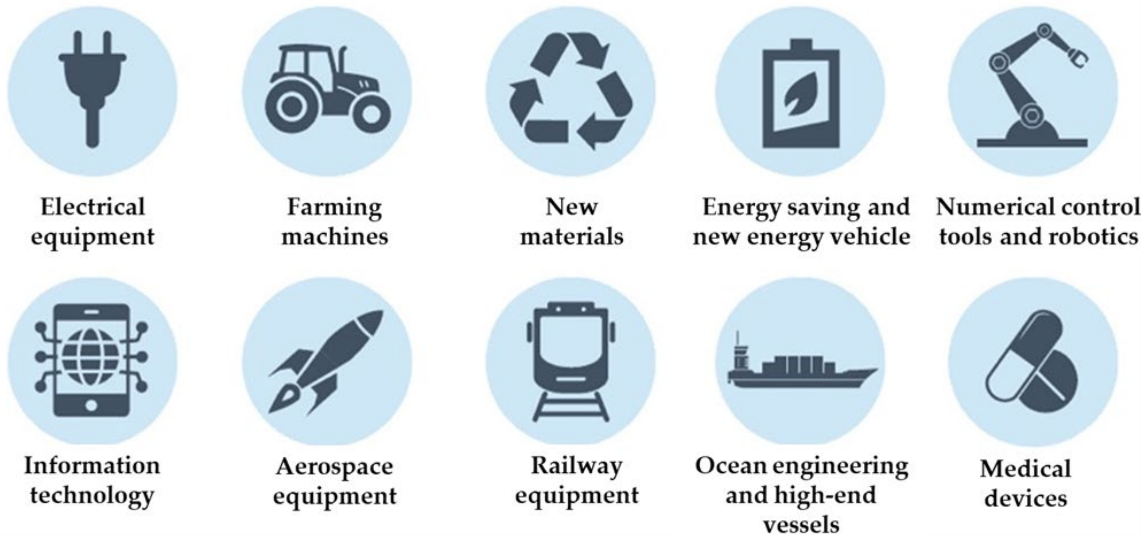

Figure 4.7 : 10 priority sectors in Made in China 2025 plan. [108]

4.2.3. New Energy Vehicle Industrial Development Plan

There are some signs that China's support for NEVs is becoming more technology neutral than it was previously. The government asks for boosting market targets for the total fleet of NEVs, rather than just BEVs and PHEVs, in the New Energy Vehicle Industrial Development Plan for 2021 to 2035, announced in 2020 [108]. The strategy is for 1 million FCVs and 2,000 HRSs, with EVs accounting for around 95% of all NEVs by 2035 [108]. NEVs have received special attention from the government. The national government, for example, has granted tax breaks and subsidies for FCVs ranging from RMB 20,000 to RMB 50,000 (about $3,200 to $7,900) depending on the vehicle type and fuel cell capacity [108]. Notably, NEV assistance is beginning to migrate away from direct subsidies, which will be phased out at a 10% annual reduction rate between 2020 and 2022 until being phased out completely by the end of 2022. Instead of direct subsidies, the government will provide financial assistance in the form of tax exemptions (for example, no car purchase tax), charge subsidies, parking incentives, and SOE R&D investment incentives [108].

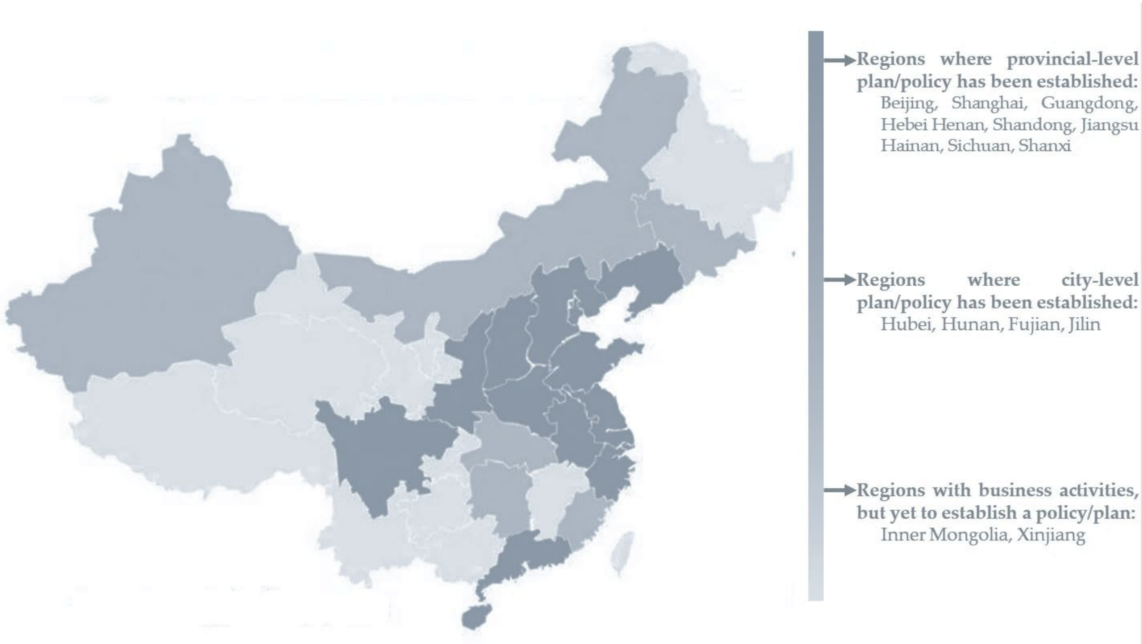

Figure 4.8 : Hydrogen in China: Local Policies and Moves. [170]

4.2.4. Fuel Cell Buses in China

On Foton Motor, Suzhou King Long, and Shanghai Volvo fuel cell buses, a Chinese-developed fuel cell power system platform is used. For a year, these FC buses serviced Beijing and took part in demonstrations at the 2008 Beijing Olympics, the 2010 Singapore Youth Olympics, and the 2010 Shanghai World Expo. Three fuel cell buses successfully completed demonstration projects for the Beijing Olympics as well as one-year public transportation services in Beijing, covering a total distance of more than 60,000 km [109]. Chinese self-developed hydrogen fuel cell city buses during the 2010 Youth Olympics in Singapore, successfully and served as the Youth Olympics' official new energy demonstration vehicles, becoming China the first country to do so.

Air Liquide and Sinopec collaborated to establish two hydrogen refuelling stations in Shanghai in late 2019, with the capacity to serve 200 hydrogen fuel cell buses in the area [109]. This happened only months after Air Liquide and Huopu, a Chinese corporation, launched a special purpose joint venture to open the first hydrogen refuelling station in Zhejiang province. In addition, the Air Liquide-Huopu joint venture has committed to building a hydrogen refuelling station in Beijing as part of the 2022 Olympic Games infrastructure [109]. The city administration has set a goal of 1,000 fuel cell buses functioning by the time the Beijing Olympic Games began in February 2022[109], laying the basis for a green Beijing Olympics. To assist the hydrogen buses servicing guests, Sinopec has promised to build ten hydrogen refuelling stations in Zhangjiakou, one of the Games' competitive zones. The succession of Memorandums of Understanding (MoUs) that government–owned China Power has signed with international technology businesses provides another evidence of how SOEs are utilizing private sector partnerships to achieve goals. Siemens and China Power reached an agreement to deliver a hydrogen production system in Beijing's Yanquing District, one of the three Olympic competition sites for 2022[109].

However, more than 1,000 hydrogen vehicles are currently cruising Beijing's streets and Zhangjiakou [110], a hilly location approximately 220 kilometres (136 miles) northeast of the capital where ski jumping, and snowboarding events are taking place. More than 800 buses from manufactures such as Beiqi Foton, Geely, and Yutong are among the vehicles [110]. Toyota's hydrogen powered Mirai vehicles and Coaster vans are also ferried athletes and Olympic personnel around the Olympic sites. Specially specialized hydrogen trucks provide services like as ski waxing to assist racers maintain their equipment, while four of Geely's hydrogen vehicles served as catering vans for Olympic employees, providing meals, hot coffee, and milk tea [110].

4.2.5. FCV Development Goals

The Chinese development goal for hydrogen refuelling stations (HRS) and fuel cell vehicles (FCV) is as follows, according to China's Technology and Industrial Development Strategy:

I. By 2025, China will have deployed FCVs with 10,000 commercial vehicles and 40,000 passenger cars [111].
    - FCV small-scale applications, with a focus on urban passenger automobiles and public transportation vehicles.
    - Structure optimization of fuel cell systems; and
    - Accelerating the commercialization of key FCV components and lowering the cost of fuel cell systems.

II. By 2030, China will have deployed one million FCVs on a wide scale and produced more than half of its hydrogen from clean energy sources [111].
    - Integrated hydrogen production, storage, delivery, and large-scale applications; - On-site hydrogen production at hydrogen refuelling stations, as well as standardization and commercialization; and
    - Establishing an entire fuel cell manufacturing and supply chain that includes FCV materials, components, and systems.

4.2.6. Commercial Vehicle Fuel Cell System Technology Roadmap

China's technology roadmap for commercial vehicle fuel cell system (engine) development (12-meter bus utilized as typical vehicle for studies), includes two developmental milestones that are expected to be completed by 2025, and 2030, respectively [108]. It will enter the market by launching a low-power fuel cell system in order to initiate volume manufacture of commercial vehicle fuel cell systems and small-scale vehicle deployment. To accomplish this, it will steadily increase commercial vehicle fuel cell system power, optimize system functions, and design, and improve system performance - with the goal of meeting commercial criteria for rated power, efficiency, environmental adaptability, durability, and prices. It will also establish high-volume manufacturing capacity of commercial vehicle fuel cell systems to fulfil commercial vehicle development requirements.

Through continuing fuel cell system performance improvement, cost reduction, and reliability enhancement, 2025 will be the year for fuel cell systems to reach wide scale use in commercial vehicles. During this stage, the fuel cell system's performance will gradually increase by increasing the system's rated power to 100kW, power density to 400W/kg and to maximize system efficiency up to 60%. Also incorporate to cold start -30ºC for practically all winter circumstances in China and have a cost less than RMB 2,000/kW [108]. The year 2030 will mark the commercialization of fuel cell systems. During this stage, the fuel cell system will meet commercial needs by improving its system's rated power to 150kW, power density to 500W/kg and to maximize system efficiency up to 60%. Also incorporate to cold start -40ºC for practically all winter circumstances in China with increased life expectancy of over 30,000 hours and have a cost less than RMB 6000/kW. [108]

4.2.7. Challenges on the Road

While hydrogen is gaining popularity in China, with an eye on extending applications beyond transportation, the 14th FYP framework was lacking in specifics [111]. More information will be provided through industrial and provincial strategies, as well as coordinated state-led activities to aid the development and implementation of innovative technologies. At first, because hydrogen is considered as a hazardous element in China, its manufacture, transit, refuelling, and storage are all heavily controlled, resulting in low transportation efficiency and high prices. Second, while hydrogen has been identified as a crucial technology to develop in the energy vehicle sector, the government has been more aggressive in promoting electric cars (EVs). Third, China lacks the fundamental technologies needed to allow renewable-based hydrogen generation, and it lags behind advanced countries in hydrogen storage and transportation technologies, as well as manufacturing capacity for crucial materials [111].

