MSc Program
Renewable Energy Systems

A European perspective on the development for hydrogen powered buses for urban transportation in cities.

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Affidavit

I, **AL AZHAR FAIYAZ RANGWALA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "A EUROPEAN PERSPECTIVE ON THE DEVELOPMENT FOR HYDROGEN POWERED BUSES FOR URBAN TRANSPORTATION IN CITIES.", 105 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

Using common mode of transport is a key success factor for future generations to rationalise intercity travel and fuel consumption, and moving to sustainable solutions is in our great interest. The objective of this research is to understand the the acceptance of fuel cell (FC) buses in Europe, by addressing on 3 key objectives; (i) methods of integration of renewables in various power systems (ii) the replacement of fossil fuels with hydrogen (H2) fueled vehicles in the inter-city bus transport sector, and (iii) the discussion on implementing H2 buses in European cities, and the associated advantages to do so.

Secondary research is carried out in this paper, with a focus on technology, economic and ecological literature that support to further understand the various elements related to this alternative source. Several case studies have been carried out in Europe to find various results on the testing and implementation of FC buses in cities. These buses are usually focused on public transport, however the similar findings could be extended to tourist run buses in cities as well. Various results are highlighted, for instance; public acceptance results, bus driver surveys, cost of implementation of additional infrastructure to make FC vehicles economically at par with diesel vehicles, reductions in greenhouse gas (GHG) emissions to name a few. The case studies presented act as a key parameter for evaluation to assess the combined result for this research.

Buses contribute to a large amount of travel covered annually around Europe, which is the target for the scope of this research. Like every technology, the time to have supporting infrastructure and policies will greatly affect the economic benefits for relevant technologies. However, from an ecological perspective it is clear to move to greener solutions. Several cities in Europe have already deployed various projects for FC buses which have varying findings that help stakeholders across the world to understand the benefits and limitations of such technologies.

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1. Introduction

The Advent of renewable energy changed everything. However are we using it today to its maximum potential? The answer is clearly, no. Countries around the world and specially in Europe are starting to implement significant renewable energy projects to support needs for electricity, transport and heating. It is necessary to overcome the myth of H2 usage in vehicles with private organisations making the lead to deploy this technology in a progressively increasing scale since 2010. Hence it is critical to know the technology in great detail in order to make the best use of it. The transport sector is a key contributor to GHG emissions, and local cities can benefit highly from FC technology to have it applied within their national infrastructure. Private organisations are paving the path to a new transition in the transport sector with many viewing a H2 economy as a breakthrough. Air Liquide, a French company operating in the gas and chemical industry is an example which is used through this research to highlight some significant facts related to their H2 plans for the future. Air Liquide (2018:3) shared that, “H2 contains three times more energy per kilogram than petrol”. H2 engines still have a long way to go, along with their related infrastructure. Through this research several ways of H2 production will be shown, but water electrolysis is widely suggested as the preferred route of production. It requires a lot of energy, and this must be provided by a connected source (solar, wind, biomass) or the grid, which may have electricity produced via mixed resources.

Air Liquide (2018:4) further explains, “electricity must be used when it is produced, and as the electricity would otherwise be lost, water electrolysis makes sense and cost effectiveness is not very relevant. H2 can be stored in liquid of gas form by cooling or compressing it. Prototype testing stages are behind us, and we now know that stored H2 can be converted back into electricity, which can be used to power a turbine or FCs”. Ajanovic and Haas (2018:281) share that, “in the 1990s technological progress for H2 led to the implementation and use in the 21st century. They quote Rifkin who speaks first of the ‘Hydrogen Economy’ which draws insights to an economy powered by H2 for various applications, with a change in our local mariners, political and social institutions adopting needed policy changes, just as it was done in the past for coal and steam power”. In the below figure (Fig.) 1, “a roadmap is presented by the European Commission showing the integration of H2 and FC technology in the transformation of the current energy system towards a more sustainable one upto the year 2050”, Ajanovic and Haas (2018:281).

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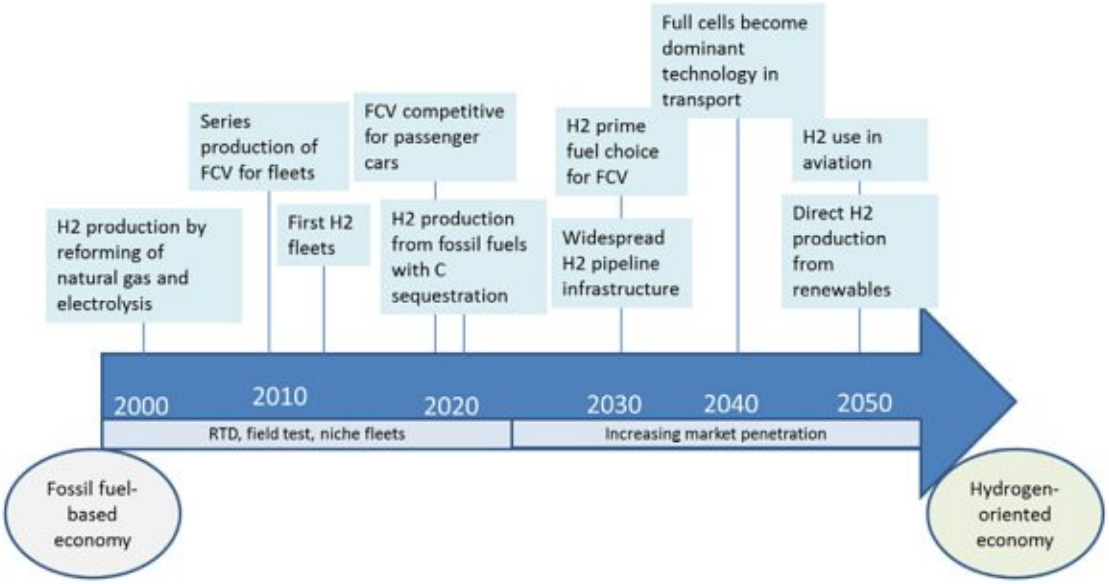

Fig. 1: Major milestones in the European H2 vision, Ajanovic and Haas (2018:281).

Frey et al. (2007:282) further stress the importance of engine attributes and the type of vehicle to assess "bus fuel consumption and efficiency. Fuel consumption is often affected by tevel speed, passenger load, road grade, number of stops and the frequency of interruptions in traffic". A quantitative understanding of various attributes as shared in sections 6 and 8 will help to understand key economic attributes and predictions for fuel consumption in the upcoming years (upto 2050) to suggest ideas for fuel economy improvements. New directives are being also put in place for transport and Sgobbi et al. (2015:20) explains that "in Europe, the EU directive reflects that refueling infrastructure will be a key motivation for countries to shift to alternative fuels. By the end of 2025, a sufficient number of publicly accessible H2 refuelling stations will be built across Europe. This has further brought action on the part of countries locally, who have developed national strategies to support the implementation of H2 and FC technologies". Sgobbi et al. (2015:20) add, "for example in Germany, the German National Innovation Programme for H2 and FC technology aim to invest heavily to deploy this resource. In France, H2 energy pathways cover around 34 roadmaps for a new industrial France. For example, France Strategie questions the role of H2 and the impact it can play in the energy transition that is currently a very costly alternative".

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2. Current State of Research

“Presently, 81% of total primary energy supply, and 66% of electricity generation are based on fossil fuels (coal, natural gas and oil), leading to almost 100% of CO2 emissions in the world”, Baykara (2018:10605). The needs for total primary energy supply will naturally increase in the future and we could see a total eradication of some non- renewable resources. Baykara (2018:10605) clarifies that “the world reserves for oil, natural gas and coal are anticipated to last for 40, 60 and 200 years respectively”. Sustainable alternatives to fuel and related infrastructure, are a key requirement for our and future generations’ mobility needs.

2.1. Introduction to H2

H2 has a very low density and larger amounts are usually required compared to diesel run engines. Air Liquide (2018:4) shared that “4.6 liters of dihydrogen compressed at 700 bars are required to produce the same amount of energy as one liter of petrol”. This shows that the production of H2 needs to be and final outcome of the alternative fuel has to take into consideration considerable storage needs to run vehicles. H2 is often extracted as a gas and can be used to power FCs. Air Liquide (2018:4) also explains that a “FC consists of the cathode (positive terminal) and the anode (negative terminal). Ions and electrons flow between the cathode and anode, and in the FC, the dihydrogen reaches the anode and the dioxygen reaches the cathode”. “The electrolyte blocks the electrons and forces them into a circuit where an electric current is generated. The H2 ions flow through the electrolyte to reach the oxygen (O2), and combine it to create water”, Air Liquide (2018:4). In several studies the total energy efficiency of FCs is higher than conventional vehicles. Air Liquide (2018:4) adds to this understanding by sharing that, “the total energy efficiency of FCs is 60%, and in comparison combustion engines with diesel or petrol have a total energy efficiency of 35%”. “Three isotopes of H2 are available: protium, deuterium and tritium. Consisting of one proton and one electron, protium is the main component of H2, the simplest element. Although it is the lightest element, H2 has the highest energy content per unit mass among all fuels. Some of its properties are given in Table 1”, Baykara (2018:10605):

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Table 1: Properties of H2, Baykara (2018:10606).

Molecular weight	2.016	Amu
ρ (gas)	0.0838	kg/m^3
HHV	141.90	MJ/kg
	11.89	MJ/m^3
LHV	119.90	MJ/kg
	10.05	MJ/m^3
T (boiling)	20.3	K
ρ (liquid)	70.8	kg/m^3
Critical point		
temperature	32.94	K
pressure	1284	kN/m^2
density	31.40	kg/m^3
T (self-ignition)	858	K
Ignition limits in air	4–75	(vol%)
Stoichiometric mixture in air	29.53	(vol%)
T (flame)	2318	K
D	0.61	cm^2/s
C_P	14.89	kJ (kg.K)

The focus of this study aims to highlight H2 as an alternative fuel to conventional diesel or petrol vehicles in the context of city buses. However, it is widely known that H2 is used for several technologies and to operate within an H2 economy in the future, synergies in supply and delivery within industries will be required for sustainable operation. Barton and Gammon (2010:8226) share “in comparison to already known usage of H2 in industry, transport applications add to the demand of H2. Production of H2 via water electrolysis displaces production of H2 from fossil fuels, which will be an advantage for the future”. See below Fig. 2 of the various applications summarised for H2.

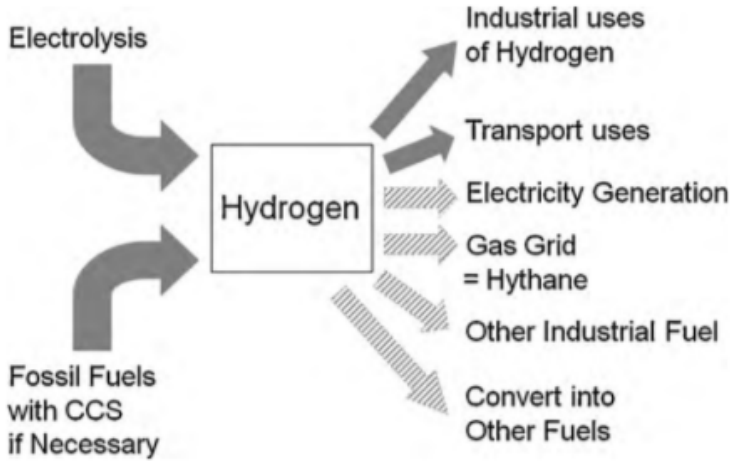

Fig. 2: Sources and uses of H2, Barton and Gammon (2010:8226).

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Barton and Gammon (2010:8226-8227) further share why H2 is likely to be used as a transport fuel:

- "If CO2 is captured via carbon capture and storage (CCS) at steam methane reformation (SMR) plants, then the H2 produced can be free of CO2 emissions.
- Compared to conventional engines (ICEVs), H2 causes less damage to air quality.
- Due to higher efficiency of FCs, wider justification for deployment of wind/solar power plants is possible".

Turon (2019:836) further explains that, "there are solutions to achieve a higher level of sustainability within the urban city public transport sector, for example; using alternative forms of mobility such as hybrid or H2 vehicles, closing city centres for cars and other private vehicles, creating dedicated zones for sustainable mobility and incentivising the purchase of electric and H2 powered vehicles".

2.2. Background

Even though H2 is seen as a very serious alternative to conventional fuel, the current production of H2 is done mainly by using electricity from non-renewable sources in electrolysis. Ajanovic and Haas (2018:282) share that "around 68% of H2 produced is from steam reforming natural gas. In Fig. 3, the share of primary energy carries in global H2 production and the share of H2 in different applications is shown. It can be seen that only about 5% of H2 is produced in 2018 by electrolysis". "However, this is expected to change in the future with higher investments in this technology now that the pilot phase has proved its effectiveness, and with the increase of surplus electricity that would be produced by including more renewable sources in the energy mix", Ajanovic and Haas (2018:282).

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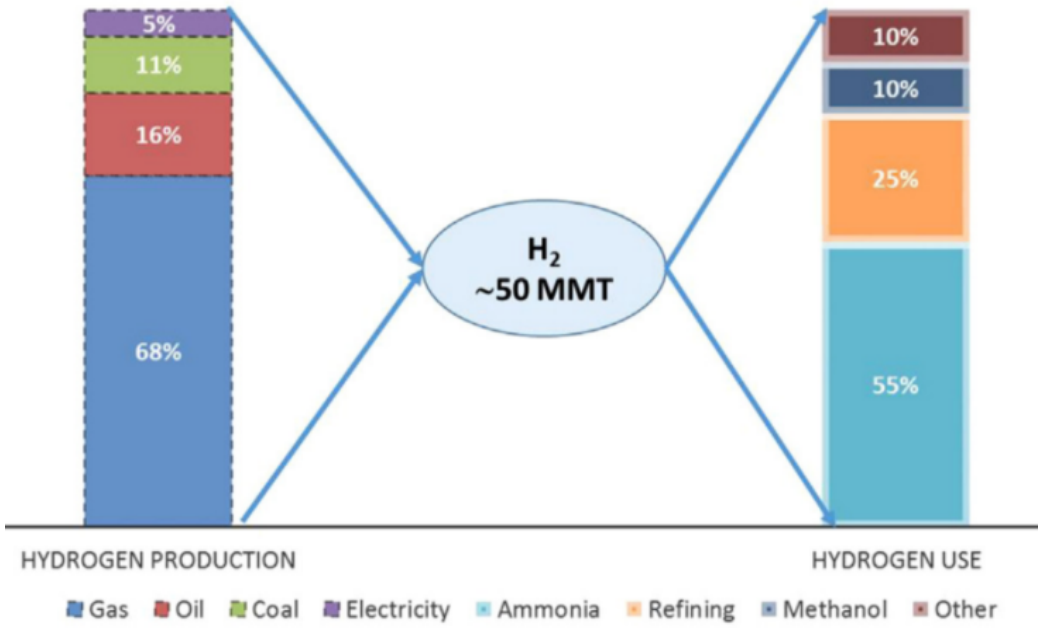

Fig. 3, Share of energy carriers in H2 production and share of H2 use for different purposes, Ajanovic and Haas (2018:282).

2.3. H2 Powered Vehicles and Related Infrastructure

Ajanovic and Haas (2018:285) clarify that, "FCVs are types of hybrid electric vehicles (EVs) with FCs instead of a battery. H2 can be used as FCs to generate energy that drives an electric motor, or it can also be used as a fuel in a traditional engine". So the need to buy purely 100% H2 vehicles is not a first priority and due to high costs, this option is not as attractive, however to convert existing vehicles with FC technology of using H2 as an alternative fuel would be recommended. Ajanovic and Haas (2018:285) explain the principle of how a H2 vehicle operates by sharing "the energy of the binding H2 and O2 in H2O (water) is smaller than the total energy of the Helium (He) and O2 molecules, hence the reaction of H2 and O2 binding water molecules generates excess energy. It can be discharged from the system as electrochemical energy for the FCs or heat". Ajanovic and Haas (2020:4) in their study share that today a very low number of FCVs exist in the world. In 2019, globally 13,000 FCVs were in operation mainly in the US, Japan and Europe as shown below in Fig. 4.

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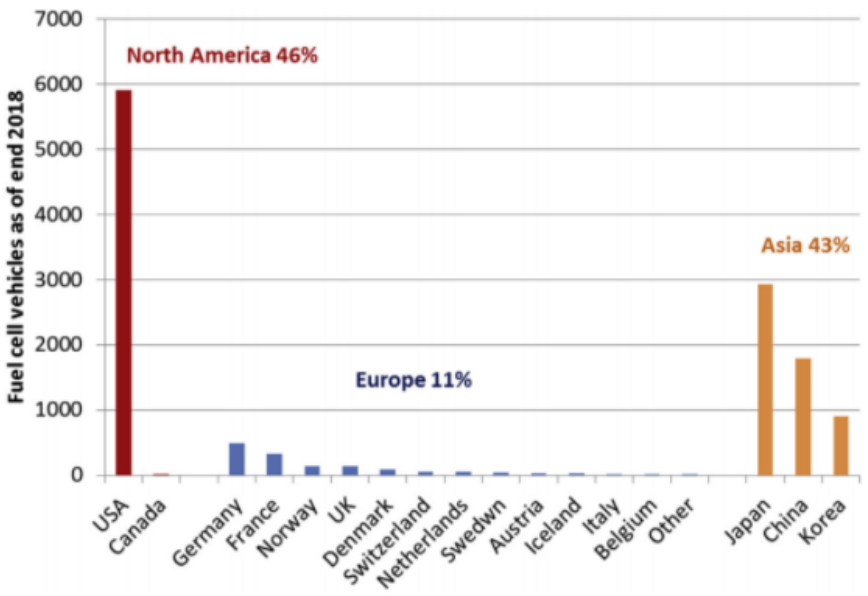

Fig. 4: FCVs as of end 2018, Ajanovic and Haas (2020:5).

H2 vehicles and engines are proven to have higher efficiency compared to ICEVs or EVs. Ajanovic and Haas (2020:5) share that "also comparing the drive range and higher load capacity, H2 vehicles perform better than EVs. Currently (2020) about 10 companies in the world produce fuel cell buses (FCBs), and below in Fig. 5, the number of H2 refuelling stations operating in the world as of 2018 are depicted":

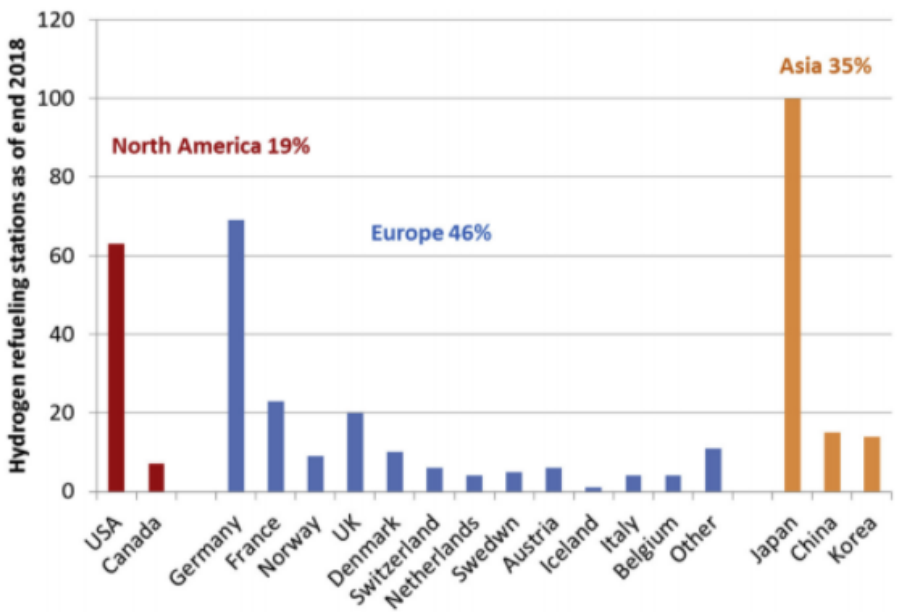

Fig. 5: Number of HRS at the end of 2018, Ajanovic and Haas (2020:6).

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H2 refueling stations (HRS) will play a huge role in the flexibility for H2 vehicles to have more opportunities to fuel around various countries. However for short distance fuel consumption as in the case of buses, the overnight fueling at a central location can be advantageous until the infrastructure is not built widely. Turon (2019:836) shares that, “to be able to use H2 as a fuel, it must be compressed H2 gas from 350 to 700 bar. H2 can be transported in pressure tanks (or via pipelines) to HRS. Other types of fueling stations can also be considered versus conventional fueling stations, where the source of power is connected”. “For example in Paris (Fig. 6), H2 can be produced on site at the HRS by electrolysis using solar or wind energy and network balancing services”, Turon (2019:836).

Fig. 6: HRS in Paris by Air Liquide, Turon (2019:837).

Air Liquide (2013) have been pioneers to support the infrastructure related to a new H2 economy. In their efforts, together with other partners they will invest “around 350 million Euros (EUR). By 2023, the German network of H2 filling stations is expected to expand over 400 stations nationally”. See below Fig. 7 of a H2 tank station in Germany from Air Liquide.

Fig. 7: H2 fuel station by Air Liquide in Germany, Air Liquide (2013).

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2.4. Current Global Market State of FCVs and HRS

Turon (2019:839) in his study stated that, “there were 6,500 fuel cell vehicles (FCVs) in the world in 2018. In 2015, around 1.1 Billion cars with ICEVs were in the market, so in comparison to FCVs this is a very high percentage (%)”. Turon (2019:839) goes on to explain that, “the US office of Energy and Efficiency and Renewable Energy (2019) share that there are 39 publicly available H2 charging stations. The H2 Roadmap Europe (2019) develops initiatives such as introducing 100,000 vehicles and 250 changing stations by 2025. In Asia, Japan plans to invest around EUR 330 million to develop infrastructure for H2 vehicles and also provide stakeholders with necessary purchasing incentives”.

2.5. Electric vs H2 Buses

Logan et al. (2020:11) compare electric and FCBs by sharing that, “in 2017 from H2 buses emissions started at 5.9 MtCO2 than those from electric buses at 2.4 MtCO2. Until 2050, it is expected that emissions from H2 buses could be at 1.33 MtCO2 compared to electric buses at 0.5 MtCO2. Under consumer evolution by 2050, emissions from H2 buses could reach 1.84 MtCO2 compared to electric buses at 0.8 MtCO2”. “Under the community renewables scenario, in 2050, emissions from H2 could be at 0.83 MtCO2 compared to electric buses at 0.3 MtCO2”, Logan et al. (2020:11). Hence it can be assumed that by 2050 electric buses emit lower GHG compared to H2 buses, however the reduction over various scenarios over the years for H2 buses is also evident.

2.6. European Examples of Current Projects for Buses

Community and related ecological factors play a huge part in the implementation for a new vision for public transportation in Europe. There are several projects highlighted by Elhajj and Ochieng (2020:13) to share the current efforts being put to implement projects for buses in Europe which act in the benefit of the environment and modernisation of technology for public transportation:

- “The Zero Emission Urban-bus Systems (ZeEUS)- pure electric and electric-diesel hybrid engines, combining intelligent transportation systems technology, priority at junctions, rapid and convenient fare collection, and is integrated with land-use policy in order to upgrade bus system performance”, Elhajj and Ochieng (2020:13).
- “The Intelligent, Innovative, Integral Bus Systems (3iBS) project aims to develop a Roadmap for European Advanced Bus Systems research, define a work-plan for the exploitation of research results, and transfer most innovative concepts to a wider audience in Europe”,Elhajj and Ochieng (2020:13).

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- “The Electrification of Public Transport in Cities project (ELIPTIC) uses battery and hybrids charged buses, and they charge e-buses ‘en-route’ (e.g. trolleybus operated on tram infrastructure) or on the spot (battery buses, hybrids charged from trolleybus, tram)”, Elhajj and Ochieng (2020:13).
- “The European Road Transport Research Advisory Council (ERTRAC) aims to accelerate road transport research to deliver sustainable road transport and mobility of goods and passengers. The main advances of ERTRAC include facilitating the exchange between cities on urban electric mobility solutions”, Elhajj and Ochieng (2020:13).

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3. H2 Production Techniques

3.1. H2 Production Techniques with Renewable Resources & Electrolysis

The production of H2 from water is possible using many different types of technologies. Baykara (2018:10606) shares a short review on some of these processes by including literature on “electrolysis, Thermolysis or direct thermal decomposition, thermochemical processes and photolysis”. Some technologies may be better than others in relation to efficiency, capacity and full load hours (FLH). Water electrolysis will be explained in more detail in the below part of this section, however we have a short review on the aforementioned technologies presented by Baykara (2018:10607):

- “Electrolysis can be performed with energy from solar and wind technologies, and based on life cycle analysis (LCA) studies, it has been proven that this type of electrolysis has a low global warming potential (GWP) at less than 5 kg CO2 eq/kgH2. Electricity used from the grid has a high GWP at 30 kg CO2 eq/kg H2. The efficiency levels for electrolysis may vary from 70% to 90%”, Baykara (2018:10607).
- “Thermochemical methods are suitable for high temperatures, for example nuclear heat and concentrated solar power (CSP). By 2018, some 2,000 to 3,000 thermochemical cycles have been studied, out of which 20 to 30 are suitable for H2 production on a large scale. The efficiency of such systems can be from 40% to 50%”, Baykara (2018:10607).
- “Pyrolysis and hydrolysis of metal hydrides produces H2 as well. Lithium and sodium borohydride (LiBH4, NaBH4), lithium and sodium aluminium hydride (LiAlH4, NaAlH4), Lithium and magnesium hydride (LiH, MgH2) are commonly considered”, Baykara (2018:10607).
- “H2 production by biohydrogen is a relatively new area which requires indirect biophotolysis of water; microbial electrolysis of organic matter by bacteria and photo and dark fermentation”, Baykara (2018:10607).
- “Biomass via pyrolysis/gasification can also produce H2. However as biomass has lower calorific value, larger plant sizes are required. Derivatives of biomass such as biogas and bio-oil can also produce H2 by thermal methods”, Baykara (2018:10607).

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In this part, we focus more on the technology of electrolysis and key related features to better understand the viable source for H2 production in the coming years. Hnat et al. (2020:93) explain that “the first water electrolysers used an alkaline solution (NaOH or KOH) with a concentration of up 30 wt% as an electrolyte. Alkaline water electrolysers (AWE) are usually equipped with diaphragm-based separators. In the AWE one of the drawbacks is that it does not allow the power output of the device to be immediately decreased to zero, as there is risk of O2 and H2 forming an explosive mixture”, Hnat et al. (2020:93). “AWE systems are also often considered to have lower efficiency. Proton exchange membrane (PEM) water electrolysis (PEMWE) is an alternate technology that uses a perfluorinated sulfonic acid (PFSA)-type membrane as the separator of the anode and cathode compartments”, Hnat et al. (2020:93). “The PEMWE technology is considered to have much higher efficiency in comparison to the AWE technology as well. A third well known electrolysis process is high-temperature water electrolysis process (SOEC), however this is so far only been used in demonstration processes and does not have commercial or market maturity”, Hnat et al. (2020:93). A comparison of the 3 technologies is show in the table 2 below:

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Table 2: Overview of the characteristics of water electrolysis technologies, Hnat et al. (2020:110-111).

	AWE	PEMWE	SOEC
Materials			
Anode	Ni, Co, mixed oxides	IrO2 on Ti	Mixed oxides of lathan, strontium, and manganese (LSM)
Cathode	Ni, Fe	Pt/C on carbon cloth	Composite of nickel particles with YSZ
Separator	Diaphragm (PTFE, PSF, PPS, composite of ZrO2 particles, and polysulfone)	Cation-exchange polymer membrane based on sulfonated fluoropolymers	YSZ ceramic electrolyte (ZrO2 stabilized by 5–8 wt% Y2O3)
Operational parameters			
Temperature (K)	333–363	323–353	973–1123
Pressure (bar)	Up to 30	Up to 30	Up to 15
Cell voltage (V)	1.8–2.4	1.8–2.2	0.7–1.5
Current density (kA m-2)	2–4	6–20	3–20
Circulating medium/ reactant	20–40 wt% KOH	Demineralized water	Water vapor, CO2
Production rate (Nm3 H2 h-1)	Up to 1400	Up to 400	Up to 40
Cell area (m2)	Up to 4	Up to 0.3	Up to 0.06
Gas purity (%)	More than 99.5	99.99	99.9
Flexibility			
Load flexibility (% of nominal load)	20–100	0–100	±100
Warm start time (s)	60–300	Up to 10	900
Cold start time (min)	60	Up to 20	More than 60
Efficiency			
Stack efficiency related to UTN (%)	63–71	60–68	100
Stack energy consumption (kWh Nm3 H2)	4.2–5.9	4.4–5.5	3.2
System efficiency (%)	51–60	46–60	76–81
System energy consumption (kWh Nm3 H2)	4.5–5.9	4.2–6.5	3.7–3.9
Others			
Maturity	Mature	Commercial	Demonstration
Stack life time (kh)	60–120	20–100	8–20
Investment costs (EUR kW-1)	1000–1500	1400–2320	More than 2000

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- **Energy Consumption**

Hnat et al. (2020:96) shares “n eq. 1, the electric power used to decompose water by water electrolysis”:

$$P = U_j \cdot I$$

Eq. 1, Hnat et al. (2020:97).

“The minimum energy consumption is equal to 2.94 kWh Nm3 H2 (32.93 kWh kg1 H2) by substituting the theoretical, that is, reversible, cell voltage Ucell,rev for Uj and current to produce 1 m3 H2 (at 273.15 K, 1.013 bar) in 1 h. It is possible to achieve values of 3.8 to 5.6 kWh depending on materials, technology and operating parameters”, Hnat et al. (2020:96).