Indeed, in the development of solar panels and wind turbines, China's clean-energy entrepreneurs depended on collaborations with international companies rather than their own R&D to gain access to new technology. However, rising worldwide concern over China's corporate practices and the fight for technological superiority may stifle the flow of these commodities to the country and limit Western investment in the country. Despite the fact that China's 14th FYP emphasizes technical self-sufficiency and efforts to create breakthrough technologies in acknowledgement of these trends, this might take time. Water electrolysis driven by renewable electricity is projected to become China's primary source of hydrogen supply, given China's 2060 goal and the predicted rise in renewables [111]. Similarly, the usage of renewable power in green hydrogen will increase, boosting renewables and assisting in the resolution of some of China's curtailment concerns. Regional plans will be revealed in the coming months, and the 14th FYP development agenda may include a national development strategy. In China, it is obvious that hydrogen applications are gaining traction, with a progressive transition from grey to blue and green hydrogen. While China's state power can be intimidating and will aid in the development of hydrogen technology and uses, there are also obstacles to overcome. As a result, it's too early to declare China the winner in the hydrogen race.

4.3. Fuel Cell Buses Roadmap for US

In the United States, the deployment of hydrogen-fuelled buses has been slow, with hydrogen buses accounting for just 3.1% of total zero-emission buses (deployed or planned) across the country [112]. By 2035, the US transit bus fleet might be all electric, costing between USD56.22 billion and USD88.91 billion. The transition model assumes that a mix of battery-electric and hydrogen fuel cell cars will be used. The automobiles themselves contribute for between 51% and 59% of the expenditures in both the low-cost and high-cost situations [112]. The US government has put in place several programs to guarantee that appropriate refuelling infrastructure is put in place, encouraging transit agencies and operators around the country to invest in hydrogen buses.

State	Fuel Cell Buses	Total Zero-emission Buses
Alabama	**1**	4
California	**52**	1160
Hawaii	**4**	35
Illinois	**4**	78
Massachusetts	**1**	28
Nevada	**2**	36
Michigan	**2**	22
Ohio	**24**	61
Total	**90**	1424

Table 4.3 : State-wise distribution of hydrogen fuel cell buses and total number of zero-emission buses deployed in the US. [112]

4.3.1. The Clean Transit for America Plan

Senate Majority Leader Chuck Schumer and Chairman of the Senate Committee on Banking, Housing, and Urban Affairs Sherrod Brown announced the new Clean Transit for America Plan on May 4, 2021, which includes USD73 billion to help the country's public transportation systems transition to zero-emission fleets [112]. Clean energy vehicles will be utilized to replace 70,000 mass transit buses and 85,000 cutaway vehicles and transit vans [112]. The proposal would prioritize financing for communities with the poorest air quality, assisting in the fight against climate change, improving air quality, and establishing a transit worker training program that will generate well-paying union employment.

The money will be made available by raising financing for the Federal Transit Administration's (FTA) Low or No Emission Vehicle Program, whose principal goal is to help the country's transit fleet migrate to the least polluting and energy-efficient cars possible. Through the Low or No Emission Vehicle Program, the FTA has given approximately USD485 million for hybrid, battery-electric, and hydrogen fuel cell buses [112]. President Biden's American Jobs Plan, which asks for USD621 billion in transportation investment and is likely to increase government spending on public transportation, was announced immediately after the plan was revealed.

4.3.2. California Zero-Emission Vehicle (ZEV) Action Plan

The California ZEV Market Development Strategy aims to assist the state provide zero-emission advantages to all residents. The action plan was launched in January 2018 with the goal of expanding the supply of ZEVs and increasing the number of charging and refuelling stations throughout California. The plan calls for the construction of 200 hydrogen fuelling stations and 250,000 electric vehicle chargers by 2025, with a goal of 5 million ZEVs on California roads by 2030 [112]. The program aims to focus multi-stakeholder efforts on implementing charging and fuelling infrastructure, as well as making ZEV ownership and operation more affordable. These objectives include Raising consumer knowledge of ZEV alternatives and advantages to the public; Providing a simple charging and fuelling infrastructure to support ZEV adoption; Maximizing the economic and job prospects created by using ZEV technology; Supporting the expansion of the ZEV industry outside of California; and setting an example for other states to follow.

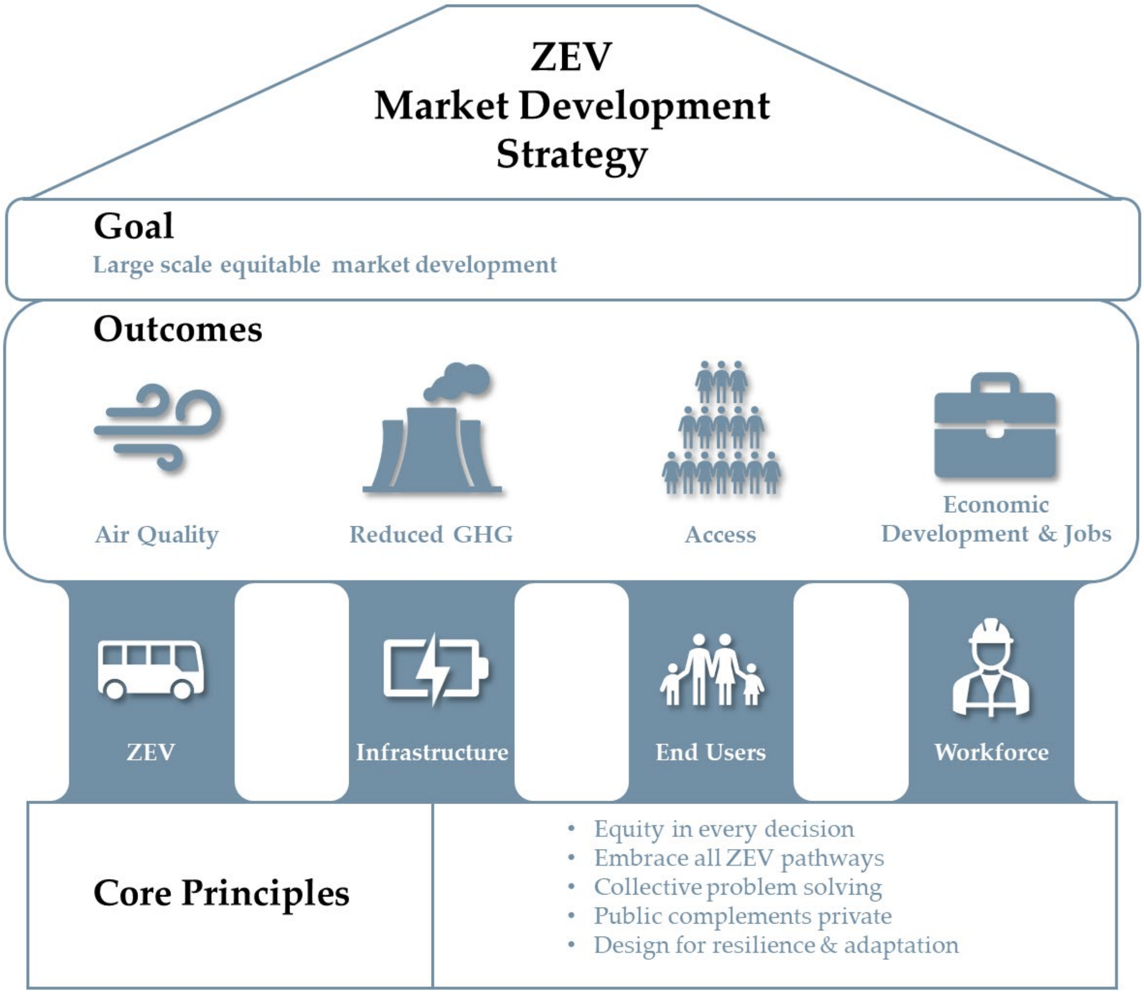

Figure 4.9 : California ZEV Market Development Strategy - ZEV Pillar Priorities Implementation. [112]

4.3.3. National Fuel Cell Bus Program

The National Fuel Cell Bus Program is a public-private partnership that aims to accelerate the commercialization of fuel cell technology in US transit buses. To date, approximately USD60 million has been given for competitively selected projects, with an additional USD60 million in private pledges from industry [113]. The US Department of Energy's National Fuel Cell Bus Program is aimed at improving transit bus efficiency and lowering petroleum use, as well as reducing transit bus emissions and carbon emissions. The program also aims to develop an internationally competitive US fuel cell bus industry and increase public understanding and acceptance of hydrogen-powered cars.

	Bus Operator	Location	Active Buses	Technology Description
1	SunLine Transit Agency (AFCB prototype)	Thousand Palms, CA	1	ENC/BAE Systems/Ballard next-generation advanced design to meet “Buy America” requirements
2	SunLine Transit Agency	Thousand Palms, CA	8	AFCB
3	Stark Area Regional Transit Authority (SARTA)	Canton, OH	18	AFCB
4	University of California at Irvine	Irvine, CA	1	AFCB
5	SunLine Transit Agency	Thousand Palms, CA	1	ENC battery dominant with US Hybrid fuel cell system
6	AC Transit	Oakland, CA	1	New Flyer articulated battery dominant, Ballard fuel cell system
7	Orange County Transportation Authority (OCTA)	Santa Ana, CA	10	New Flyer battery dominant, Ballard fuel cell system
8	AC Transit	Oakland, CA	10	New Flyer battery dominant, Ballard fuel cell system
9	SunLine Transit Agency	Thousand Palms, CA	5	New Flyer battery dominant, Ballard fuel cell system
10	U.S. Air Force at Joint Base Pearl Harbor– Hickam	Honolulu, HI	1	BYD battery electric bus (BEB) with US Hybrid fuel cell range extender
11	County of Hawai'i Mass Transit Agency (Hele-On Bus)	Hilo, HI	3	Shuttlebus, electric drive with fuel cell range extender
12	AC Transit, Zero Emission Bay Area	Oakland, CA	15	Van Hool bus and hybrid system integration
13	Other	-	16	
	Total		**90**	

Table 4.4 : Fuel Cell Transit Buses in Active Service in the United States. [115]

4.3.4. The 2029 Vision by CaFCP

The California Fuel Cell Partnership was formed in January 1995 when three state government agencies—the California Air Resources Board, the South Coast Air Quality Management District, and the California Energy Commission teamed up with six commercial firms: Ballard Power Systems, DaimlerChrysler, Ford Motor Company, BP, Shell Hydrogen, and ChevronTexaco. The purpose was to show and promote the benefits of fuel cell vehicles (FCV) as a clean, safe, and practical alternative to internal combustion engines [114]. CaFCP envisage a development path from 100 FCEBs in 2020 to over 25% of all zero-emission buses (ZEB) by 2029, including fuelling infrastructure. California will be able to completely comply with the ICT law thanks to fuel cell electric buses [113]. Using FCEBs helps California transit agencies to plan for the implementation of the Innovative Clean Transit (ICT) policy [115] based on reasonable considerations for their individual requirements. Hydrogen electric mobility solutions are like natural gas mobility solutions in that they give the transit agency complete control over the design, construction, and operation of their fleet and fuelling infrastructure without relying on complex utility programs and allowing them to control their operating costs. Long, expensive grid integration studies, as well as large-scale public works projects for substation and feeder construction for all grid-charging fleets, can wrest control of bus infrastructure schedules and costs away from transit agency planners [113]. FCEBs can help transportation agencies maximize facility use and manage ICT transition plans (Table) [113]. For the ICT rule to be successful, transit planners must be able to balance their fleets with battery electric choices when their operations allow, while relying on FCEBs to offer full coverage in all situations, including longer and FEMA ordered evacuations and FCEBs as a backup of the electric grid for more difficult-to-fill routes and emergencies such as resilience in the event of a natural catastrophe [113]. The different transit programs which involve in this vision are AC Transit, SunLine Transit and Orange County Transit.

AC Transit is making strides toward a cleaner and quieter future. AC Transit has the most complete fuel cell program in North America, with 13 fuel cell electric buses on the road and two hydrogen stations [117]. In the Bay Area, AC Transit's FCEBs have travelled over 1.3 million miles and transported over 5 million passengers [117]. In 2018, AC Transit installed ten additional fuel cell buses. SunLine became the first public transport operator to use 100% alternative fuel cars when it transitioned from diesel to CNG overnight in 1994. SunLine became the first transit hydrogen station in the world and began running a fuel cell bus in 2000. SunLine installed 12 fuel cell transit buses and two shuttle buses in 2018[117], as well as improving its hydrogen station, which currently has five FCEBs in regular service. In the summer of 2016, OCTA introduced its first fuel cell bus to the fleet, with plans to deploy 10 more buses with accompanying fuelling infrastructure for future [117]. OCTA expects to run the first bus on a variety of routes for around 16 hours per day, 292 days per year during the two-year trial program, which is the same timetable as other buses in their fleet [117].

In the United States, behind electric buses, hydrogen fuel cell buses are the second most frequent form of zero-emission bus. Only 3.1 percent (87 buses) of the total 2,790 buses (deployed or planned) have hydrogen fuel cells [112]. The low number of hydrogen buses on the road can be ascribed to increased procurement costs, a lack of supporting infrastructure, and agency preferences. Many transit agencies have declared intentions to expand bus lines, which would likely raise demand for hydrogen fuel cell cars in the future.

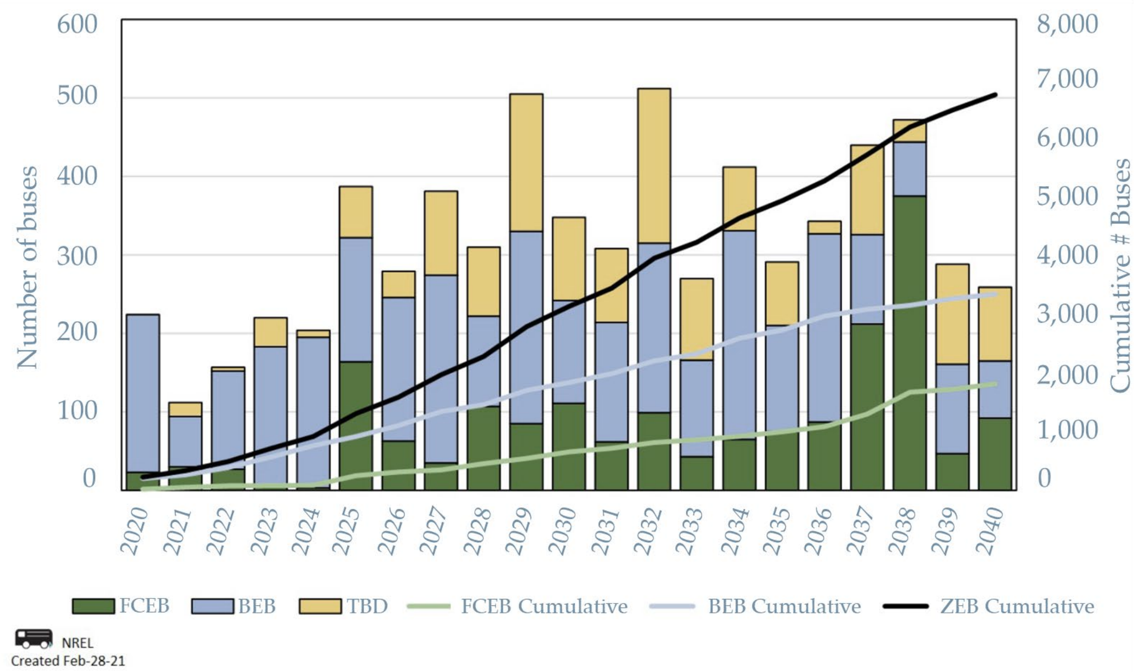

Figure 4.10 : Planned or potential ZEB purchases in California by year. [115]

The graph above depicts the planned or probable ZEB purchases by agencies through 2040. According to an analysis of future bus plans, these agencies in California will purchase almost 1,800 FCEBs between 2020 and 2040. For certain agencies, the technology to be purchased will be selected after early deployments have provided sufficient data to make informed decisions. These purchases, indicated as to be determined (TBD), amount over 1,500 buses. According to NREL, a percentage of these buses will be powered by fuel cells, increasing the number of FCEBs in the state. Some of these buses are replacements for FCEBs that are already in operation or were ordered early in the period.

4.3.5. Recent Developments

Recently in May 2021, BAE Systems and Plug Power have established a partnership to provide hydrogen-based electric propulsion systems for transit buses. The system is projected to improve transport operators' efficiency, reliability, and emission-free alternatives. Plug Power's fuel cell engines will be integrated into BAE Systems' electric drive systems to power buses. Around February 2021, eleven firms in the United States have created the Hydrogen Forward consortium to work on hydrogen-related innovations. Air Liquide, Anglo American, Bloom Energy, CF Industries, Hyundai, Cummins Inc., Hyundai, Linde, McDermott, Shell, and Toyota are among the original members. The coalition's goal is to promote policies that speed up the transition to new clean energy sources and to build a plan for the development of hydrogen technology and infrastructure [112]. In April 2021 the

Stark Area Regional Transit Authority (SARTA) collaborated with China Energy's research and development arm in the United States, NICE America Research. SARTA's main headquarters now have a submerged pump mobile refuelling station, which will be utilized to refill the transit authority's 10 buses and five hydrogen-fuelled Pro-Line vehicles. For the first time, the demonstration was carried out in real-world situations during a three-month period [112].

5 Indian Hydrogen Economy

5.1. Transport Sector in India

India's present transportation infrastructure is being strained by rapid urbanization and motorization, resulting in increasing pollutants, and energy consumption. In India, traffic is diversified, with around a dozen different kinds of slow- and fast-moving vehicles. Two-wheelers and cars (including jeeps) account for more than 80 percent of the vehicle population in most large cities. While India took nearly 60 years to get 105 million registered automobiles (1951-2008), it only took six years (2009-15) to double that figure [120]. However, from 11% in 1950 to 0.6 percent of all registered vehicles in 2016, the percentage of registered buses has decreased [121,122]. According to CSE forecasts, public transportation's proportion of total passenger kilometres will fall from 75 percent in 2000-01 to 44.7 percent in 2030-31, while personal transportation's part would climb to more than 50 percent [124]. In India, just 7% of trips are taken by public transportation, compared to 86 percent in Singapore and 29 percent in Brazil [123]. The below graph Oil interprets that demand climbed faster than any other fuel, with transportation driving the majority of the increase.

The Ministry of Housing and Urban Affairs (MoHUA) forecasts that urban roadways and mass transport networks would require INR 21 lakh crore in investment between 2011 and 2031. If public transportation is primarily provided by buses, an extra 460,000 buses, in addition to other forms of public transportation, will be required by 2031 at present usage levels [118]. However, although the metro budget climbed from 12% in 2009 to 54% in 2017, there was no comparable increase for buses or system integration, despite the fact that buses transport significantly more people. About 80% of India's crude oil is imported, while more than 40% of oil and its derivatives are utilized to power cars. The road transportation sector accounts for 10% of total GHG emissions across all sectors. Until 2040, the transportation sector will continue to have the highest growth rate in energy consumption (up to 7%), followed by industry (6.4%) and the construction sector (2.4%). Energy demand in the transportation industry will be driven by demand from light-duty and heavy-duty trucks [124]. This opens up the possibility of adopting effective mobility solutions that encourage people to switch from light-duty private modes to public transportation. The government recognized this by allocating INR 18,000 crore to buses in the Union Budget 2021-22 [125].