- **Electrolyzer Construction**

In this section, we will review the 2 main configurations of the strolysis stack; the electrodes and separator. This information will be followed by the details to explain the gas phase separator as well. The review of this part is provided from the study of Hnat et al. (2020:102) on the construction of electrolysers.

<u>Electrodes</u>

“The electrodes normally consist of two main parts; a porous substrate coated with a catalyst layer. The main requirements on the substrate are; (i) high electrical conductivity, (ii) stability under the conditions of AWE, (iii) good permeability for the reactants and products and (iv) low costs”, Hnat et al. (2020:102). In Fig. 8, the schematic of the catalyst layer with the catalyst deposited on the support and the ion-selective polymer binder is shown:

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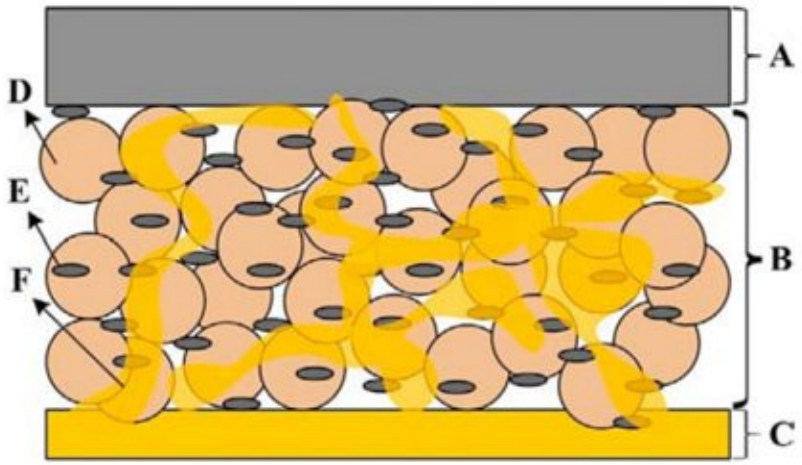

Fig. 8: Scheme of the catalyst layer structure with the ion-selective polymer binder. (A) electron conductor, (B) catalyst layer, (C) ion-selective polymer separator, (D) catalyst support particle, (E) catalyst particle, and (F) ion-selective polymer binder, Hnat et al. (2020:105).

Separator

"Separators can be distinguished in two categories; membranes and diaphragms. Characteristics of separators are; (i) resistance to atomic O2 generated on the anode, (ii) high ionic conductivity when exposed to working conditions and (iii) high resistance to the environment at operating temperatures", Hnat et al. (2020:102). "The diaphragm (a porous, ionically inactive material) is a widespread variant of the separator. A free space between the electrodes and the diaphragm is required as diaphragms do not usually separate gases efficiently", Hnat et al. (2020:102).

- **Gas Phase Separators**

"The electrolysis stack is left in the form of gas phase dispersion in a liquid phase due to the gases produced. The gas phase has to be separated and the liquid phase is recycled for subsequent storage and/or utilization. Two main groups of gas liquid separators are available; low gas-to-liquid ratio and high gas-to-liquid ratio", Hnat et al. (2020:102-103). "The separator contains 4 main parts; (i) gravity settling section, (ii) mist extractor (surface area to collect and remove the small droplets of liquid),(iii) inlet diverter (to improve separation performance) and (iv) liquid collection section. In Fig. 9, the scheme of the vertical vertical and horizontal separators are shown", Hnat et al. (2020:102-103).

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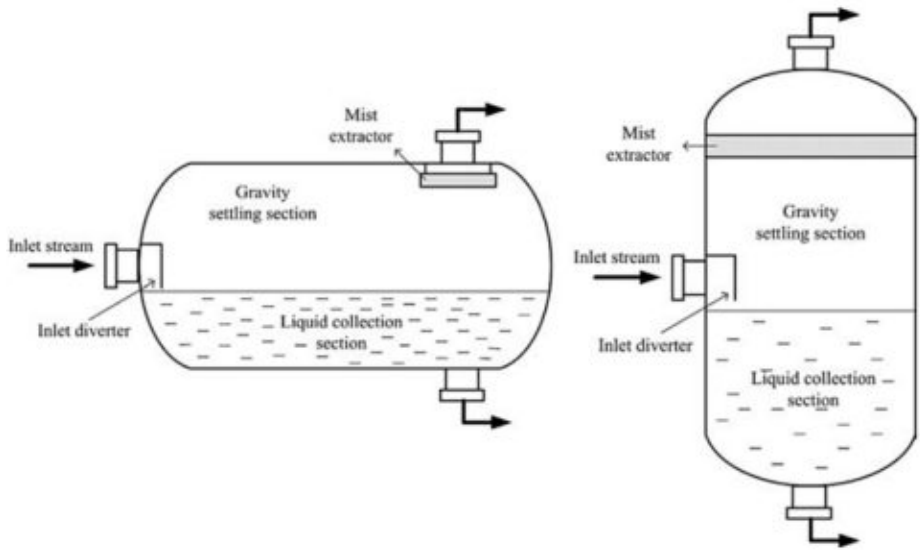

Fig. 9: Schemes of the horizontal and vertical separators, Hnat et al. (2020:107).

3.2. H2 Production Techniques with Non- Renewable Resources

As fossil fuel based production for H2 has maturity in production, the level of efficiency is high and products costs are lower. Baykara (2018:10606) shares that “Coal gasification (Koppers-Totzek process) is the widely used technology for H2 production. SMR process is commonly used for H2 production from natural gas, with an efficiency of 65-75%. Another known process is the partial oxidation of natural gas, with an efficiency of 50%”. The decline of these resources of bottleneck of supply might cause a breakdown of the entire system as it is built today. These production techniques from non- renewable resources play a major part in having H2 in the market today. “It may be possible to keep fossil-based H2 production in practice in the near term and mid term through application of carbon sequestration and solar thermal processes”, Baykara (2018:10607).

- **Converting Fossil Fuel to H2**

Natural gas and coal is used to create H2 and Bartels et al. (2010:8372) explains that, “the hydrocarbon fuels are used as the energy source and the H2 source to drive both processes. In both of the processes, fuel is mixed with O2 and steam in an autothermal process to produce synthetic gas, mainly consisting of carbon monoxide (CO) and H2, with some water, methane (CH4) and CO2”, Bartels et al. (2010:8372). “By using reactions, the synthetic gas is further processed, shifting CO and CH4 into H2. In the below eq. 2 and 3, two main chemical reactions in relation to steam methane and CO shift reactions are shown below”, Bartels et al. (2010:8372):

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$$CH_4 + H_2O \rightleftharpoons CO + 3H_2 \quad \text{Methane–Steam Reaction}$$

Eq. 2: Methane steam reaction , Bartels et al. (2010:8372).

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \quad \text{CO Shift Reaction}$$

Eq. 3: CO shift reaction, Bartels et al. (2010:8372).

- **H2 from Natural Gas**

From the study of Bartels et al. (2010:8372) the below Fig. 10 shows the countries with the largest natural gas reserves. As it can be seen Russia has the majority of the reserves, with nations from the Middle East having a second large share (see, Iran, Qatar, Saudi Arabia and UAE). In comparison, the US has relatively small reserves, and Europe has the poorest number of reserves (less than 1% in the world). Hence, Europe is heavily dependent on importing natural gas, with various pipeline related projects. Bartels et al. in 2010 shared that "the worldwide reserves add up to 177.39 Tm3, and at the current rate of consumption, we are expected to have another 60 years available of natural gas from reserves".

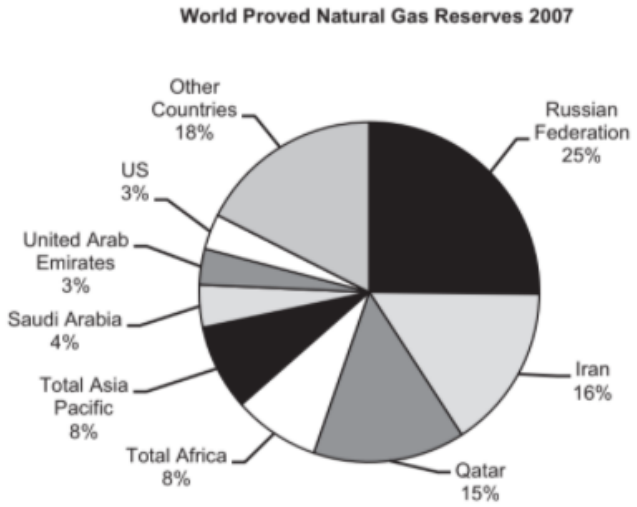

Fig. 10: World natural gas reserves by country, Bartels et al. (2010:8372).

Bartels et al. (2010:8372) explains that, "using SMR, the cost of producing H2 is highly sensitive to the natural gas cost, to this effect Gray and Tomlinson have created an equation to show this relationship":

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$$\text{Hydrogen Cost } (\$/\text{MMBtu}) = 1.27 \times \text{NG price } (\$/\text{MMBtu}) + 0.985$$

Eq. 4: Gray and Tomlinson formula for cost of H2 production using steam methane, Bartels et al. (2010:8372).

With the above eq. 4, Bartels et al. (2010:8372) shares that "it can facilitate about 100 million standard cubic feet per day (SCFD) production capacity of 236,238 kg/day with a capital cost of 0.54 to 0.66 EUR/SCFD of plant capacity. The cost of natural gas was approximately 8.24 EUR/MMBtu in 2008, and from the eq. 4, the cost of H2 at this price is approximately 2.04 EUR/kg". Penner also provides a similar H2 cost equation that is shown in the eq. 5 below.

$$\text{Hydrogen Cost } (\$/\text{kg}) = 0.286 \times \text{NG price } (\$/\text{MMBtu}) + 0.15$$

Eq. 5: Penner formula for cost of H2 production using steam methane, Bartels et al. (2010:8372).

Bartels et al. (2010:8372) further assesses the Penner formula and shares that, "using the same natural gas cost of 8.24 EUR/MMBtu, the Penner equation gives a H2 cost of 2.61 EUR/kg".

- **H2 from Coal Gasification**

In Fig. 11, Bartels et al. (2010:8372) illustrates that by the end of 2007, the US had the largest coal reserves in the world, followed by Russia and China. "From 2007, if all the coal is mined out of the reserves in the 3 aforementioned countries with the largest coal reserves, then for the US it would mean 234 years of supply, for Russia it would be 500 years and for China it would be 45 years. For the rest of the world, it would be 133 years of remaining coal supply", Bartels et al. (2010:8372-8373). As it can be seen Europe is part of the other countries which comprise 10% of the total reserves, so a very low number of reserves in Europe exists comparatively.

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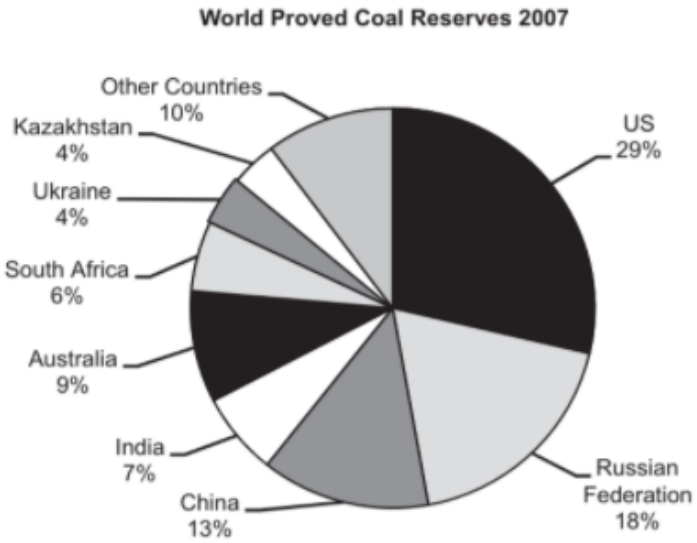

Fig.11: World coal reserves by country, Bartels et al. (2010:8373).

Bartels et al. (2010:8373) also quote “the study authored by Gray and Tomlinson in 2002, called the Mitretek Systems study. Here 10 different designs and technologies with production facility sizes, with varying costs were analysed. The system includes designs with or without carbon sequestration and with different amounts of co production of electrical power”.

Table 3: Summary of the Gray and Tomlinson results for several coal gasification technologies, Bartels et al. (2010:8374).

	Design 1	Design 2	Design 3	Design 4	Design 5	Design 6	Design 7
Gasifier	Texaco	Texaco	E-gas	E-gas	E-gas	E-gas	E-gas
Carbon sequestration	NA	PSA	Membrane	NA	PSA	PSA	Membrane
Electricity production	HRSG	HRSG	HRSG	CC	CC	SOFC & CC	SOFC & CC
Sequestration percentage	0%	87%	100%	0%	95%	90%	95%
H_2 production, kg/day	309,500	281,100	373,300	352,000	361,400	352,000	354,400
Coal consumption, tons/day	3000	3000	3000	6000	6000	6000	6000
HHV efficiency %	63.7	59	75.5	62.4	56.5	64.5	65.2
Net electrical power, MW	20.4	26.9	25	475	358	509	519
Capital cost, M$	495	562	573	1228	1281	1399	1375
RSP of H_2 $/GJ LHV	8.78	10.51	7.57	6.97	7.25	3.59	3.08
RSP of H_2 $/kg	1.05	1.25	0.90	0.83	0.86	0.43	0.37

Bartels et al. (2010:8373) explains table 3, “the different cost of the technologies. For example in design 6 and 7, it is visible that the solid oxide FC approach provides the lowest cost of H2 production but has a high capital cost of the plant.A plant such as design 2 using conventional technology with carbon capture, has the highest cost of H2”. In table 4 the economic assumptions for the analysis is provided.

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Table 4: Financial assumptions for the Kreutz et al. study, Bartels et al. (2010:8374).

Coal price (2001 avg cost to electric generators)	$1.26/GJ LHV
Capacity factor	80%
Return on equity	15%
Interest during construction	12.3% of overnight capital
Debt/equity	55/45%
Real discount rate	7.80%
O&M costs	4% overnight capital
Cost of CO_2 transport and storage	$5/tonne CO_2
Co-product electricity price	6.23 ¢/kW h
Depreciation	MACRS
Federal and state income tax	38.2% combined
Plant life	25 years
Construction period	4 years
Levelized capital charge rate period	30 years

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4. Research Question & Methodology

4.1. Research Question

In this research, we will analyse and discuss several economic facts of H2 use in the energy system with a core focus on: (i) the integration of variable renewables in power systems, (ii) the substitution of fossil fuels in the transport sector, and (iii) the discussion on benefits to implement H2 buses in European cities. The technological learning of this is also relevant to understand the current situation of maturity and the future scenarios when there is a higher level of market competitiveness. The focus has been put on larger sized vehicles, in particular buses of European cities, which play a big part in local commutation. There will be several case studies presented from published work on projects implemented for buses with FCs in cities around Europe, which act as a key part of the results within this research to further discuss the combined feedback on potential growth areas for the future. H2 powered vehicles are considered to be high in efficiency and the cleanest environment solution for transport. However in relation to H2 technologies, people do have myths about the H2 and FC technology within transport. Turon (2019:837) shares that, "many people believe the process of refueling H2 vehicles resembles the process of charging EVs, with a long wait time. However this is not true, and depending on the type of charging station and vehicle type , the refuelling can take from 3 to 5 minutes, which is quite similar to conventional cars. Another advantage of H2 vehicles is the high range (around 500 km) that can be covered with a full tank".