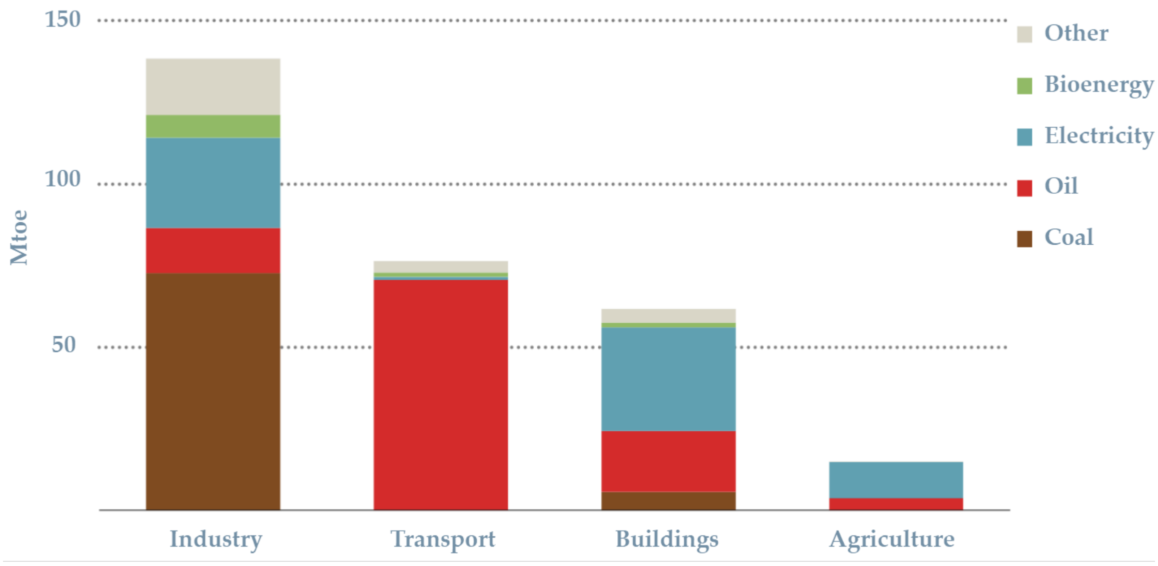

Figure 5.1 : Change in energy demand by fuel in selected end-use sectors, 2000-19. [119]

Eleven states in India have notified or created particular EV policies, which include features such as a unique price for EV charging, construction regulations to accommodate EV charging, and experimenting with e-buses in state transportation fleets, among other things [126]. The Delhi government has demanded that all government cars be replaced with electric vehicles within six months [127]. India's EV value chain is estimated to reach USD 4.8 billion by 2025. In FY20, 1.52 lakh two-wheelers, 3400 vehicles, and 600 buses were sold, resulting in a 20 percent increase in overall EV sales over the previous year [128]. Rickshaws, automobiles, and two-wheelers are the most potential electrification categories in India, with over 40 lakh units predicted by 2025. The industry's prognosis is upbeat, with 30-35 percent of sales predicted to be electrified by 2025 [129]. India began its pollution-control initiatives by gradually adopting EU regulations, starting with Euro-I. It was the first country to leap-frog from Euro-IV to Euro-VI in a short period of time. India has given alternative fuels a major push, both from an environmental and energy security standpoint. Since the turn of the millennium, CNG and LPG have become important alternative fuels in India. Ethanol and biodiesel have been accorded similar priority as transportation fuels, with the present focus on infrastructure development in Tier-II cities.

Recently, the government has made electrification of transportation vehicles a priority for lowering pollution in cities. The FAME India initiative (Faster Adoption and Manufacturing of (Strong) Hybrid and Electric Automobiles in India) was launched in 2015 with the goal of promoting environmentally friendly commuting choices by sponsoring battery-powered vehicles. The FAME India scheme's second phase focuses on electrifying India's public and shared transportation systems by providing subsidies for electric buses, passenger automobiles, and two-wheelers. In August 2019, the government announced plans to acquire 5,585 electric buses to help conserve the environment. Starting from 1st-April-19 over a period of three years, India implemented FAME India Scheme Phase II. FAME II has three broad verticals: Incentive based on Battery kWh, Charging infrastructures development and IEC (Information, Education and Communication). FAME II has a project estimation of 1.5 billion USD [130]. Major efforts have been made to establish a regulatory framework for PEV/HEV/H2FC that is compliant with EU regulations. There are regulations in place for both environmental and safety considerations. The focus is on getting EU regulations/ GTRs for PEV/HEV/H2FC into Automotive Industry standards (AIS) as quickly as possible.

5.2. India's Hydrogen Mission

The National Hydrogen Mission seeks to reduce carbon emissions and enhance renewable energy consumption while aligning India's efforts with international best practices in technology, policy, and regulations. The Indian government has set out Rs 25 crore in the Union Budget for 2021–22 for hydrogen energy research and development, with the goal of producing three-quarters of its hydrogen from renewable sources by 2050 [131].

On the 75th anniversary of India's independence, Indian government announced the commencement of the National Hydrogen Mission (NHM), with the goal of reducing carbon emissions and increasing the use of renewable energy sources. The National Hydrogen and Ammonia Mission (NHM) intends to take use of the country's vast geography as well as cheap solar and wind tariffs to manufacture low-cost green hydrogen and ammonia. Pilot projects, infrastructure and supply chain, research and development, laws, and public outreach have all been recognized as major areas for investment. Delhi became the first city in India to employ hydrogen enriched CNG buses in October 2020. This was viewed as a first step toward the city of Delhi operating completely hydrogen-powered buses. Several firms, including Indian Oil Corporation and NTPC, are aiming to increase the number of hydrogen-powered buses on the road in India. In Leh and Delhi, NTPC is launching a pilot project to run ten hydrogen fuel cell (FC)-based electric buses and numerous hydrogen fuel cell-based electric automobiles. IOC has expressed interest in purchasing 15 buses and plans to build a specialized hydrogen production plant at its Faridabad research and development centre to power the buses [132]. The timeline for hydrogen-related initiatives in India is depicted below.

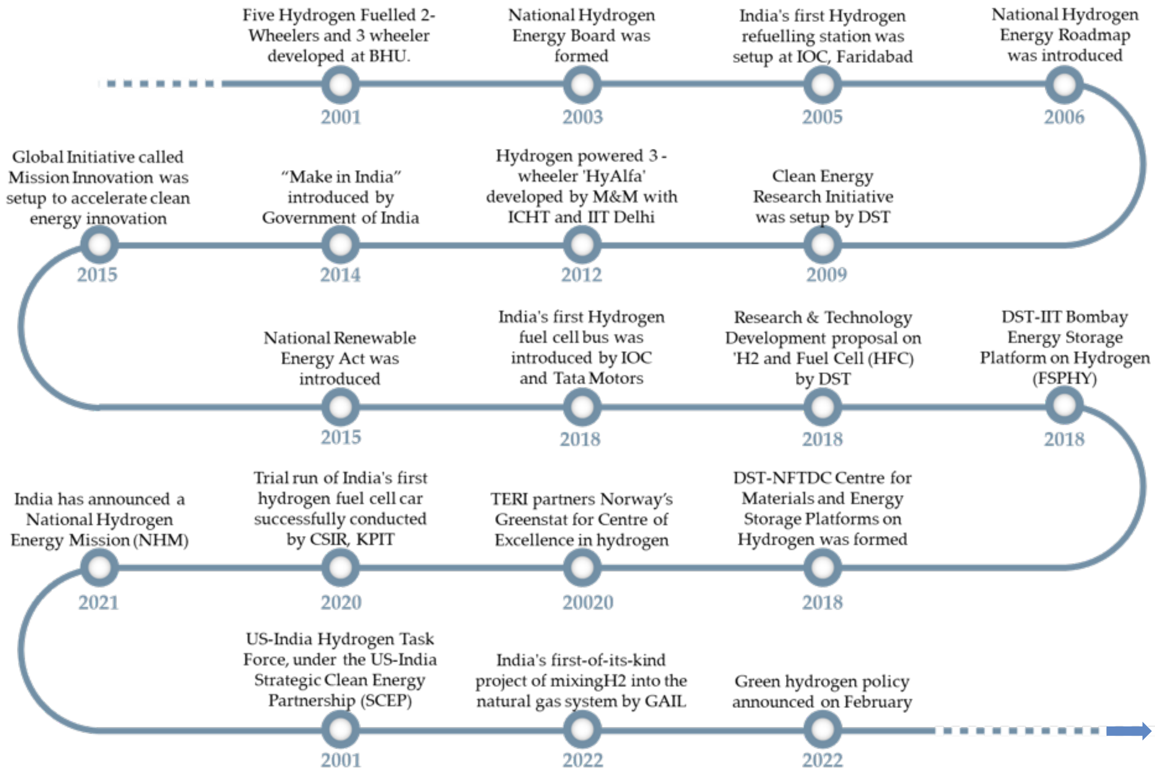

Figure 5.2 : Road map of achievements and major milestones by India's H_2 related projects. [131-167]

The National Hydrogen Energy Board was established in 2003, and the Ministry of New and Renewable Energy published the National Hydrogen Energy Road Map in 2006 [131], which identified transportation and power production as two important green energy efforts. 10 India is taking part in the Mission Innovation Challenge for Clean Hydrogen, with the goal of accelerating the growth of the global hydrogen industry. In India, R&D initiatives are aimed at increasing the efficiency of the water-splitting reaction and developing novel materials, catalysts, and electrodes to speed up the process. International companies like Praxair, Air Products, Fuel Cell Energy and H2Scan from USA, Linde a global-member of hydrogen council, Inox which is an Indo-US joint venture, Air Liquide and SAGIM from France, ITM Power from UK, Heliocentris from Germany and home-grown companies like Aditya Birla, Bhoruka Gases Ltd, Gujarat Alkalies and Chemicals Limited, Gujarat Heavy Chemicals Limited, Air Science Tech and Sukan Engineering Private Limited [131] put their efforts to stimulate collaboration in the energy transition. India and Italy have committed to research green hydrogen development, renewable energy corridor construction, and joint natural gas projects. The two leaders agreed to promote joint investments of Indian and Italian firms in the energy transition-related sector, according to a joint statement released by India and Italy after the G20 Summit in Rome [133].