- **Vehicle Type Selection**

For the selection of the research question, it is critical to review the potential available H2 FCVs types available on the market globally. This will support scope of this study to empower local economies to assess the mass scale deployment with related economic and ecological benefits. We can separate the local transport needs within major European cities as private (cars) and public (buses, trains, taxis etc.) used vehicles. For the public used vehicles, it is further relevant to go deeper within the potential scope for deployment.

- **H2 FC Cars Current Limitations**

In this section we briefly review the current status of the FC private cars to illustrate major gaps today which do not promote a shift to a H2 economy until 2030 or even going upto 2050. As the number of cars and related mixed emissions are clearly higher than public transport vehicles such as buses, it is an important point for future researchers to develop cars to a low cost option compared to today (2020-21), and this can be done by learning from implementation of larger vehicles into a H2 economy such a as urban city buses. However it is important to understand the current situation for cars to better clarify why this

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cannot be a viable option for H2 development currently. Turon (2019:838) shared that “the average cost of buying a H2 powered car in 2019 was between EUR 55,000 and 70,000 (depending on the type of model). In comparison to buying ICEVs in the same period, with the same model and drive type, this value is around 50% higher”, which makes it difficult for decision makers to make a purchase. Iordache et al. (2017:29631) in their study share the “EU car fleet (2015, including Norway and Switzerland) in table 5. The number of cars surely provides a solid business case once H2 and FC technology is further developed and widely used with lower costs from production to vehicle purchase that will come with market maturity”.

Table 5: Passenger cars in the EU in 2015, Norway and Switzerland, Iordache et al. (2017:29631).

Country	Number of cars	Country	Number of cars
Austria	4,748,048	Latvia	679,048
Belgium	5,623,579	Lithuania	1,244,063
Bulgaria	3,013,863[a]	Luxembourg	381,103
Croatia	1,499,802	Malta	275,380
Cyprus	487,692	Netherlands	7,932,000[c]
Czech Republic	5,115,316	Poland	20,723,423
Denmark	2,580,000[b]	Portugal	4,699,645[a]
Estonia	676,596	Romania	5,155,000
Finland	3,234,860	Slovakia	2,034,574
France	32,326,000	Slovenia	1,078,740
Germany	45,071,000	Spain	22,355,549
Greece	5,107,620	Sweden	4,668,262
Hungary	3,196,856	United Kingdom	30,250,294
Ireland	2,060,170	Norway	2,610,000
Italy	37,080,753[a]	Switzerland	4,458,000

[a] Numbers for 2014.
[b] Numbers for 2008.
[c] Numbers for 2013.

As explained in the above sections, FC cars are comparatively higher in cost vs. ICE cars. However, for the first stage of deployment of any technology, economies of scale need to be achieved in order to have economic benefits. As a focus of this paper, we will concentrate on FC buses as the selected vehicle type to be able to meet the points highlighted in section 4.1.

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4.2. Methodology

This research is based on secondary sources and assess several case studies carried out in various cities of Europe to understand the implementation and challenges to deploy FC buses locally. In order to keep the currency consistent, the common currency used in this research is EUR and all other currencies and values have been converted as per the EUR conversion rate of January 2021. In order to answer the research questions a comprehensive technologies, economic and ecological review is presented as the next parts of this research, which act as key literature in relation to assessing FC technology. As a second part of the research, case studies for FC implemented larger vehicles (namely buses will be provided in the following cities with the methods of study provided:

- Stockholm, Sweden- part of the clean urban transport for Europe (CUTE) survey and the perceptions of passengers and bus drivers is provided in relation to questions that cover ecological and economic aspects.
- Rhine Main area, Germany- the current energy source for H2 in this area and the growing need for FCBs is provided. There are also predictions made for the growth of the H2 supply in relation to meet future demand scenarios.
- Tuscany, Italy- A life- cycle assessment (LCA) is provided to show the competitiveness of FCVs in the region.
- Valencia, Spain- A latent class model is provided with 3 main classes defined in relation to environmental concern (low, medium and high) and a survey is made to college students to understand their perception and future expectations of the technology.
- Porto, Portugal- A comparative study between diesel buses (1 from the US and 1 from Porto) versus a fuel cell bus (FCB) is provided.

These case studies are further analysed in the results section with the result of each study and along with consolidated results from all studies is provided. In the discussion part of this research, further literature review is used to support the points that are considered as barriers and opportunities for FCBs in cities in Europe and its related infrastructure.

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5. Technological Review

5.1. Comparative Review of Diesel and Electric Buses

Within this section, we will review 4 main drivetrain technologies as depicted in Fig. 12 below:

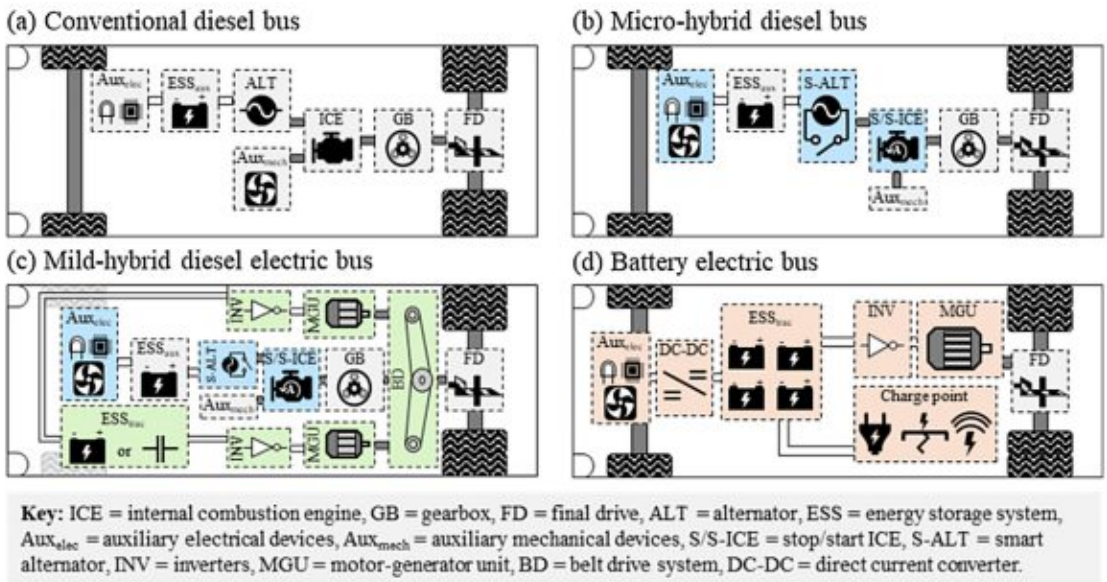

Fig.12: Drivetrain architectures of (a) conventional diesel; (b) micro-hybrid; (c) mild-hybrid and; (d) battery electric bus configurations, Harris et al. (2020:3).

In Fig. 12a, which represents the conventional diesel bus, Harris et al. (2020:3) shares that “in 2016 about 96% of buses and commercial vehicles in Europe were of this type”. In Fig. 12b, micro hybrid diesel buses are an attractive option to convert conventional buses, that can reduce fuel consumption (for example; automatic stop- start functionality, smarter electrified auxiliaries and regenerative braking systems). These types of buses are not true hybrids but are a smarter solution and can be less expensive to retrofit compared to other technologies. Harris et al. (2020:3) in Fig. 12c shares that, "mild hybrids offer lower acquisition costs compared to battery EVs (Fig. 12d), with significant fuel and emissions reductions compared to Fig. 12a”. Harris et al. (2020:3) explain the role of “operators or bus owners who might want to still find cost effective options but with a higher environmental awareness might go for the mild hybrid option Fig. 12c as a cost effective and low emissions option”. In Fig. 12d, battery electric vehicles (BEVs) offer the best possible reductions in emissions compared for Fig. 12a, Harris et al. (2020:5) share that “the capital cost for BEVs uptake might be almost twice the cost of the Fig. 12a type buses, but could offset potential life cycle GHG savings due to the high environmental impact of battery manufacturing”. The understanding of these 4 main types of powertrains is important as these are currently the most available types of vehicles in the market.

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5.2. H2 Range Extender Hybrid City Bus

A holistic view is presented in this paper to evaluate H2 powered vehicles due to the benefits of lower GHG emissions, with several versions of buses could pave a way into the future of the transition for intercity travel via buses in Europe. However in order to focus on the technological review of a foreseeable realistic type conversion, as represented in this section would be the convert electric city buses to FCs hybrid city buses. The content of this section will clarify the technology which may be adaptable as a benchmark case. Sergi et al. (2013:287) in their research focus on converting an electric bus to a FC hybrid city bus. The targets of the project are shared below:

- "Overall autonomy increased (þ30%) in respect to the electric bus.
- Reduced size of FC system to have lower cost of investment.
- Battery recharge time to be minimised.
- To maintain the same weight for the initial number of passengers", Sergi et al. (2013:287).

This case is selected to show a real life example to illustrate the technological review for applicable cases. Sergi et al. (2013:287) in their study selected a range extender powertrain and the selected city bus was "Model Alè Elettrico, Rampini Carlo SPA, able to fit 44 passengers with regenerative braking system compatible AC drive motor of 85 kW (rated power), see Fig. 13":

Fig. 13: Hybrid city bus developed, Sergi et al. (2013:287).

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Sergi et al. (2013:287) further explains the characteristics of the bus to share, “The FCS through the DC/DC step up converter works in parallel with the battery pack, and both supply energy to the DC side of the motor inverter. The principal energy source is the battery pack. The FCS, working at constant power, pushes the State of Charge (SoC) of the batteries during the bus stops, but is also used during the traction”. “Six Zebra batteries and a low power FC system was the level of hybridization applied on the electric bus. The roof of the bus was equipped with the PEM system which is fed by H2 stored in 2 tanks located in the bus, containing 4.8 kg of H2 each”, Sergi et al. (2013:287). For the sake of consistency, we will maintain the Euro January 2021 currency data to evaluate prices displayed in other currency in the literature presented in this research. Sergi et al. (2013:287) find that “the capital cost of a hybrid bus (HEB) is around 15% more than an only-batter bus, due to the reduced battery pack and extra costs of the needed H2 supply and infrastructure”. Currently the costs of electric buses is commonly known to be lower in cost compared to hybrid or even completely H2 run buses. Sergi et al. (2013:287) predicts, “the cost of this HEB to be around 27.23€ per day”, Sergi et al. (2013:287). The advantages shared for this range-extender are below:

- “Fast refueling of H2 and extension of such buses will eventually reduce the number of vehicles needed to manage the electric bus fleet.
- Early market introduction of other H2 vehicles with lower cost investment predicted due to such conversion projects and subsequent increase of H2 demand and supply”, Sergi et al. (2013:287).

- **Electrical Architecture**

For this study, Sergi et al. (2013:287) further helps to understand the electrical architecture of the bus by sharing Fig. 14. This details the following:

- “2 batteries in total, installed inside and in the rear of the bus consisting of; 6 ZEBRA batteries with a rated energy of 21.1 kWh and efficiency of 90% divided into 2 sub batteries”, Sergi et al. (2013:287).
- “A FC system with nominal power of 5 kW, 40 cells in series with efficiency of 55% was positioned on the roof of the bus”, Sergi et al. (2013:287).
- “A DC/DC step-up converter with nominal power: of 6 kW, and efficiency of 89%”.
- “An AC induction motor with 3 phase inverter”, Sergi et al. (2013:287).

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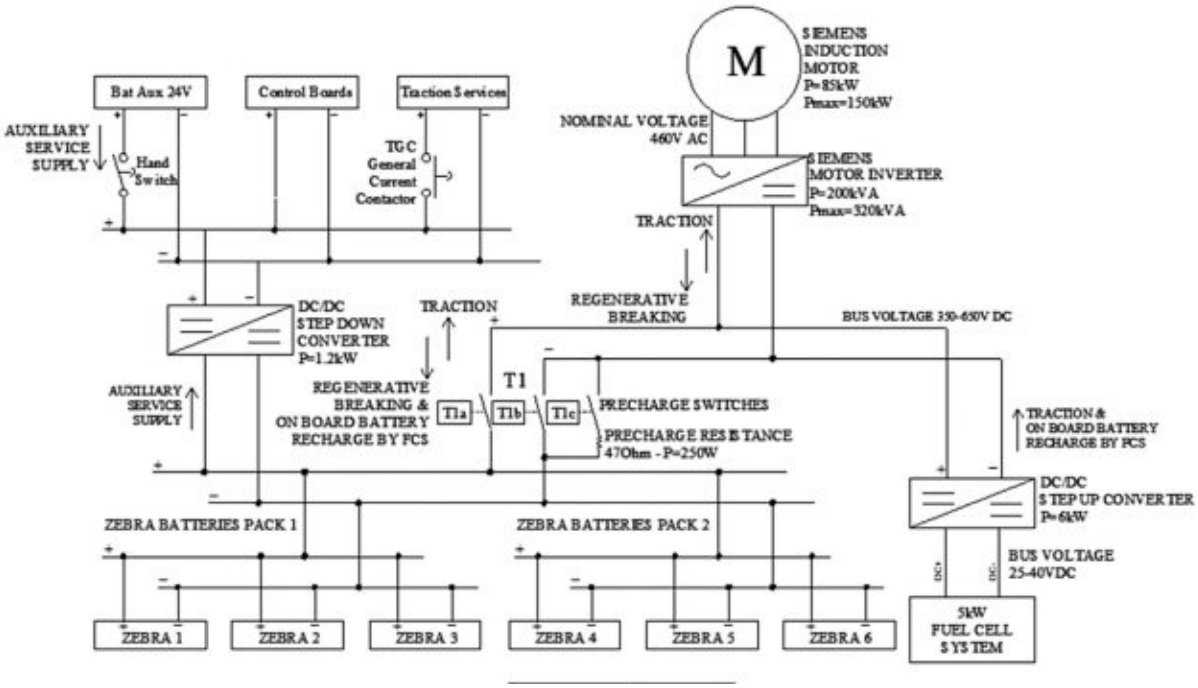

Fig. 14: Electrical architecture of the powertrain, Sergi et al. (2013:288).

Further in the below table 6, Sergi et al. (2013:287) shows the city bus configurations:

Table 6: City bus configuration, Sergi et al. (2013:287).