5.3. Partnership with GCC

India and the GCC countries have a strong energy partnership. India purchased approximately 53% of its energy from the Persian Gulf in 2017–18, and the UAE and Saudi Arabia were India's third and fourth largest commercial partners, respectively [131]. India and the Gulf Collaboration Council are natural energy partners with a lot of room to further cooperation in greener fuels like hydrogen. The GCC countries have established a variety of goals for renewable energy self-sufficiency and export capacity, including hydrogen. By investing in the Helios Green Fuels facility in NEOM city [134], Saudi Arabia hopes to become the world's largest producer of hydrogen valued US$ 700 billion by 2050. According to the UAE's Energy Strategy 2050 [135], renewable energy will supply 44% of the country's energy demands, and Masdar wants to become a hydrogen manufacturing centre. Oman aims to achieve 40% of its energy demands with renewables by 2040, as stipulated by Vision 2040 [136]. The Ministry of Energy and Minerals is forming the National Hydrogen Alliance (Hy-Fly) to encourage and ease the production, transportation, and use of clean hydrogen for domestic and international purposes. In Al Wusta Governorate, Oman plans to construct one of the world's largest green hydrogen plants. Kuwait also plans to produce 15% of its power from renewable sources by 2030[137], while the Kuwait National Petroleum Company's Clean Fuels Project, which involves the development of a new hydrogen plant at the Mina Abdullah Refinery, intends to improve downstream operations. As part of Vision 2030 [138], Bahrain aims to generate 10% of its power from renewable sources. In addition, GCC is working on a number of additional initiatives in conjunction with the United States, France, Japan, and Belgium. Products for the Air at the Jubail Industrial City, Qudra, a Saudi–US joint venture, will create Grey Hydrogen. The YASREF refinery, the SAMREF refinery, and three industrial complexes in Yanbu will be supplied with hydrogen by Air Liquide Arabia, a Saudi – French joint venture. Etihad Airways, Lufthansa Group, Siemens Energy, and Marubeni Corporation of Japan have signed MoUs with the Abu Dhabi Department of Energy and Abu Dhabi Future Energy Co. to establish a demonstration-scale green hydrogen plant at Masdar City. The HYPORT Duqm Green Hydrogen Project will see DEME Concessions of Belgium and Oman's state oil firm OQ develop a 250MW–500MW electrolyser facility [131]. The SOHAR Port and Freezone in Oman will house a large-scale solar-powered green hydrogen generating facility.

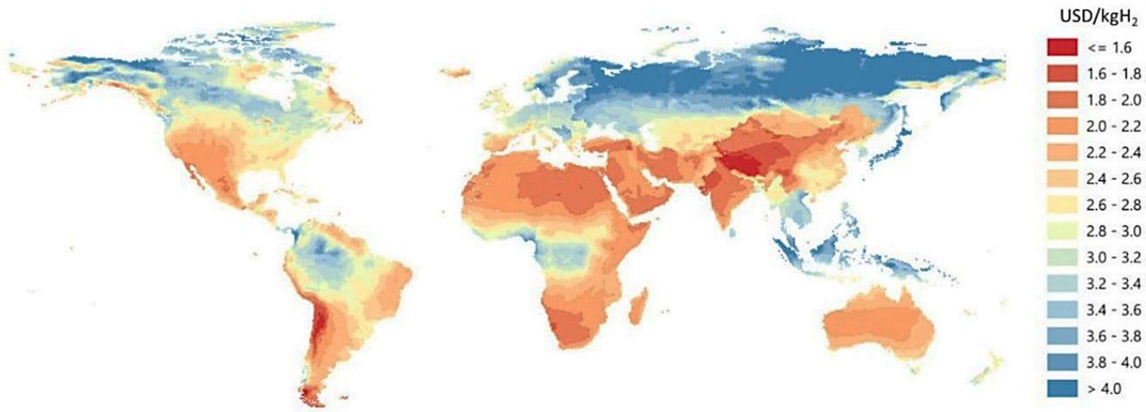

Figure 5.3 : Hydrogen costs from renewable energy (hybrid solar PV and onshore wind systems) in the long-term. [77]

India and the GCC countries have a lot of potential for hydrogen collaboration in terms of investment and knowledge transfer. The above figure shows, India and the GCC countries are projected to be among the lowest-cost regions in the world for green hydrogen production, due to their very high direct normal irradiance and wind speed (>8 m/s). The incompatibility of electrolysers with salty water is one of the most pressing difficulties confronting GCC countries when it comes to hydrogen fuel production. Sea water must first be desalinated before electrolysis can take place. Several Indian research institutes are concentrating their efforts on manufacturing hydrogen from saltwater. The Central Electrochemical Research Institute in Karaikudi, for example, is working on the design of electrodes and electrolytes for hydrogen production from seawater, while the International Advanced Research Centre for Powder Metallurgy and Seawater Electrolysis is being investigated in Chennai. Similarly, GCC nations have an abundance of solid waste that may be utilized to make hydrogen as a result of their rising consumption patterns. The Indian Institute of Science (IISc), Bangalore, the National Institute of Technology (NIT), Rourkela, the Indian Institute of Chemical Technology (IICT), Hyderabad, and the National Institute of Technology (NIT), Raipur are conducting research on the production of Bio Hydrogen from waste, paving the way for collaboration between New Delhi and the Gulf Cooperation Council (GCC) countries, particularly the UAE, which produces the world's highest daily per capita municipal solid waste. The Gulf Cooperation Council (GCC) nations, particularly Saudi Arabia and the United Arab Emirates, have invested in improving carbon capture, use, and storage, and there is opportunity for Indian universities working on the subject to interact in terms of information transfer [131]. India's National Hydrogen Mission is a far-sighted goal that may assist the country decrease carbon emissions while also diversifying its energy portfolio and reducing dependency on foreign sources. Hydrogen energy is still in its infancy, but it holds a lot of promise in terms of achieving India's energy revolution. As a result, this is a good moment for India and the Gulf Cooperation Council (GCC) to enhance their relationship in hydrogen energy research and development, production, storage, and transportation.

5.4. Hydrogen Chain in India

5.4.1. Hydrogen Production & Storage

In India, hydrogen is already widely employed, mostly as an industrial feedstock for the production of ammonia-based fertilizers. In India, the majority of hydrogen is produced via reforming methane (CH4), which results in large carbon dioxide emissions. Carbon capture and storage (CCS) technology has the ability to collect these emissions, albeit it is still undeveloped in India [139]. While there is a lot of research going on in the field of electrolysis, photolysis, and biogenic hydrogen production, these low-carbon technologies have yet to be adopted at scale. This is partly owing to the current high costs of producing hydrogen from low-carbon sources, which are greater than the costs of producing hydrogen from fossil fuels or other fossil-fuel equivalents. It is possible, however, that in the future, these prices will equalize, with green hydrogen undercutting grey hydrogen in favourable places. This is made easier in India, where renewable energy costs are already among the lowest in the world and natural gas sources are scarce and expensive. The capital cost of electrolysers, in addition to energy rates, is a key component in lowering the costs of green hydrogen.

5.4.1.1. Green Initiative for Power Generation (GIP)

Through various stages of technological development and demonstration, the Green Initiative for Power Generation (GIP) aims to develop and demonstrate hydrogen-powered IC engine/turbine and fuel cell-based decentralized power generating systems ranging from tiny milliwatt capacity to MW scale systems. High-temperature fuel cells are a viable solution for decentralized, efficient, and sustainable energy generation. Apart from electricity generation in metropolitan regions, this effort will aid in supplying clean energy to rural and distant locations in a decentralized way. The ultimate objective would be to mass-market power generation systems capable of matching the technical performance of a traditional fossil-fuel-fuelled generator. The main objectives of GIP are the pipeline and mechanisms for storing hydrogen in bulk must be in place, as well. Infrastructure supporting a high number of dispensing stations. The salient features of Generators produced under this scheme are [140].

- Single-unit capacity of up to 500 kW
- Operation indefinitely
- Heat Control System
- Fuel cell stack efficiency is over 70%, with a life expectancy of more than 50,000 operational hours [140].

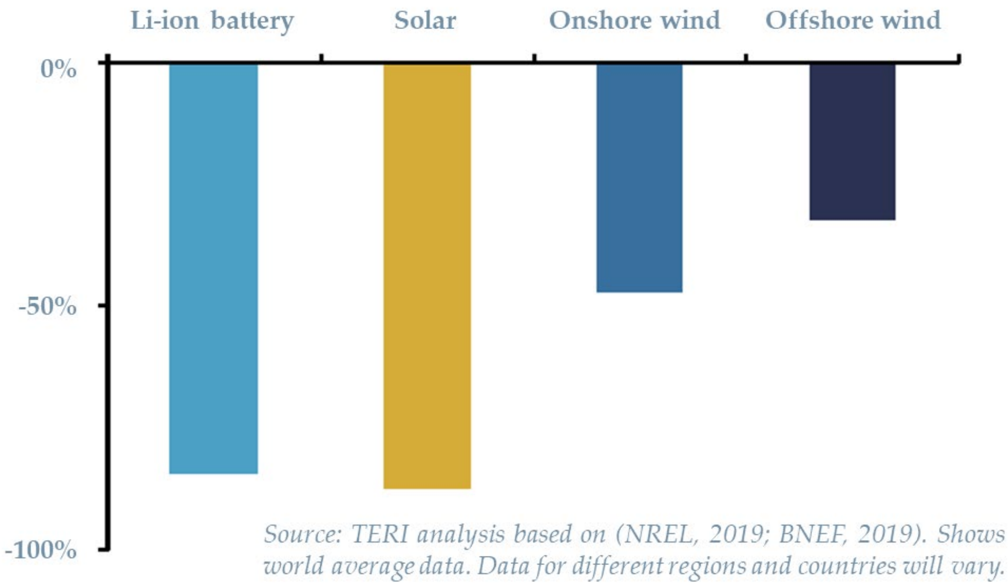

Figure 5.4 : Cost reductions for key clean energy technologies, 2010-2018. [142]

Fusion Fuel will build a small demonstrator plant for BGR Energy in Cuddalore, Tamil Nadu, India, utilizing its market-leading HEVO-SOLAR technology to create cost-competitive green hydrogen. The firms will subsequently work together to build projects across India, using BGR Energy's enormous client base and established commercial reach. Given BGR Energy's extensive expertise in the energy, environmental, and industrial sectors, the firms will also look at other areas of possible collaboration [141].

In his book 'Generation H,' Marco Alvera, CEO of Snam Chemicals, believes that the world will need to create 50 GW of electrolyser capacity (vs. 135 MW currently) to help push green hydrogen prices down to $2/kg, where it will be competitive with a variety of fossil fuels (Alvera, 2019; BNEF, 2020) [142]. Since 2006, when the first Hydrogen and Fuel Cell Roadmap was released, the Ministry of New and Renewable Energy (MNRE) has seen hydrogen as a strategic priority (MNRE, 2006). MNRE produced a study in 2016 that included a detailed plan for expanding R&D activities [142]. This includes major investment into various electrolyser technologies and their integration with renewable power sources, which, given the cost and availability of renewable electricity in India, has a lot of promise. There are significant initiatives in India's industry to build a hydrogen economy, as a result, Indian businesses have begun to use the technology. This transformation is being led by five firms.

5.4.1.2. Reliance Industries

The country's largest private oil and gas giant, Reliance Industries Ltd (RIL), has announced aspirations to go green. The corporation has stated its goal of being a carbon-neutral company by 2035 [143]. Clean power and hydrogen will be used to replace transportation fuels. Over the next three years, the conglomerate plans to invest 750 billion in renewable energy, according to the company. It would put $600 billion into the Dhirubhai Ambani Green Energy Giga Complex in Jamnagar, Gujarat, which is a 5,000-acre green energy integrated complex. The complex will comprise solar cell and module manufacturing facilities, a battery unit for energy storage, a fuel cell factory, and a green hydrogen electrolyser plant. In addition, the organization is looking for partners to help it introduce new and innovative technologies to India. While this will be costly (green hydrogen costs roughly US$3.6-5.8/kg), Mukesh Ambani, the company's chairman, hopes to generate hydrogen for "around US$1/kg within a decade" [143].

5.4.1.3. Gas Authority of India Limited

GAIL (India), a state-owned company, too has big aspirations for green hydrogen. As part of its goal to bolster its natural gas business with carbon-free fuel, the PSU wants to develop India's largest green hydrogen facility. GAIL chairman and managing director Manoj Jain said at a recent event that the business has launched a global tender to acquire an electrolyser. He went on to say that the corporation has decided on 2-3 locations for the unit, one of which is in Vijaipur, Madhya Pradesh [144]. The factory will take 12-14 months to build up. The projected plant will have a capacity of 10 MW, making it the country's greatest thus far. On a trial basis, GAIL has begun combining hydrogen with natural gas in one of the cities. Before scaling up, the business is evaluating the mix percentage. GAIL aims to sell the hydrogen it produces to fertilizer companies, who are obligated by law to utilize hydrogen as a fuel. NTPC, like GAIL, intends to commercialize the production of green hydrogen. From its forthcoming 4,750 MW renewable energy facility in the Rann of Kutch, the business intends to accomplish this. The facility will have a 5 MW capacity (megawatts). NTPC is now conducting a trial project at its Vindhyanchal facility, where hydrogen costs are expected to be under US$2.8-3/kg [144]. In Leh, Ladakh, NTPC also intends to open its first green hydrogen fuelling station. To begin with, it will operate five hydrogen buses. Leh will be the country's first city to execute a green hydrogen-based mobility initiative as a result of this.

The green hydrogen project is another step in NTPC's aggressive quest to green its portfolio.

5.4.1.4. National Thermal Power Corporation Limited

NTPC, like GAIL, aspires to make green hydrogen commercially viable. The company's upcoming 4,750 MW renewable energy complex in the Rann of Kutch will help achieve this. The facility will have a capacity of 5 MW (megawatts) [145]. NTPC is now running a pilot project at its Vindhyanchal facility, with hydrogen prices projected to be less than US$2.8-3/kg [145]. NTPC also plans to construct its first green hydrogen fuelling station in Leh, Ladakh. It will start with five hydrogen buses. As a consequence, Leh will be the first city in the country to launch a hydrogen-based green transportation strategy.

5.4.1.5. Indian Oil Corporation

Indian Oil is another PSU that intends to take use of the green hydrogen opportunity. Indian Oil owns 11 of India's 23 refineries. It now has a hydrogen capacity of 659,000 mtpa, which is expected to increase to 866,000 mtpa by 2030 [146]. By 2024/25, it expects to convert 70,000 mtpa of this capacity to renewable hydrogen. The country's largest fossil fuel reseller has revealed intentions to construct a green hydrogen plant at its refinery in Mathura, Uttar Pradesh. The unit's capacity is expected to be roughly 160,000 barrels per day. It will transport electricity from its Rajasthan wind farm to its Mathura refinery, where it will be electrolyzed to make 100% green hydrogen [146]. It also intends to build a stand-alone green hydrogen production unit in Kochi, which would be powered by the Kochi International Airport's solar power facility. Kochi Airport, with a total capacity of 40 MW, is the world's first totally solar-powered airport. The plan is to run hydrogen buses between Cochin and Thiruvananthapuram. Indian Oil has set a goal to convert at least 10% of its hydrogen use at refineries to green hydrogen by the end of the year. By 2024, 10% of the energy used in the Mathura refinery will be transferred to green sources as a first step [146].

5.4.1.6. Larsen and Toubro

L&T, a leading engineering firm, also intends to enter the green hydrogen market. The company said that a green hydrogen plant will be developed at its Hazira facility, which is slated to be completed this fiscal year, and that it would collaborate with Norway's HydrogenPro to manufacture gigawatt-scale green hydrogen electrolysers in India. It also intends to build a few additional green hydrogen plants at its other factories. Aside from that, it is now assessing the feasibility of producing electrolysers. Subramanian Sarma, L&T's Director and Senior Executive Vice

President (Energy), remarked at the most recent press conference that it was very much on the cards and that an announcement may come as early as this fiscal year. L&T stated in its most recent annual report that it wants to achieve net-zero emissions by 2040 [147]. The transition to renewable energy, green hydrogen, and biodiesel would account for 90% of this, while the remaining 10% would be offset by the creation of carbon sinks. The corporation expects to invest between $10 and $50 billion in green projects over the next few years [147].

5.4.2. Hydrogen Distribution

The H2 supply chain includes establishing an efficient long-distance transportation system, storing hydrogen for a short or seasonal period of time, and developing a hydrogen distribution network appropriate for a variety of uses. A substantial and constant supply of hydrogen is required for applications such as big industrial operations (refineries, steel mills, paper mills, chemical industries). This necessitates the connection of clean hydrogen production to H2 delivery networks (in blend with natural gas, or in dedicated hydrogen pipelines) [148].

Given the present use of hydrogen, it is predicted that around 4500 km of hydrogen pipes with diameters of 25-30 cm and operating pressures of 10-20 bar have been built globally. Furthermore, some have been in operation for more than 60 years [149,150]. However, as Hu et al. [151] and Edwards et al. [149] point out, building hydrogen pipes is more costly than building natural gas pipelines. Indeed, the typical construction cost of a hydrogen pipeline with a diameter of 30 cm is about 854 USD/m [152,153], which is roughly 10% to 20% more expensive than natural gas pipelines [154]. Due to the low molecular weight of hydrogen and its accompanying diffusivity, this can be linked to the requirement for larger diameters and other extra expenditures like as welding operations, leak testing, and compression [155]. The current basic idea for promoting hydrogen penetration is to use the existing natural gas network and supplement it with hydrogen. This method not only provides for a decrease in infrastructure construction expenditures, but it can also help to reduce greenhouse gas emissions, especially if the extra hydrogen is green hydrogen. Hydrogen is already being injected into the gas grid in a number of projects throughout the world.

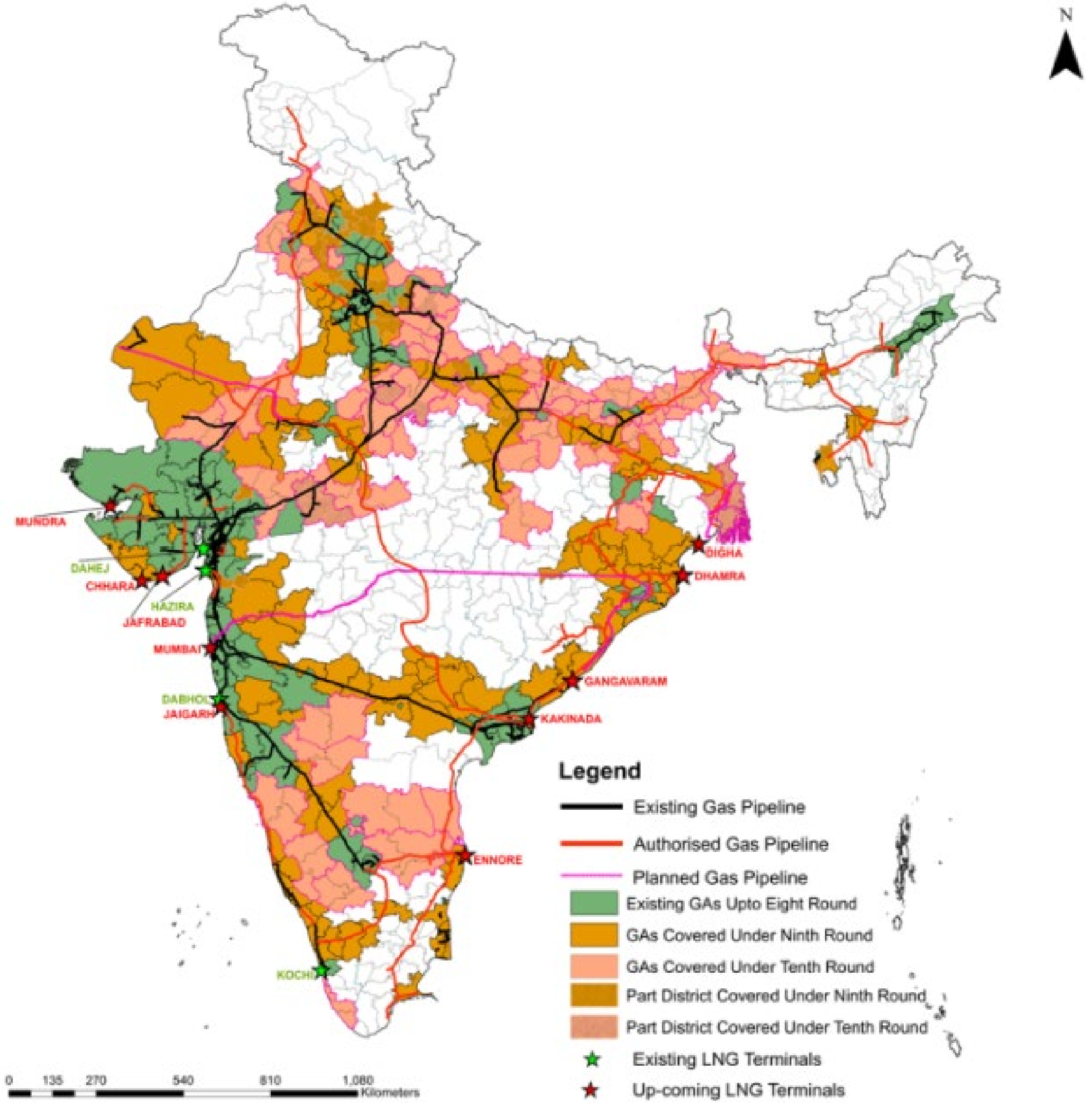

Figure 5.5 : Existing and Planned Gas Distribution in India [159]

GAIL (India) Ltd, India's state-owned gas utility, has started a one-of-a-kind initiative in Indore, Madhya Pradesh, to mix hydrogen into the natural gas system. Haveli. The hydrogen mixed natural gas will allegedly be given to Avantika Gas Ltd as part of the project. It is a joint enterprise between GAIL and HPCL. In particular, the mixed hydrogen gas would be used to supply CNG to autos and piped natural gas to homes in Indore. At Indore's city gate station (CGS), GAIL has begun combining grey hydrogen. "This grey hydrogen would be replaced with green hydrogen in the future," the report stated [156].