Parameter	Unit	Value
Bus weight	kg	10904
Bus dimensions	mm	7570 × 2200 × 3120
Bus n_{seats}	–	44
Bus electrical engine	kW	85
Bus Vnom, DC	V	650
Bus Vop, DC	V	300–750
Fuel cell system power	kW	5.6
Fuel cell system output voltage	V	27–40
Fuel cell DC–DC converter voltage (nominal)	V	$36_{down} - 600_{up}$
Fuel cell DC–DC converter power (nominal)	kW	6
Cylinder volume	l	150
Number of cylinders	–	2
Cylinders pressure	bar	200
Hydrogen mass	kg	4.89
Single battery energy	kWh	21,2
Single battery power	kW	30
Number of batteries	–	6

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- **DC/DC Step-Up Converter Development**

Sergi et al. (2013:288) in this section explains that “this type of converter pushes the output voltage of the FC system from 27V to 40V up to the DC link voltage and regulates the output power of the FCs at a constant value of 5.6 kW. Per day only 1 FC startup and shutdown were foreseen as the cell works every 5.6 kW, during driving on the urban route and during the terminal stops”. The DC/DC step up convertor typology is shown below in Fig. 15.

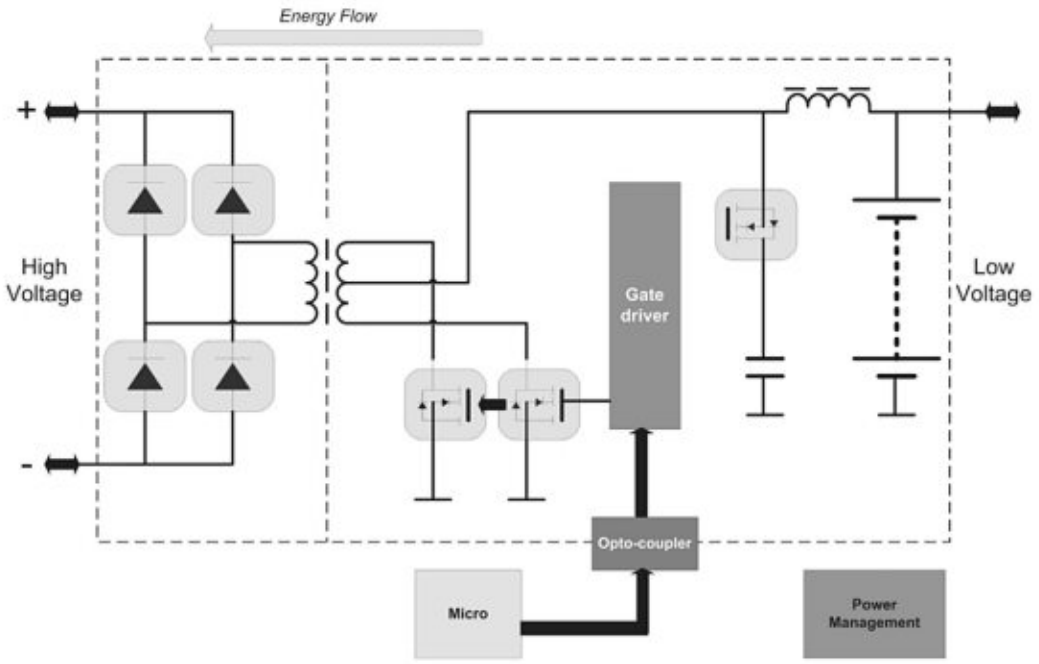

Fig. 15: DC/DC converter topology, Sergi et al. (2013:288).

- **Master Controller (MC)**

A MC was developed that would have special functionalities. Sergi et al. (2013:290) shares that this “dedicated supervisor would control the functionality and integration of the new devices installed in the bus. The MC was equipped with a dedicated software that manages the operation of the bus, such as; start up, shut down and all procedures related to warning/faults”. The MC is presented in the Fig. 16 shown below, that reports the connections between the main equipment of the use.

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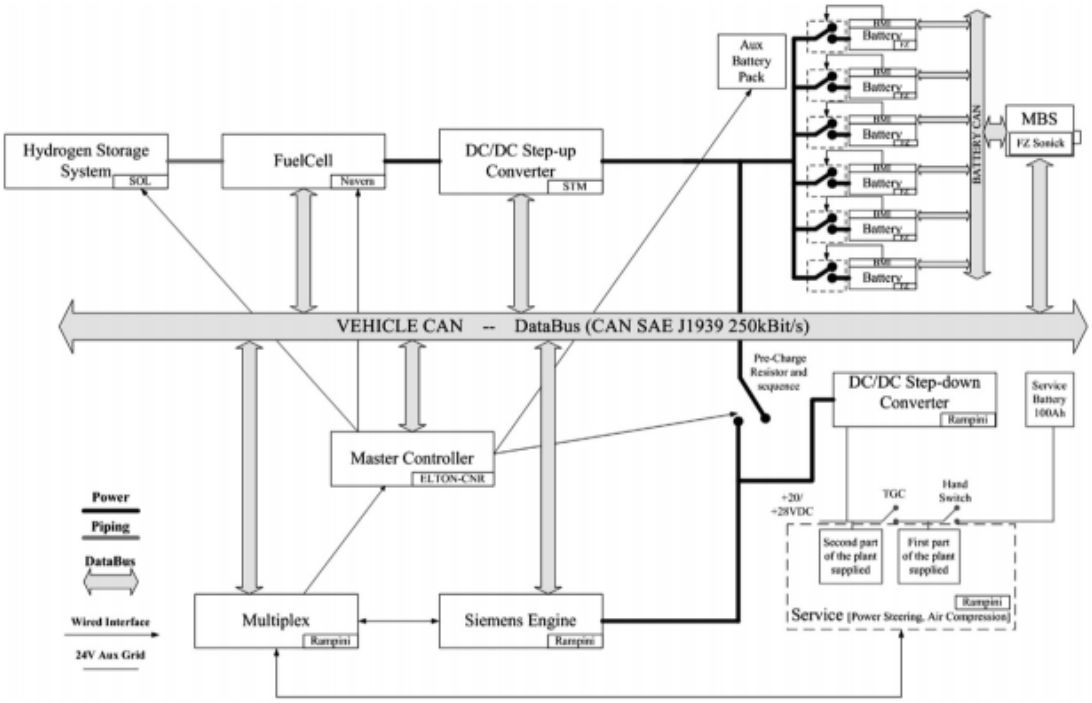

Fig. 16: City bus control architecture,Sergi et al. (2013:290).

- **Start-Up**

There are specific actions to keep in mind when starting up the bus. Sergi et al. (2013:292) explains that, “switching on the bus by turning the key for the first time helps the MC to communicate to all the other devices. The key must be turned a second time for all the devices to be active, and the bus can be considered as switched on. The driver has put the bus in hybrid mode to activate the FCs and it usually takes some time to warm up the FCs. The H2 tanks equipped contain about 90 kWh of available energy”.

- **Logic of the bus operating during running and shut-down**

Sergi et al. (2013:288) explains this part by sharing that, “the batteries are recharged by an electric motor that works as a generator during regenerative braking of the bus. The full power of the FCs is delivered to the batteries during every stop, and when the vehicle reaches the terminal stop, the FCs continue to supply energy to the battery pack on board”. “The shut down logic and flow chart is shared in Fig 17. During the shut down the FCs need to be supplied with 24 V as the stack would switch off and needs some time before it is fully off”, Sergi et al. (2013:288).

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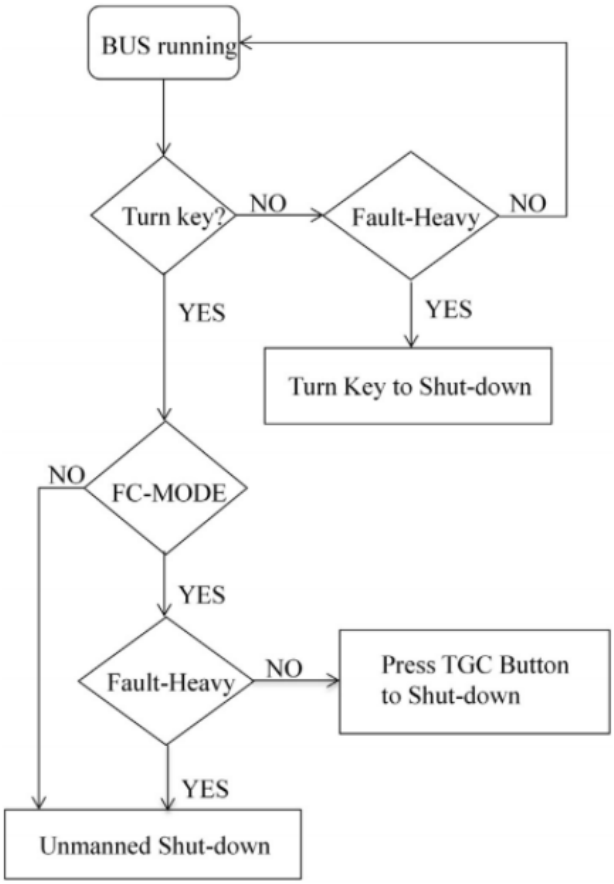

Fig. 17: Flow-chart of the shut-down logic, Sergi et al. (2013:292).

- **System Review**

The review of the entire system shows the feasibility of a hybrid system that can be used to convert electric buses combined with FC technology. Sergi et al. (2013:295) summarises the system review by sharing that, “the behaviour of the stack was analysed for 12 hours of continuous operation, and comparing this vehicle to the electric vehicle, the cost difference is limited at about 15%”. This hybrid version consts a bit more than the only battery version, however the short size of the FC system and reduced battery pack also show the below benefits:

- “Reduction of vehicles needed for the electric bus fleet (due to battery charging and range of use) can be made by moving to hybrid FC solutions.
- The fast refueling of H2 also offers more autonomy.
- The early market creation of H2 buses, will facilitate the reduction of costs for investment, operation and maintenance”, Sergi et al. (2013:295).

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5.3. Supercritical Cryo-Compressed H2 Storage for FCEBs

Today the most common H2 storage on buses and FC technology as mentioned by Ahluwalia et al. (2018:10215-10216) entails, “fuel cell electric buses (FCEBs) being equipped with 8 H2 cylinders that have a total of 40 kg of H2 providing a driving range just a bit over 500 km. The current generation of FCEBs store H2 compressed gas at 350 bar in type 3 tanks”. “The 8 H2 cylinders are metal and reinforced with carbon fiber (CF) carrying a majority of the pressure load and represent a significant fraction of the tank cost. New studies emerge for compressed hydrogen (cH2) with storage at 700 bar in type 4 tanks. For bus depots that have usually large HRS, on site liquid hydrogen (LH2) storage is preferable”, Ahluwalia et al. (2018:10215-10216). “In 2018, cryogenic LH2 pups have become available, offering an outlet pressure >850 bar, flow rate >100 k g/h, and H2 density >80 g/L. Such pumps can replace high pressure gas hydrogen (GH2) compressors with high efficiency of around 80%”, Ahluwalia et al. (2018:10215-10216).

- **Onboard Storage System**

Within this section the onboard storage system performance (as shown in Fig. 18) will be explained. Ahluwalia et al. (2018:10218) explains the onboard storage system in Fig. 18, “consists of 4 type 3 tanks with each tank consisting of a metal liner wrapped with T700S CF designed to withstand 225%. Having a nominal storage pressure and a minimum fatigue life of 15,000 cycles. The main vessel is completed by a thin aluminium outer shell separated from the inner tank by space rings. A calculation was made on the thickness of the insulation to limit the heat transfer rate from the ambient to 10 W”.

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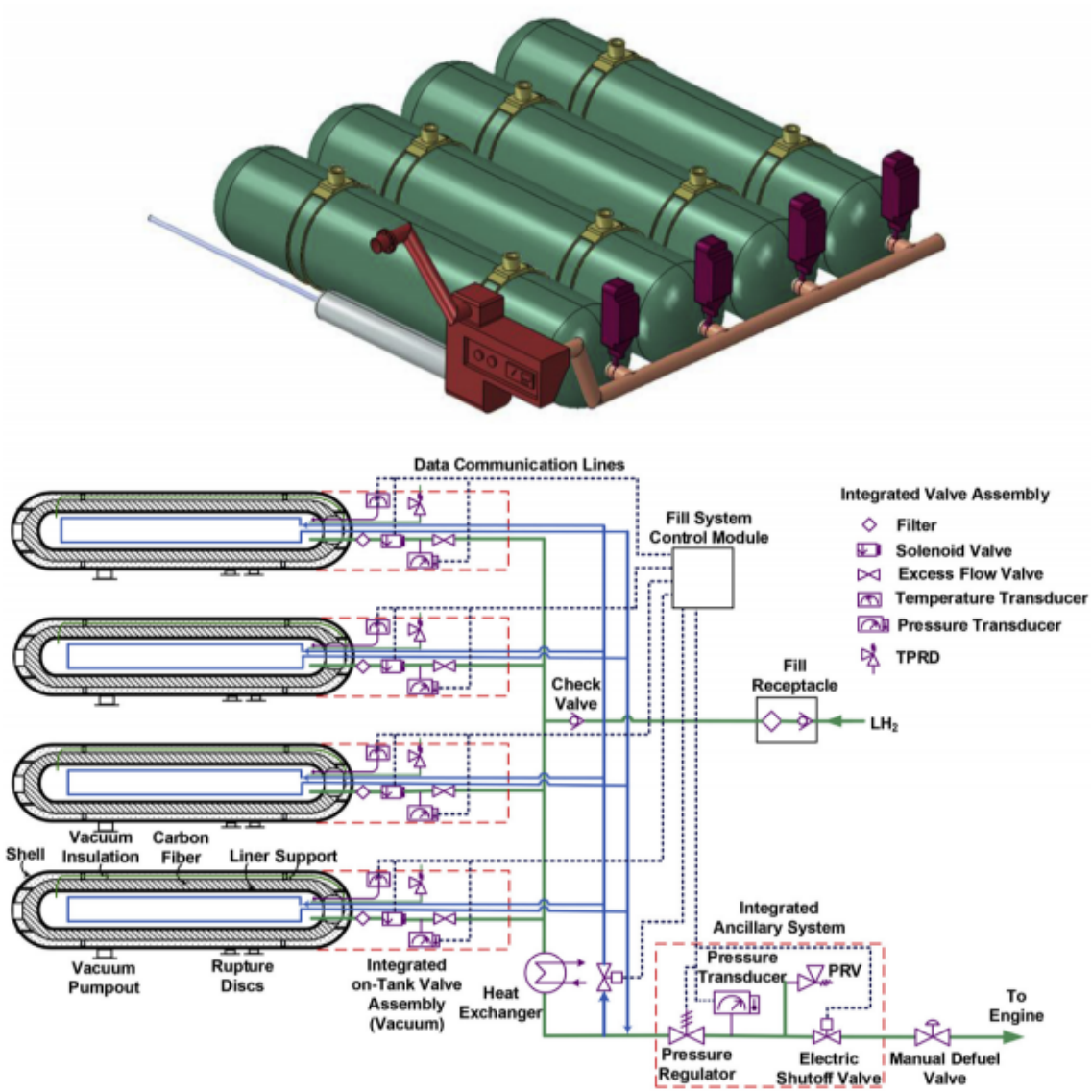

Fig. 18: Schematic of a 4-tank cryo-compressed H2 storage system, Ahluwalia et al. (2018: 10219).