Figure 5.6 : Gas pipeline distribution along with Refineries. [160]

Based on how it is created, hydrogen is classed as blue, green, or grey. Blue hydrogen is created when natural gas is broken down into hydrogen and CO2. CO2 is collected and stored. Grey hydrogen is created in the same way as blue hydrogen is created, except CO2 is not absorbed and is released into the atmosphere. Natural gas pipelines are India's most important and critical energy assets, as well as the backbone for achieving a gas-based economy. GAIL has contributed to the expansion and development of natural gas pipeline infrastructure and the natural gas market throughout the years as a leading gas pipeline operator. It already has a 13,840-kilometer gas pipeline network with a capacity of 204 million Standard Cubic Meters of Gas per day (MMSCMD) [157]. GAIL's existing natural gas pipeline network spans 20 states (Andhra Pradesh, Assam, Bihar, Delhi, Goa, Gujarat, Haryana, Himachal Pradesh, Jharkhand, Kerala, Maharashtra, Madhya Pradesh, Punjab, Rajasthan, Tamil Nadu, Tripura, Uttar Pradesh, Uttarakhand, and West Bengal) and two union territories (UTs) (Puducherry & Dadra Nagar Haveli). Further GAIL have under construction pipeline network for 4,285 km with a capacity of 111 MMSCMD, which is expected to complete before 2024 [157].

Another key player in India for Natural Gas pipeline is GSPL, which runs the network for another 5041 km in states like Gujarat, Rajasthan, Haryana, Punjab, and UT of Jammu & Kashmir. This has a capacity of 162.5 MMSCMD [158]. IOCL have constructed a gas pipeline for 1553 km in Haryana, Punjab, Uttar Pradesh, and Tamil Nadu. Among this Tamil Nadu have a major network of 1421 km throughout the state with a capacity of 84.7 MMSCMD. IOCL has a capacity to distribute 105 MMSCMD in total. Apart from these major firms in India, NG pipeline infrastructure developers like GITL, PIL, APGDC, ONGC etc. built a network for 7837 km throughout India with a capacity for another 320 MMSCMD [158].

5.4.3. Hydrogen Refuelling Station

In 2021, 142 hydrogen refuelling stations were operational throughout the world, which is a record number. In Europe, 37 new hydrogen stations opened, 89 in Asia, and 13 in North America. This is the outcome of the 14th annual assessment of H2stations.org, a Ludwig-Bölkow-Systemitechnik information service (LBST). Hydrogen refuelling is currently available in 33 countries [161]. But in India the number of refuelling stations which are functional are very low and data about the same are not well shared. New Delhi Indian Oil Public Hydrogen Refuelling Station funded by Indian government is right now out of service as they were introduced as a demo project to study hydrogen fuelling. After the functional period larger stations where planned but that couldn’t kick start. New Delhi Indian Oil Public Hydrogen Refuelling Station was primarily started in 2010 to supply fuel for the 15 hydrogen-powered three-wheelers which previously mentioned [162].

Currently there are only two functional hydrogen fuelling stations India [162]. The Indian Oil R&D Centre in Faridabad and the National Institute of Solar Energy in Gurugram have each installed hydrogen refuelling stations. The station in Gurugram is part of a project supervised by the National Institute of Solar Energy (NISE), which is being carried out by India's University of Petroleum and Energy Studies (UPES) and supported by the Ministry of New and Renewable Energy (MNRE). The National Thermal Power Corporation Renewable Energy Ltd (NTPC REL), a wholly owned subsidiary of NTPC, has issued a domestic tender for the construction of a green hydrogen fuelling station in Leh, Ladakh. The competition comes after NTPC Vidyut Vyapar Nigam Limited (NVVN) recently announced a contract for fuel cell buses in Ladakh. NTPC REL and NVVN will collaborate on this green transportation initiative. NTPC REL is also building a separate 1.25 MW solar plant in Leh to make the hydrogen fuelling station totally green [163].

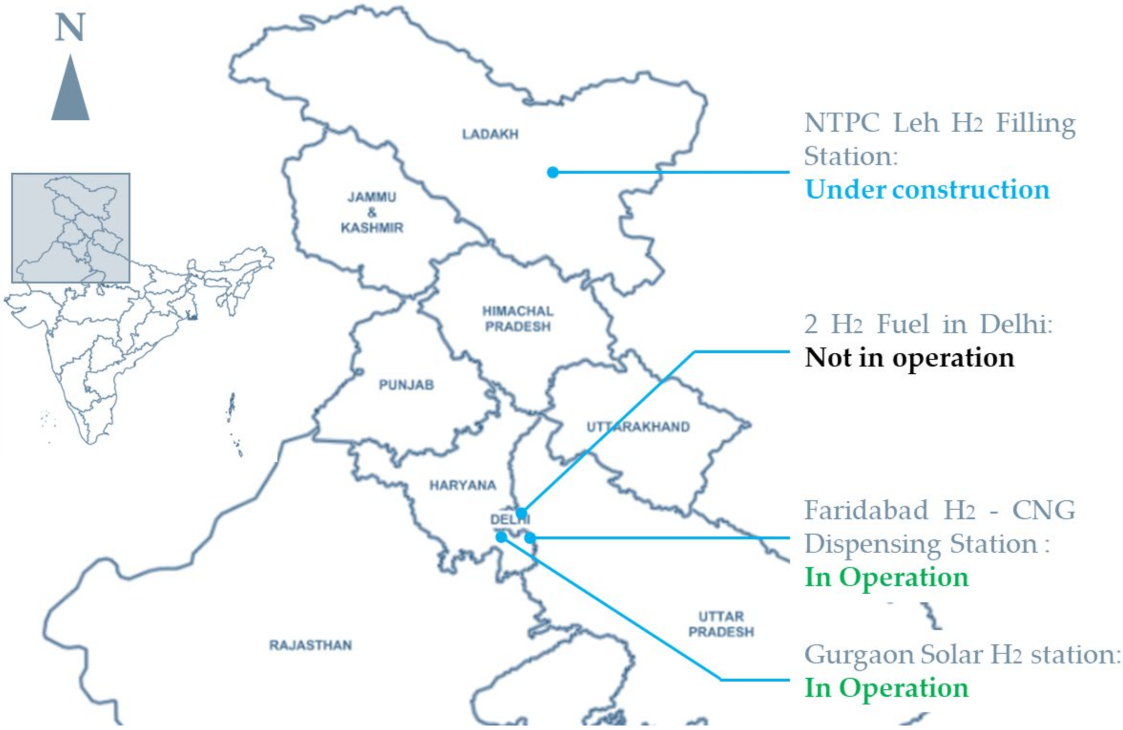

Figure 5.7 : Hydrogen Fuelling Station in India. [162]

Indian Oil Corporation (IOC), an oil refiner and supplier of petroleum products, is launching a demonstration hydrogen refuelling station for heavy-duty vehicles in Gujarat as part of its Green Drive to promote the use of electric cars in India. Nuberg oversees engineering, procurement, and construction, while FIBA Technologies Inc. in the United States is in charge of high-pressure hydrogen storage. The fuel for the demonstration facility will come from an existing hydrogen generating plant and will be stored in a 550-bar cascade system [164]. "IOC is becoming a big participant in the hydrogen fuel industry," says Jean-Christophe Poussin, FIBA's International Sales Manager. It has already built a hydrogen plant in Delhi to fuel buses, and it intends to have 15 fuel-cell buses operating [164]. It has also struck an agreement with Greenstat Norway to develop a Hydrogen Centre of Excellence. The Indian Oil Corporation (IOCL) is making aggressive steps to expand into alternative fuel generation. "Indian Oil is devoted to the usage of hydrogen, and we are conducting a lot of study in this specific aspect," said Shrikant Madhav Vaidya, chairman of Indian Oil. He went on to say that hydrogen will be used "in a large way" in the future. MNRE has been sponsoring a broad-based Hydrogen Energy and Fuel Research, Development, and Demonstration (R&D) program. Projects at commercial, academic, and research institutions are being financed to solve issues in hydrogen production from renewable energy sources, its safe and efficient storage, and its use for energy and transportation applications. In terms of transportation, Banaras Hindu University, IIT Delhi, and Mahindra & Mahindra have all received significant funding. As a consequence, we can expect a large number of Hydrogen refuelling stations in India in coming near future once the number of hydrogens fuelled vehicles have reached the point of viability.

5.4.4. Hydrogen End Utilization in Mobility

Through Indian Oil Corporation and the Society of Indian Automobile Manufacturers, the Ministry of New and Renewable Energy has financed a number of demonstration projects. The Indian Oil Corporation's initial demonstration project was to put up a dispensing station. The dispensing station at their R&D center in Faridabad, which features an electrolyser with a 5 Nm3/hr hydrogen production capacity (about 11 kg/day) [139], was commissioned in 2008-09. The electrolyzed hydrogen is mixed with compressed natural gas (CNG) for use in demonstration and test cars. The goal of the project is to get hands-on expertise managing hydrogen for use in cars as well as providing field performance feedback on hydrogen-CNG blends as a vehicle fuel.

5.4.4.1. Green Initiative for Future Transport (GIFT)

The Green Initiative for Future Transportation (GIFT) aims to develop and demonstrate hydrogen-powered internal combustion engines (IC engines) and fuel cell-based vehicles ranging from small two-wheelers to large trucks. It is estimated that one million hydrogen-powered vehicles would be on Indian roads by 2025 [140]. The performance of hydrogen-fuelled vehicles must be comparable to commercially available choices in terms of performance, safety, convenience, and cost to the consumer. This would necessitate a well-thought-out and coordinated industry-led response strategy. The main objective of GIFT is to bring the cost of hydrogen down to Rs. 60-70 per kilogram at the delivery site, hydrogen bulk storage technologies and pipeline conveyance will be in place. Safety laws, legislation, and standards are being developed, as well as a 1000 MW hydrogen-based power generation capacity. The main features of vehicles developed under GIFT are.

- Vehicle Fuel Cell stack life > 5,000 working hours; range per charge of hydrogen stored on board is up to 500 km; depending on the kind of vehicle, range per charge of hydrogen stored on board is up to 500 km [140].
- Refuelling at a convenient location; Refuelling the storage system should take no more than 5 minutes [140].
- Emissions reduction
- Hydrogen safety characteristics

- Other vehicle features, such as engine power, will be identical to current systems.

On the campus of Banaras Hindu University in Varanasi, about 15 hydrogen-fuelled bikes are being demonstrated [140]. Many development and demonstration operations are underway to enhance and develop hydrogen-fuelled cars and tiny generators. Near-commercial models for longer demonstrations of hydrogen use in vehicles are expected to be ready in approximately a decade. Small power generation systems will very certainly be developed by then.

5.4.4.2. DELHY-3W (**Del**hi **Hy**drogen – **3 W**heelers)

Mahindra unveiled 15 hydrogen-powered three-wheelers, a world first, as part of the DELHY-3W project in January 2012 and a hydrogen refuelling station in the Pragati Maidan [165]. Except for the fact that the internal combustion engine is fuelled with hydrogen, the three-wheeler in service is identical to the diesel-powered twin. It took three years for the project to see the light of day. It cost little more than $1 million US dollars to complete, including a contribution of 0.5 million US dollars from the United Nations Industrial Development Organization (UNIDO) International Centre for Hydrogen Energy Technologies (UNIDO-ICHET) in Istanbul, Turkey. Hydrogen can quickly replace fossil fuels, resulting in a cleaner and more environmentally friendly world. Water vapor and traces of NOx are produced as a by-product of burning hydrogen, making it cleaner from well to wheel. IIT Delhi, Mahindra, Air Products, India Trade Promotion Organization, UNIDO, India, UNIDO-ICHET, and UNIDO collaborated on this project. Prof. L.M. Das of the Indian Institute of Technology, Delhi, has been working on this project alongside Mahindra, which is assisting in the development of hydrogen-powered cars [165]. All of the hydrogen in these cars was created on-site, either by natural gas reforming or electrolysis.

5.4.4.3. Hydrogen Bus Projects

The government has completed a strategy to promote hydrogen as a transportation fuel, with the country soon having a major fleet of buses that run on Compressed Natural Gas Coupled with Hydrogen (HCNG). As a demonstration project, 50 buses of the state road transport corporation are presently running on HCNG in the national capital region [166]. At a recent event here, Union Minister of Petroleum and Natural Gas (MoPNG) Dharmendra Pradhan announced that the government wants to spread the initiative across India's major cities in the coming months. The company wants to run 75 Hydrogen Fuel-Cell (HFC) buses on historic routes including Vadodara to the Statue of Unity and Delhi to Agra, according to Ramakumar, head of research and development at Indian Oil Corporation (IOCL).

IOCL plans to announce the findings of Delhi's experimental HCNG bus project, in which the fuel mix comprises 18 percent hydrogen by volume, resulting in lower emissions. By linking hydrogen to natural gas, Pradhan claims, it can be easily introduced into the energy mix without needing a major overhaul of present infrastructure [166]. Hydrogen, according to the minister, may be utilized in combination with other government programs that assist waste-to-energy projects. Analysts have noted, however, that the government has considerable challenges in building a viable eco-system for this new form of energy, owing to the high prices and lack of supporting infrastructure now in place.

Greenstat Hydrogen India Pvt Ltd is collaborating with Midwest Energy on the "Green H2Chennai" project, which aims to establish, test, and operate a pilot project that includes a fleet of hydrogen-powered buses, as well as the necessary infrastructure, technology transfer, and system and process development [167]. This research is intended to pave the way for large-scale hydrogen transportation deployment in India.

6 Conclusion

As discussed earlier about green hydrogen, which is created solely from renewable energy sources such as solar and produces almost no greenhouse emissions, offers significant decarbonization potential for India's transportation industry. Given that it is a new sector with significant early capital expenditures and legislative support would be required to achieve cost reductions that would make it competitive with other fuels. When it comes to renewable energy on a larger scale, we can predict that when nations like India begin to develop their own renewable energy, oil and other greenhouse emitting products that are imported would be phased out. As a result, the total logistics involved will be reduced prominently. For emerging countries like India, this will be a larger benefit on all fronts. Furthermore, the current situation in Ukraine and Russia has prompted most countries, notably those in Europe, to rely increasingly on energy produced on their own land, which is still in its early stages of development. This might push the opportunities for developed countries, especially in Europe to accelerate their transition to clean energy since their technologies is well prepared to recover and benefit from it. However, in the case of India, the developing country should invest extensively in renewable energy technology and cope-up with their respective roadmaps to prevent falling victim to a situation like this.

Hydrogen Fuel cell buses and hydrogen energy is still in its early stages of development, but it offers a lot of potential for India's energy revolution. As a result, now is an excellent time for India to invest in hydrogen energy research and development, production, storage, and transportation. To fulfil the targets specified in the National Hydrogen Energy Road Map, a well-structured and coordinated National Hydrogen Energy Program is required. This would need tight collaboration among all stakeholders in order to pool the limited technical, financial, and human resources and implement a targeted national program. It is widely acknowledged that large-scale hydrogen use in power generation and transportation will be achievable only once the country's hydrogen production and delivery infrastructure has been established. GIFT and GIP, the two demonstration projects on transportation and power generating applications, would necessitate significant expenditures in support infrastructure as well as product development.

In order to gradually introduce hydrogen energy into India's energy mix, in addition to different technological and engineering development and demonstration, safety legislation, codes, and standards must be devised and validated with the active participation of key authorities. Hydrogen provides a number of distinct benefits over traditional fuels, as well as the ability to decarbonize a variety of industries. Globally, both hydrogen as a fuel and hydrogen-based technologies are gaining unprecedent presidential attention, and the next decade will be crucial. Several high TRL level technologies will be scaled up and deployed in the coming decade to achieve the needed potentials. Support for the 'Make in India' program, which aims to increase domestic manufacturing content across the value chain, including joint partnerships with foreign corporations commits India to a rapid growth of the hydrogen economy by 2030, assuring the cost-effective deployment of low-carbon hydrogen technologies in transportation, manufacturing, and electricity.

Some major considerations for India, include the fact that, with the implementation of Euro VI, the cost of diesel engines has grown, allowing alternative technologies such as FCEVs to gain market share. FCEVs have been deployed in public transit in a number of locations, including Vancouver, California, and Tokyo, Japan. Hybrid systems, on the other hand, must be launched first in order to build demand for FC accessories. The long-term objectives must be determined, as well as the obstacles to realizing them. A clear, step-by-step plan for reaching those objectives must be devised. Policy support, assistance in demand development, reduction in related risk for investors, established norms and regulations, R&D funding, public awareness, and projection of all data are all needed to instil trust in hydrogen and hydrogen-based technologies. Filling stations and related systems, as well as safety, are serious flaws in the India's infrastructure. Demo projects involving filling systems that include all long-term performance assurance as well as safety standards must receive adequate funding. Another important area that requires a lot of R&D is different storage methods. Many sections of pressure cylinders must be indigenized during development. Start-ups might be aided in meeting such needs. The notion of H2 generation, storage, and applications must all be completed at the same time.

The necessary facilities are dispersed around the country, and they must be consolidated and accessible to the whole research community. Existing technologies must be strengthened, and new materials-based research must be promoted. Hydrogen production from renewable sources should be promoted. The government should look at programs that will subsidize the cost of hydrogen produced from renewable sources. Currently in India infrastructure is required for deployment while demand is required for infrastructure development. This issue may be resolved with the help of the government. The expansion of refuelling stations as well as the use of FCEVs should be encouraged. The focus should be on developing and testing fuel cell technology for transportation and using in public transportation, as well as gradually decarbonizing other industries.

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List of Abbreviations

FCS	Fuel Cell Systems
FCEV	Fuel Cell Electric Vehicles
BEV	Battery Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
SC	Sector Coupling
ZEB	Zero Emission Vehicle
FCB	Fuel Cell Battery
CNG	Compressed Natural Gas
PEM	Proton Exchange Membrane
SOFC	Solid Oxide Fuel Cells
AFC	Alkaline Fuel Cells
PAFC	Phosphoric Acid Fuel Cells
MCFC	Molten Carbonate Fuel Cells
SOFC	Solid Oxide Fuel Cells
SET	Strategic Energy Technologies Plan
EC	European Commission
FCH JU	The Fuel Cells and Hydrogen Joint Undertaking
ARPA - E	The Advanced Research Projects Agency-Energy
DOE	Department of Energy
EERE	Energy Efficiency & Renewable Energy
HFTO	Hydrogen & Fuel Cell Technologies Office

HRS	Hydrogen Refuelling Station
NEBUS	New Electric Bus
ZEBUS	Zero Emission Bus
STEP	Sustainable Transport Energy Program
ECTOS	Ecological City Transport System
CHIC	Clean Hydrogen in European Cities
3Emotion	Environmentally friendly Efficient Electric Motion
JIVE	Joint Initiative for Hydrogen Vehicles across Europe
MEHRLIN	Models for Economic Hydrogen Refuelling Infrastructure
NEV	New Energy Vehicle
RMB	Renminbi
SOE	State-Owned Enterprises
MoU	Memorandums of Understanding
FYP	Five Year Plan
FTA	Federal Transit Administration
ZEV	Zero-Emission Vehicle
CaFCP	California Fuel Cell Partnership
NREL	National Renewable Energy Laboratory
SARTA	Stark Area Regional Transit Authority
CSE	Centre for Science and Environment
MoHUA	Ministry of Housing and Urban Affairs
INR	Indian Rupees
FAME	Faster Adoption and Manufacturing of Hybrid and Electric Automobiles in India
PEV	Plug-In Electric Vehicle

HEV	Hybrid Electric Vehicles
AIS	Automotive Industry Standards
NHM	National Hydrogen Mission
GCC	Gulf Cooperation Council
NIT	National Institute of Technology
IICT	Indian Institute of Chemical Technology
CCS	Carbon capture and storage
GIP	Green Initiative for Power Generation
MNRE	Ministry of New and Renewable Energy
RIL	Reliance Industries Ltd
GAIL	Gas Authority of India Limited
NTPC	National Thermal Power Corporation Limited
MMSCMD	Million Standard Cubic Meters of Gas per Day
REL	Renewable Energy Limited
IOC	Indian Oil Corporation
GIFT	Green Initiative for Future Transportation
DELHY-3W	Delhi Hydrogen – 3 Wheelers
UNIDO	United Nations Industrial Development Organization
ICHET	International Centre for Hydrogen Energy Technologies
HCNG	Compressed Natural Gas Coupled with Hydrogen
MoPNG	Ministry of Petroleum and Natural Gas
HFC	Hydrogen Fuel-Cell
TRL	Technology Readiness Level
MTPA	Million Tons Per Annum

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- **Immaculate Febious Jaivin Selvaraj**