- **Cryo-Compressed Tank**

The analysis of Ahluwalia et al. (2018:10218) shows that, "a 2-mm Stainless Steel (SS) liner in a cH2 tank for FCEBs meets the 15,000 fatigue cycle life for storage up to 700 bar pressure. Excessive weight and volume of the tank is added with the aluminium alloy 6061 liner as its thickness exceeds 13 mm".

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5.4. H2 Fueling Review

During fast filling for H2, there is a temperature rise of the gas. Liu et al. (2007:9243) explains that “the temperature rise occurs due to 3 thermodynamic factors; (i) the compression of the H2 gas in the cylinder, (ii) the isentropic expansion of the H2 gas that occurs with the dispenser and (iii) A part of the kinetic energy of incident H2 gas is converted into the heat”. Further assumptions in relation to the complexity of the filling process is shared:

- “The temperature of the H2 gas in the cylinder is the same as the ambient temperature during the beginning of filling. The heat exchange between the environment and the cylinder must be considered”, Liu et al. (2007:9243).
- “As an isotropic, the heat transfer characteristics of CF/epoxy composite laminate (CFEC), high density polyethylene liner (HPDE), aluminium alloy and glass fiber/epoxy composite laminate (GFEC) can be considered”, Liu et al. (2007:9243).
- “The filling rate is considered as a constant which equals average mass flow rate as the inlet gas pressure is considered as a constant, the same as the ambient temperature”, Liu et al. (2007:9243).
- “There is no mechanical deformation on all solid components in the system”, Liu et al. (2007:9243).

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6. Economic Review

With an increasing generation of electricity from renewable sources, there is an increase in imbalance between supply and demand. Ajanovic and Haas (2020:5) share that “one of the options to solve the aforementioned issue is to use H2 and a long term electricity storage option, see Fig. 19. With this in mind, H2 has a long term benefit in electricity storage which can improve economic efficiency for renewables investments and can enhance the security of power supply with a carbon free long term storage solution”.

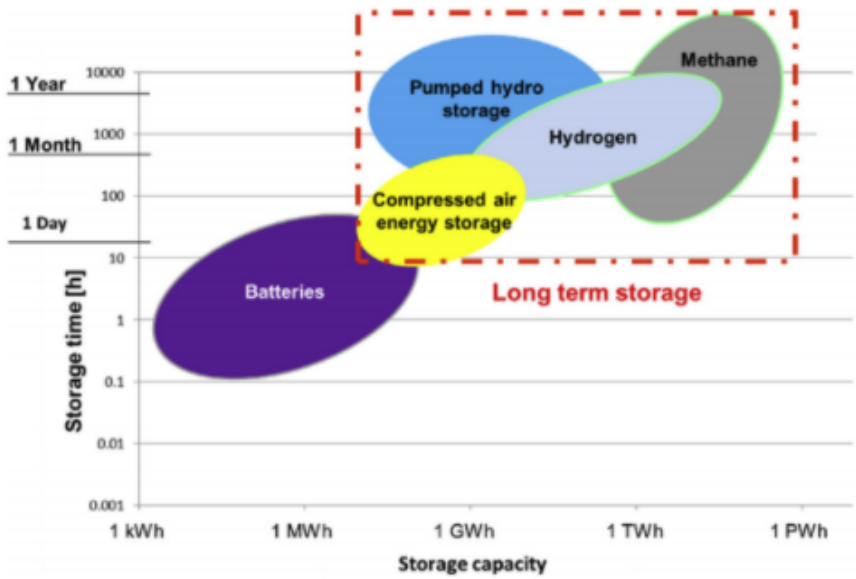

Fig. 19: Different Storage Options, Ajanovic and Haas (2020:6).

6.1. H2 production costs depending on FLH

Ajanovic and Haas (2020:6) explain in eq. 6, “the relation between H2 costs, electricity price and FLH of electrolysers:

$$C_{H_2} = \frac{\frac{C_c + C_{O\&M}}{T} + C_E}{\eta} \quad (\mathrm{EUR/kWh})$$

Eq. 6: H2 cost calculation formula, Ajanovic and Haas (2020:6).

Where CC is the capital cost, O&M are the operating and maintenance costs, T is the number of FLH per year, CE is the electricity costs, and h is the efficiency of the η electrolyser”.

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“Large scale electrolysis with investment cost of around 1550 EUR/kW, a depreciation time of 25 years and efficiency of 70% is used. The average electricity costs are calculated from the German (EPEX) electricity market from 2015 to 2018, with average prices below specific FLH used. As seen from the below Fig. 20, the capital costs per kWh produced is declining and the average electricity costs are increasing with increased FLH”. From these assumptions, “it can be considered that the cheapest H2 cats could be reached if the FLH was between 4500 to 8000 FLH”, Ajanovic and Haas (2020:6-7).

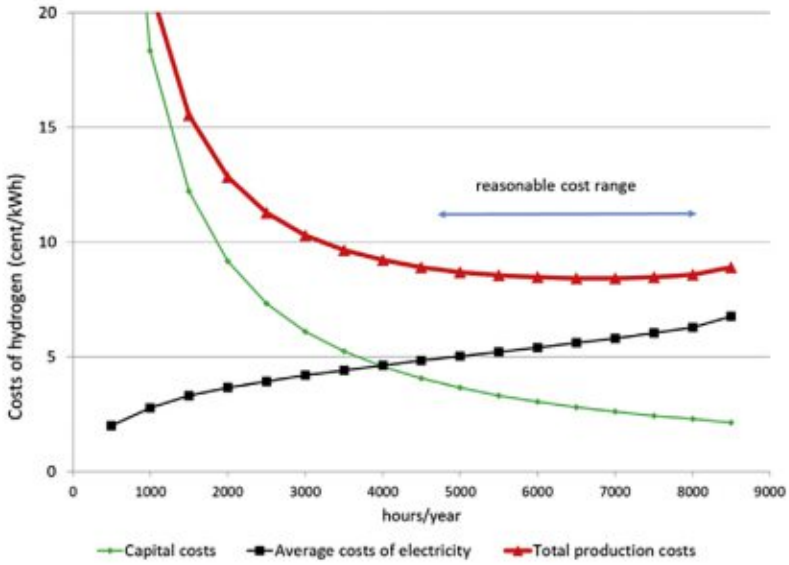

Fig. 20: H2 production costs depending on full-load hours, Ajanovic and Haas (2020:6).

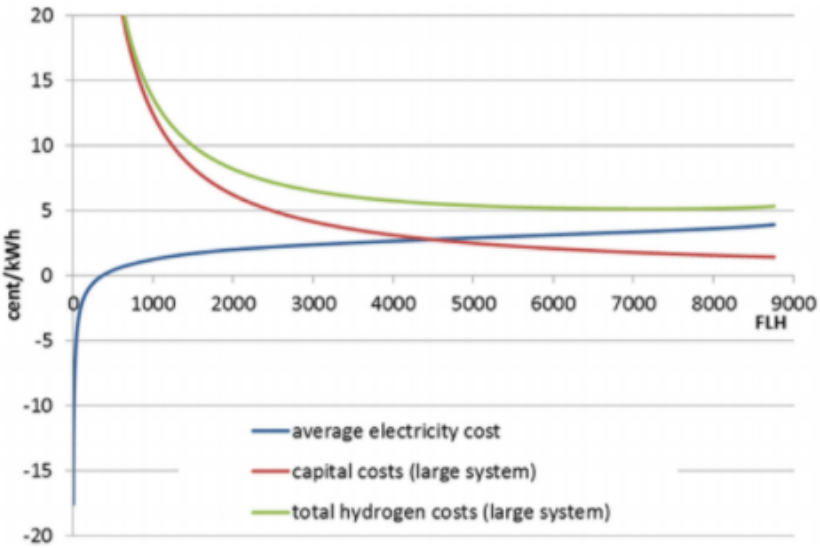

Fig. 21: The cost of H2 from large electrolysis systems (10 MWEle) depending on the number of the FLH, Ajanovic and Haas (2018: 284).

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Fig. 21 presented by Ajanovic and Haas (2018:284) “the total cost of H2 generation in a large electrolysis system dependent on the number of FLH. In this case, it is presented that the lowest cost of H2 could be reached when the FLH is at 4,500 hours per year”. “The lowest costs are approximately 5 cents/kWh starting from about 4,500 FLH in the large system. For 6,000 FLH, the cost is approximately 8 cents/kWh in a small system. As a summary, and from a practical known lesson; a maximum of 2,800 FLH would be realistic and would have a H2 cost in the range from 7 cents/kWh to 12 cents/kWh”, Ajanovic and Haas (2018:284).

6.2. Cost Analysis of FCBs

The Hydrogen council is a community of private organisations trying to foster the development of a future H2 economy. They speak of FCBs and make a cost analysis considering “three specific cases of use (per refueling): long distance travel with a range of 500 km, long distance urban transport with a 450 km range and short distance urban buses with a 150 km range”. As expressed previously the cost of investment for a new technology and bus is always important to the buyer. Key decisions for a bus operator (or buyer) is the cost of purchasing the buses and operating them. Other parameters of importance also include; comfort, refueling tie, operations in different climates, cost infrastructure required to refuel and flexibility across line requirements. To this effect, the Hydrogen council (2020) share the following points:

- **Cost Competitiveness**

“FCEBs outcompete full battery buses when the range required is more than 400 km. For urban buses with shorter ranges, BEVs and even ICE buses remain competitive before 2030 as shown below in Fig. 22. It is expected that by 2030, urban short range electric and FCBs will reach cost parity and remain so until 2050”, Hydrogen council (2020).

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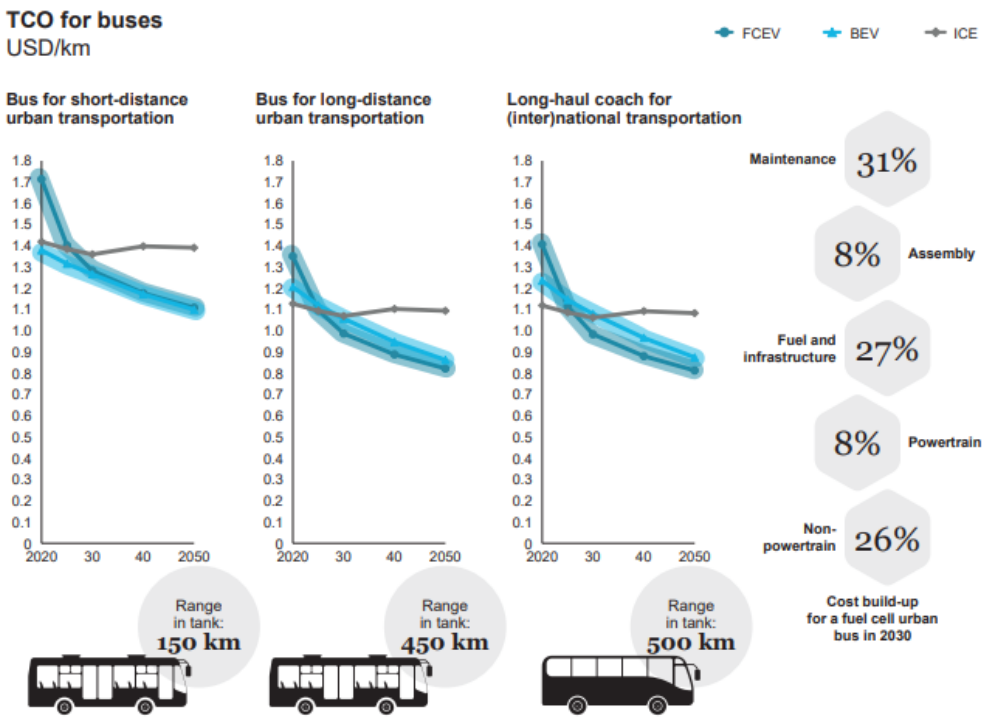

Fig. 22: TCO trajectory of buses, Hydrogen Council (2020).

"Additional benefits of FCEBs include more flexibility for longer ranges and as lesser investment than BEVs with no impact on refueling time. However BEVs batteries can also get smaller and effectively cheaper, and hence to compete FCEBs will need to have a steady growth in the market", Hydrogen council (2020).

- **Cost Development**

"As shown in the above Fig. 22, roughly 10% of the total cost of ownership (TCO) is contributed by the FCs powertrain and 25% by fuel. For the coach, the cost is differently divided because of a larger motor and higher total fuel consumption; to have cost parity will need a scale up for both the manufacturing of FCEB components and the H2 overall value chain", Hydrogen council (2020). "Private organisations will most likely reach parity with coaches and long-range urban buses when yearly manufacturing reaches 2,500 buses, while what really is required is 20,000 buses annually for short range urban buses to be cost competitive with BEVs", Hydrogen council (2020)", Hydrogen council (2020). "If 20,000 FCBs are manufactured annually, high scale supply of H2 and distribution value chains can be created. With these annual production volumes, fuel costs will reduce compared to today (2020) around 50%, reaction costs of approximately 3.30 EUR to 4.12 EUR per kg, due to market demand driving down costs", Hydrogen council (2020). When the cost of equipment will reduce, it will be a major cost driver for the entire H2 economy.

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7. Ecological Review

The Paris Agreement is a great collaboration between political forces in the world to consider, set goals and implement sustainable sources in the energy mix with promoting renewable energy and technologies, that the topic on savings of emissions becomes a high priority worldwide. Salazar et al. (2020:1) shares that, “in the European Union, 23% of CO2 emissions comes from the transport sector with almost 73% people living in urban cities. Currently on 2.1% of the total bus fleet is made up of alternative fuels, and hence the gradual introduction of hybrid electric technologies and/or FCBs can provide an average reduction of 21% in GHG emissions and 26% savings in fuel consumption”. In the entire fuel process chain, it is important to evaluate the conversion efficiencies and specific emissions. Hence a complete assessment of the ecological and energy aspects of various fuel paths are required. Ramesohl and Merten (2006:1253) share that “first, this concerns fuel processing from the primary energy source to the vehicle, i.e. the specific GHG emissions per unit of final energy [g CO2 eqv/MJ]”. In table 7, they mention the specific emission factors used for the various fuel types presented, and this is specifically to be seen from the perspective of the transport sector.

Table 7: Selected emission factors of H2 fuel chains vs. gasoline and diesel, Ramesohl and Merten (2006:1254).

Specific GHG-emissions	Fuel chain ($g\,CO_2eqv/MJ$)	Vehicle emissions ($g\,CO_2eqv/MJ$)[a]	Local CH_4 and N_2O emissions ($g\,CO_2eqv/MJ$)[b]	Total ($g\,CO_2eqv/MJ$)
Gasoline	12.5	73.4	2.4	88.3
Diesel	14.2	72.8	1.7	88.7
CGH_2 700 bar (EU gas mix, decentral. MSR)	104.6	0.0		**104.6**
CGH_2 700 bar (waste wood gasification)	10.7	0.0		**10.7**
CGH_2 700 bar (wind power, decentral. electrolysis)	0.0	0.0		**0.0**
LH_2 (MSR)	124.0	0.0		**124.0**
LH_2 (wind power, central electrolysis)	2.0	0.0		**2.0**

Source: CONCAWE, EUCAR, JRC, 2003, LH_2 paths are taken from LBST (2002a).
Renewable energy paths are seen from the transport sector and do not reflect systemic effects.
CGH_2: compressed hydrogen; LH_2:liquefied hydrogen; MSR:methane steam reforming
[a]CO_2 content of fuel.
[b]Conventional drive trains.

Ramesohl and Merten (2006:1253) further share that “the total emissions of a fuel pathway are affected by the propulsion technology that converts fuel to motion. The efficiencies of the Otto engine /the diesel engine), the H2 internal combustion engine (ICE) or the H2 FCs can differ quite significantly”. They share the values for conversion efficiency [MJ/km] of the selected propulsion technologies below in Table 8.

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Table 8: Assumptions on development of fuel consumption of powertrains, Ramesohl and Merten (2006:1254).

Trend (BAU)	2000 (MJ/Pkm)	2010 (MJ/Pkm)	2020 (MJ/Pkm)	2030 (MJ/Pkm)	2040 (MJ/Pkm)	2050 (MJ/Pkm)	2000–2050 (%)
Gasoline	2.10	1.74	1.50	1.37	1.26	1.16	−45
Diesel	1.92	1.53	1.38	1.28	1.19	1.10	−43
Hydrogen ICE	2.10	1.56	1.35	1.23	1.15	0.95	−55
Hydrogen FC	2.10	1.25	1.20	1.10	1.00	0.90	−57
High-Saving (HS)							
Gasoline	2.10	1.67	1.33	1.05	0.86	0.45	−79
Diesel	1.92	1.59	1.25	1.00	0.81	0.43	−78
Hydrogen ICE	2.10	1.51	1.19	0.94	0.63	0.41	−80
Hydrogen FC	2.10	1.25	1.05	0.90	0.60	0.39	−81

ICE: internal combustion engine; FC: fuel cell; Pkm: person-kilometre. *Source*: Ramesohl et al., 2003.

7.1. Fleet Consumption Future Assumptions and Related CO2 Emissions

There are certain indicators that can help to track performance measures to compare one technology to the other. For example, one important factor is to compare the CO2 emissions from one period (decade) to the other. The situation in 2050 for the transport sector is expected to develop itself into having a mix of vehicle technologies. Ramesohl and Merten (2006:1253) share below two areas of development for the average energy consumption between vehicles in 2000 and 2050:

- "Between 2000 and 2050, it is assumed that the average fleet consumption will drop by 57% (FCVs) and 43% (diesel). This will decrease emissions from 135 million tons CO2eqv in the year 2000 to 78.3 million tons CO2eqv in 2050", Ramesohl and Merten (2006:1253).
- "Even though the above is a significant reduction of CO2 emissions, it is not in line with some local ambitions. For example, this still falls short of the CO2 emissions reduction target by the Germany Federal Environmental Agency's sustainability scenario of reducing to 30.4 million tons CO2eqv by 2050", Ramesohl and Merten (2006:1253).

In order to achieve these CO2 emissions a strong push towards moving away from fossil fuel based resources is strongly recommended. The high costs in the short terms will relate to future unprecedented benefits for local communities though GHG emissions.

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7.2. Energy Systems Comparison

Alternatives to established fossil fuel energy systems are required and it is essential to have a comparative analysis to understand the characteristics of different systems. Baykara (2018:10608) shares that “competitive technologies could include solar H2 systems and coal/synthetic fossil fuel systems. Clearly, solar H2 systems offer clean and primary energy, the same as other derivatives such as hydro, wind and waves”, Baykara (2018:10608) compares the 3 aforementioned technologies and considers factors such as vapor generation, pollution and environmental damage are substantially low for solar H2 energy systems compared to the alternatives as shown in table 9 below.

Table 9: Environment related properties of the three energy systems, Baykara (2018:10608).

Energy system	Pollutants (kg/GJ)						Vapor generation (10^{12} kg/y)			Environ-mental damage ratio[c]	Environ-mental compatibility factor
	CO_2	CO	SO_2	NO_x	HC	PM[a]	Energy system	Global warming	(%)[b]		
Fossil fuel	72.40	0.80	0.38	0.34	0.20	0.09	8.9	3900	0.782	18.24	0.055
Coal/Syntehic fosil fuel	100.00	0.65	0.50	0.32	0.12	0.14	9.3	3900	0.782	22.62	0.044
Solar-hydrogen energy	0.00	0.00	0.00	0.10	0.00	0.00	6.0	0.0	0.001	1.0	1.00

[a] Particulate matter.
[b] With respect to annual vapour generation due to solar heating (5×10^{17} kg/y).
[c] (Damage due to fuel)/(Damage due to solar hydrogen).

As seen from the above table 9, solar H2 energy system is a very beneficial variant for the environment, with yerop pollutants and significantly low vapor generation as compared to the other 2 technologies. The environment damage ratio is also very low, which is a very good sign. Baykara (2018:10609) shares the work done in 1958 where, “atmospheric concentrations of CO2 for half a million years before the twentieth-century could have varied between about 200 and 300 parts per million by volume (ppmv). In the twentieth century, this rose to 370 ppm by 2001, a much larger increase. Projections shared by the Intergovernmental Panel on Climate Change (IPCC) that by the end of the twenty- first century, this could rise upto 700 ppmv”. The year 2100 might seem as a long way ahead, however the end of the century will provide a clear picture to the future generations about where they stand. If CO2 emissions are not drastically reduced this will give a rise to the surface temperature, which will lead to extremes in climate that may be currently unimaginable.

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7.3. Life Cycle Analysis

For many technologies a LCA is recommended to establish a cradle to grave approach for technologies. Ally and Pryor (2007: 405) help to assess within this section key understanding for the LCA approach. They share that “determination of the outputs to the environment by calculating the material and energy flow is a main objective of LCA. Impact categories as shared in the below table 10 will help to assess the environmental relevance of those subjects. Further in Fig. 23, for each selected impact category the life cycle impacts are depicted”.

Table 10: Life-cycle impact categories, Ally and Pryor (2007:406).

Impact category	Short description	Examples
Global warming potential (GWP)	Emissions that contribute to global warming	CO_2, CH_4, etc.
Acidification potential (AP)	Emissions that cause acidification of rain, soil and water	SO_2, etc.
Eutrophication potential (EP)	Emissions that change nutrient concentration in lakes, rivers and soil	P and N compounds
Photochemical ozone creation potential (POCP)	Emissions that increase the production of tropospheric ozone	Hydrocarbons, etc.

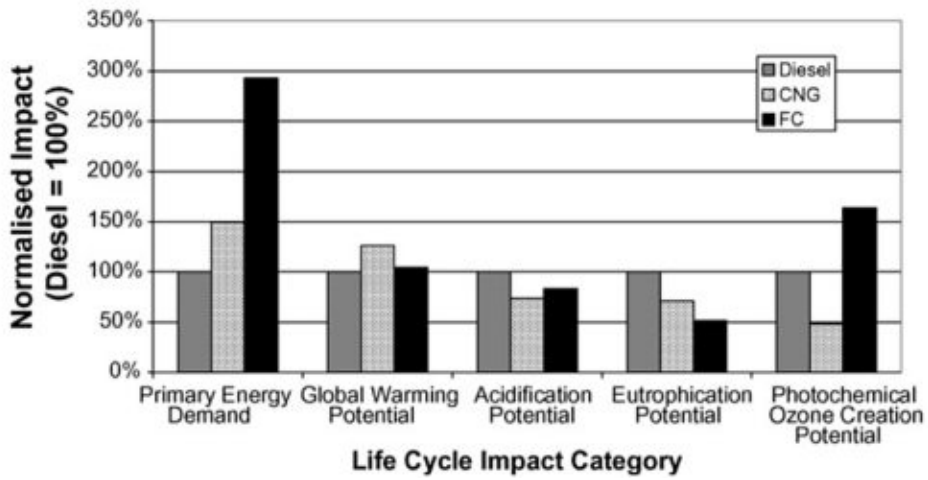

Fig. 23: Life-cycle impact assessment results, Ally and Pryor (2007:405).

Within the study of Ally and Pryor (2007:406), they “individually modelled the life-cycle of each bus and the results compared with respect to a functional unit of vehicle kilometres (km). A lifetime of 16 years is the average lifespan for a H2 bus that can travel upto 55,000 km annually”. “The impact criterias are compared in the above table 10. As expected, fuel production dominated H2 profile and tailpipe emissions generally dominated the diesel and CNG profiles”, Ally and Pryor (2007:406). Below each criteria are further explained to have a comprehensive view on these findings.

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- **Global Warming Potential (GWP)**

The production of electricity from any non renewable resource will lead to a high GWP. It is in our interests to convert systems to hybrid or fully renewable in order to manage the issue of global warming. Ally and Pryor (2007:406) share that, “currently due to crude oil extraction and the use of coal based electricity, the H2 production GWP is significantly high. Furthermore, the CNG bus system has a higher GWP compared to the diesel bus system. This is due to the low fuel efficiency on the CNG buses and tailpipe emissions of CH4 from the natural gas systems”.

- **Primary Energy Demand (PED)**

The high PED of the CNG bus compared to the diesel bus is evident, and H2 has the highest PED compared to all, see Fig. 23. However Ally and Pryor (2007:406) shares that “many factors play a role in the efficiency loss and the energy efficiency of the vehicle, and the lower energy density of the gas fuel increases the energy used during storage and transport (caused by compression losses). The FC system uses around three times more energy compared to the diesel or CNG system, however there is room for improvement”.

7.4. Key parameters for an improved life-cycle profile

“The increase in efficiency for H2 FCVs is an advantage and improvement to ICEVs. Further improvement in life cycle findings and improvements will be needed for the future. LCA can always help decision makers compare their results and find quantitative and qualitative findings”, Ally and Pryor (2007:407).

- **FC Durability**

The production of FCs contributes to high energy and emissions for bus manufacturing and the replacement for FCs should be taken into account when doing the LCA analysis. Ally and Pryor (2007:407) explain that “the PGM catalysts and the flow field plates have a high recyclability and are significant contributors to the energy demand and environmental footprint of FC production. In Fig. 24, the change in PED and GWP as a function of the FC durability is shor. A substantial improvement will be achieved with a slope change of 10,000 h durability, with a >40% reduction in GWP and >20% reduction in PED”.

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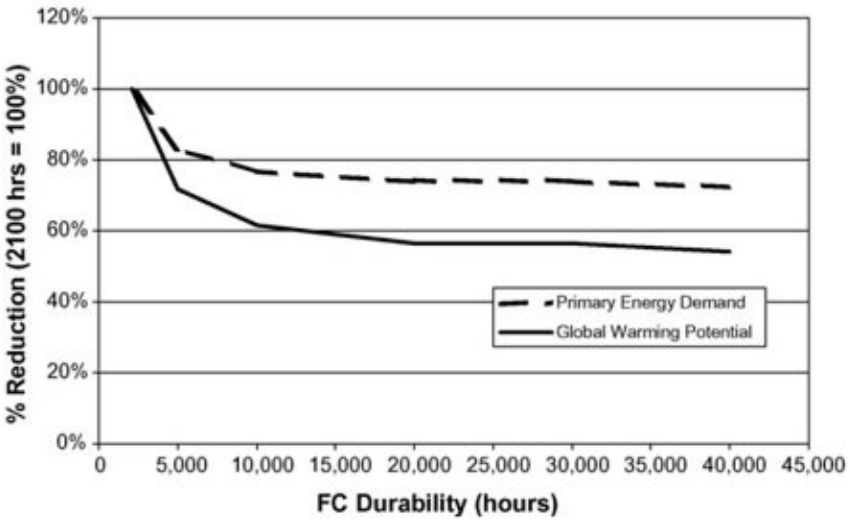

Fig. 24: Effect of FCs durability on PED and GWP. Current stated FCs durability = 2100 h, Ally and Pryor (2007:407).

- **H2 Loses at HRS**

Pilot scale H2 projects do not really help to understand the full scope implementation on a wider scale. Low number of HRS for example, make the technology currently visible only as a niche market, even though established in the local network. Ally and Pryor (2007:408) share that at “HRS, there can be also significant losses of H2, leaks from the compressor and associated piping have occurred already. The required purge cycles at HRS also increases the losses of H2 as the system is dismantled. Bus depot HRS in particular have a loss of around 2.4% H2 over a period of 3 months. In the CUTE project as well, the H2 loss at HRS was in the range of 5-7%”.

- **Energy Efficiency**

Ally and Pryor (2007:408) in this section reference studies from other researchers; “Ahluwalia et al. studied concluded that H2 fuelled compact, mid-size and sports utility vehicles would achieve 2.5 times the fuel economy of conventional gasoline fuelled vehicles. Colella et al. concluded that the fuel efficiency estimates show an efficiency ratio of future FCVs at 2.9 times compared to today’s conventional vehicles". In Fig. 25, the energy efficiency of the various fuelled vehicle types is shown. A fuel efficiency of 2.4 times that of the current diesel buse affects reduction in the GHG emissions within the life cycle.

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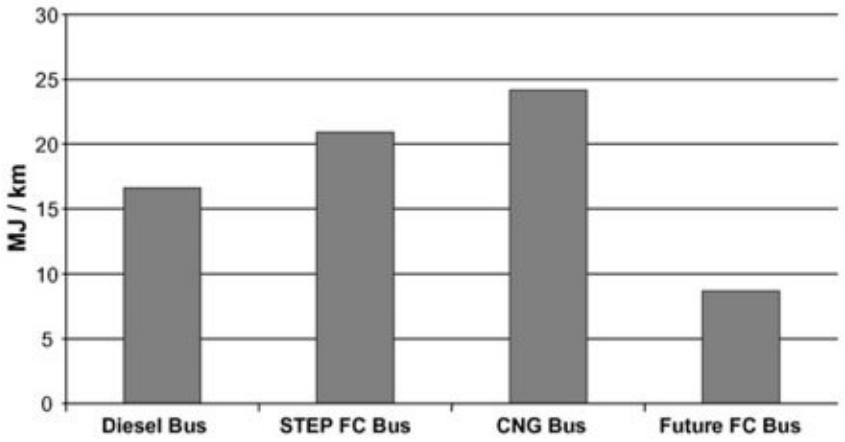

Fig. 25: Comparison of vehicle energy efficiency for diesel, natural gas, H2 FC, and future H2 FCEBs, Ally and Pryor (2007:410).

7.5. Beyond cost and carbon; co-benefits of low carbon transitions in Europe

Economic research tends towards providing cost structures for equipment, production, storage, delivery, fuel consumption etc. However, there is a key shift in attitude needed where comparing costs may not always be the best strategy. Sovacool et al. (2019:16) help to understand that on an ecological value chain path, "future low carbon transitions may need complementary innovations across several technology types", for example:

- "New market arrangements and business models (back-up generation capacity);
- Increasing capacity and connecting remote renewables by linking systems.
- Storage of energy (examples- pumped hydro, batteries, compressed air).
- Smart grids (to improve management and flexibility); and
- Demand response (combining smart meters and new tariffs)", Sovacool et al. (2019:16) .

Hence, policymakers and analysts must recognise and also evaluate that low carbon transitions are finally processes that involve social affairs, technical innovation dynamics and political events as they cover environmental and economic domains.

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8. European Case Studies

Europe was the selected area of this research as the countries within Europe have a big part to play currently in the development of H2 technologies. Salazar et al. (2020:1) share information from the European Commision who reported in 2013 that, “in the European Union, around 73% of people live in cities and urban areas and through their usage of conventional fuels, account for 23% of the CO2 emissions derives from the transport sector”. Using communal transport within cities and urban areas and promoting alternative fuels could require behavioural shifts of people among other things. However public transport can be effectively used to reduce CO2 emissions and create a sustainable future. Salazar et al. (2020:1) further shares that, “alternative fuel vehicles make around 2% of the total bus fleet in 2018 for countries in Europe. As such, introducing hybrid electric technologies in the short term can reduce 21% of GHG emissions and 26% in fuel consumption”.

This can be considered as a very important stepping stone in a low carbon mobility market. One of the major projects conducted in Europe was the CUTE project and was conducted in 9 cities. Haraldsson et al. (2005:318) share in their research that “both H2 powered FCEBs and H2 infrastructure were tested and used during 2 years.The survey results of the CUTE project included 27 buses after a year’s operation along with recurrent usage of the associated infrastructure”. The key goal of this project can be considered to make H2 and FC technology more visible within practical use through the buses. Within this section, we will discuss the following cities; Stockholm (linked to CUTE project), Rhein-Main area, Tuscany, Valencia and Porto. Each case study will be individually presented and further on in the results section the findings from each case study along with a combined final result for this research will be shared.

8.1. Stockholm, Sweden

Haraldsson et al. (2005:319) in his research shared that “in January 2004, 3 FCEBs first operated on a trial road called the water route in downtown Stockholm, and after 8 months the 3 buses were put in service on route 66 in central and busy Stockholm”. The bus layout of the 3 FCEBs used is shown in Fig. 26. The model of the bus was Mercedes-Benz Citaro low-floor city bus, and in the FC version of the bus, the ICE has been replaced by a central electric motor, powering an automatic gearbox. A special feature of the FCEB used is that the auxiliaries are powered by the central electric motor via a special addition gearbox at the rear end of the motor. The FC system and the H2 storage unit is located on the roof of the bus, for safety and space.

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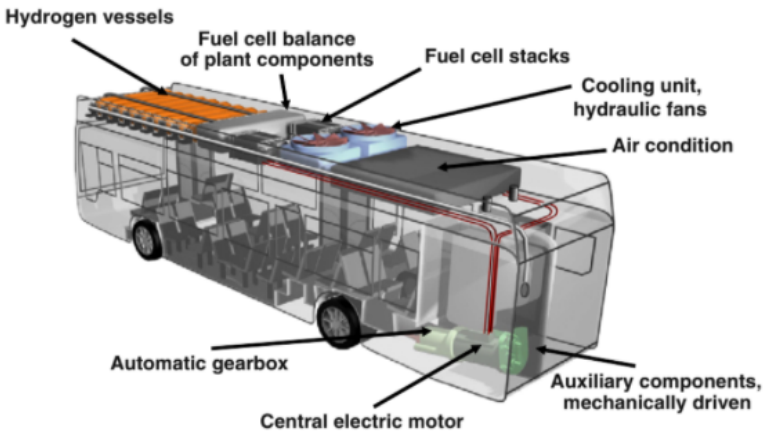

Fig. 26: The Mercedes-Benz FCs Citaro, Haraldsson et al. (2005:319).

Haraldsson et al. (2005:319) also adds that "at the time, this topic was a huge success in the newspapers and the media often pointed out the benefits of such buses where emissions were only water and humid air compared to GHG that we are used to from ICEVs". In the below sections, we will see the process and results received from surveys sent to the general public who travelled on these buses and the bus drivers who drove these buses.

- **Passenger survey for CUTE project**

This part of the research for Stockholm was very important to understand the current mindset of the people and future prospects for change that were expected. Haraldsson et al. (2005:319) shares that "518 commuting passengers participated in a field survey that lasted in total 3 days of operation on route 66 in 2004 to understand passengers' attitude and acceptance to H2 and FC technology and overall experience. The conventional buses referred to in the survey were in reference to conventional buses using ethanol, diesel or biogas that are the type of buses currently operated by SL". The following questions were asked:

- "General information (for example; age, gender and travel patterns).
- Knowledge on the CUTE and FCEB project, and willingness to learn more.
- Attitude towards performance/characteristics compared to conventional buses.
- Safety aspects of H2 and FC technology in the buses.
- Key factors affecting the choice of transportation means.
- Willingness to pay (WTP) a higher fee", Haraldsson et al. (2005:319).

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The broad range of questions along with the trail on the FCEB bus was a good experience for the local community to feel part of a change that might happen in the future, and got the opportunity to voice their opinions. The results for the questions asked are explained below. Haraldsson et al. (2005:320) also shares that, “there was an answering scale that the passengers had to use which started from 1 (strong disagreement) to 7 (strong agreement). The passengers were also allowed to put a zero in the case they did not have any opinion on the question”.

- **The Bus Drivers Survey**

Haraldsson et al. (2005:322-323) within this section shared that “the team of Luxembourg who were part of the CUTE project as well developed the questionnaires for the drivers and distributed them to the other 9 cities. The 23 drivers who operated the FCEBs volunteered to do the job, and in contrast to the female majority seen above in the passenger surveys, the drivers were all male with ages varying from 24 to 62 years old”. Not a very diverse group in terms to analyse various opinions, however the information received is still relevant. Haraldsson et al. (2005:323) further shares, “the driving experience of the drivers also varies vastly, with 40% having driving experience of 5 years, 20% having 5 to 10 years of experience and, almost 40% having worked for 15 years or longer”. “For the preparation to do the job with the FCEBs, the 23 drivers completed a 5 day course for information on various subjects involving; the CUTE project, FC technology in buses, safety training and management on H2 as vehicle fuel”, Haraldsson et al. (2005:323). For operators or technical staff working on new technologies, training and prior information is vital in the success for the overall implementation.

8.2. Rhein-Main area, Germany

The Rhein-Main area in Germany has seen a shift in their energy going towards the renewable sources as much as possible. However, the growing supply needs to match the demand and in the case of H2, the production and dimensioning of the electrolysis units must be sufficiently sized. Various options for delivery and storage are also very important for H2 implementation. Coleman (2019:5123) shares that, “common scientific practices such as ARcGIS acting as a geographic information system (GIS) can be used for location analysis. One option could be BEVs including a technology associated grid extension. Another option is to change from fossil fuels to renewable H2 produced in power to gas (PtG) plants and its use in FC electric vehicles instead of ICEVs”.

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- **Case Study**

The area that is covered in this case study in Mainz, Wiesbaden and Frankfurt am Main, with a population of around 5.7 million people. Coleman (2019:5124) shares that, “the bus fleet of the 3 cities consume about 14,200 tonnes of diesel annually and emit 45,200 tonnes of CO2, 35 tonnes of CO, 209 tonnes of nitrogen oxides (NOx), 4 tonnes of hydrocarbons and 2 tonnes of particulate matter”. This information is very helpful to understand the current bus fleet’s fuel consumption and related environmental impacts.

- **Energiepark Mainz**

Energiepark Mainz is a key source for H2 in the region. Coleman (2019:5124) shared that there is a “6 MW PEM electrolysis plant, with three skids having a peak power of 6MWel and an output of 1000 Nm3 H2/h (80.9 kg H2/h). This plant is connected to a 8MW wind farm. The objectives for this power plant were to check for provisions of ancillary services for the power grid and to store energy as H2. The produced H2 is compressed with an ionic compressor in two stages up to 22.5 MPa”, Coleman (2019:5124). “This allows different utilisation of the stored H2; in the chemical industry, at fuel stations supplied via tube trailers anr/or it can be fed into the natural gas grid. More than 225 tonnes of H2 had been produced by the plant by the end of 2018 and the operators of the power plant signed a long term H2 production contract with Energiepark Mainz”, Coleman (2019:5124).

- **H2-Bus Rhein-Main**

With a good source to produce H2 at Energiepark Mainz, the expansion into transport as an alternative fuel is highlighted as one of the key uses of produced or stored H2. Coleman (2019:5124) shares the “H2- bus Rhein Main project which is a cooperation of the public transport operators from Frankfurt, Mainz and Wiesbaden. As part of the object, they acquired eleven FCEBs, which would be operated using shared infrastructure in the Rhine- Main region. The storage demand of H2 is defined by weekdays and with a high number of fleet km”. “They made 303 daily round trips covering 39,000 km in total. The longest trip is 397 km and the shortest one is 8km. In table 11, the assumptions on trailer capacities and H2 consumption are shown”,Coleman (2019:5124).

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Table 11: Basic bus operator model input and H2 assumptions, Coleman (2019:5125).

Parameter		Unit	Value
Routes		#	41
Round trips		#	303
	Sum	km	39,000
	Average	km	128
	Longest	km	397
	Shortest	km	8
Operation	Start	hh:mm	03:30
	End	hh:mm	01:30
Buses	Standard (12 m)	#	141
	Articulated (18 m)	#	107
H_2 consumption	Standard (12 m)	kg/km	0,10
	Articulated (18 m)	kg/km	0,14
H_2 delivery capacity	GH_2 200	kg/trailer	400
	GH_2 500	kg/trailer	1100
	LH_2	kg/trailer	3000

“Fig. 27 shows the distance of all considered round trips that are suitable for substitution”, Coleman (2019:5125). “Fig. 28 shows the round trips over the course of one day. It can be seen that especially in the morning hours a maximum number of buses is required. This is due to the school bus traffic and the rush hour in general”, Coleman (2019:5125).

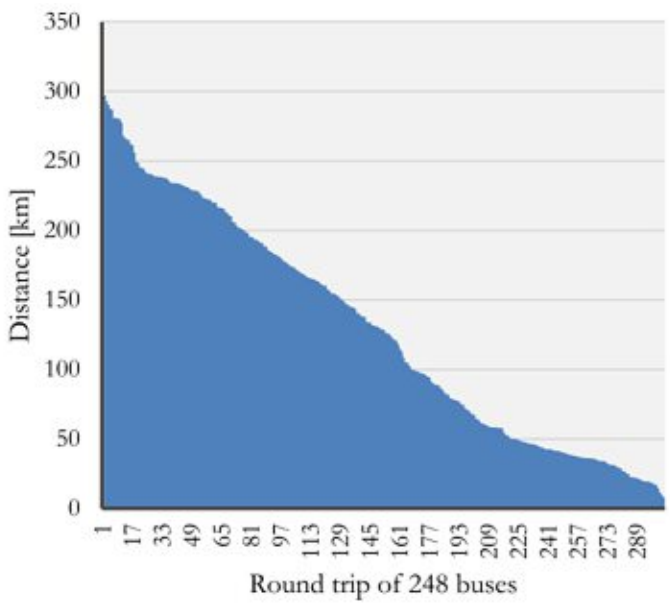

Fig. 27: ICEVs round trip distances for a common weekday, Coleman (2019:5125).

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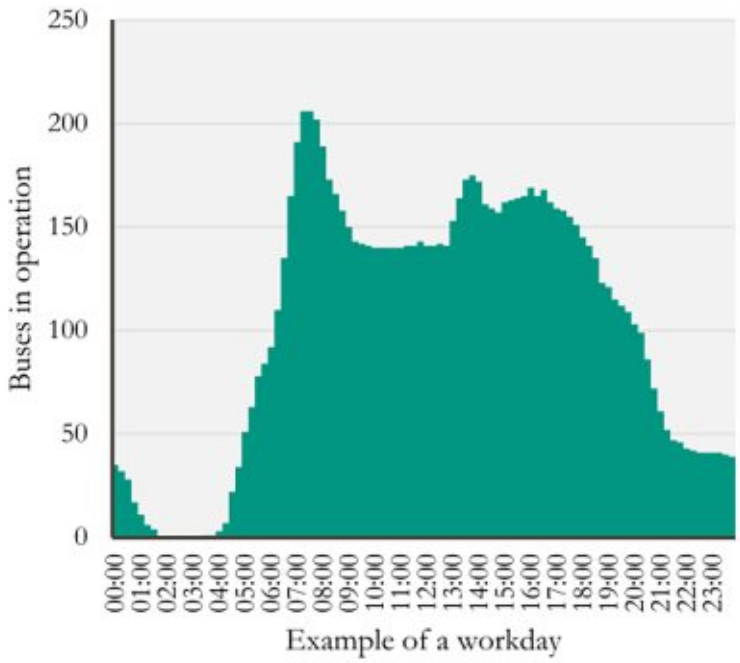

Fig. 28: Bus operation over the course of one day, Coleman (2019:5125).

- **Bus Fleet Substitution Scenarios**

In relation to planning for a transition to FCBs some infrastructural and fleet considerations must be kept in mind. Coleman (2019:5125) shares that, "H2 delivery by tube or tank trailer by less than one day due to the spatial restrictions of the bus depot. The charging of the buses should be done overnight during non operating hours, with intermediate charging through round trip optimisation". Below there are 2 types of scenarios provided namely the 'pro batter' and 'pro FC+' scenarios. Keeping in mind these 2 scenarios, Coleman (2019:5126) shares that "in the pro batter scenario the range of the drive on the bus is estimated larger than 250 km, and the pro FC+ scenario has a maximum driving range of 150 km".

- **Pro Battery Scenario**

Coleman (2019:5127) envisages this scenario to have an "ambitious linear ramp up of battery electric buses until 2022, with a saturation reached at 60% of the bus fleet by 2025. For round trips over 200 km in this scenario will place a big role as well. By 2023, if the fleet share of H2 buses is around 17%, then approximately 700 kg/d of H2 will be required with delivery of 1 trailer per day".

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- **Pro FC+ Scenario**

Coleman (2019:5127) explains that “due to range restrictions, standard BE buses can only achieve 20% fleet share due to range restrictions <150 km. In this scenario, the need for 39% standard and 41% articulated FCBs by 2025 are needed. By 2021, if the FCBs share becomes around 11%, H2 demand will be 850 kg/d. By 2022, if the H2 fleet share becomes 26%, the demand for H2 will be 1,800 kg/d”. The increasing scenario of the FCBs in this scenario, require for supply to be able to steadily rise and match the predicted demand.

- **Resulting H2 production costs for the different scenarios**

The above scenarios and level of alternative technologies for urban bus transport will clearly increase the demand for supply of H2. In this section, we assess the findings to match the current capacity and Energie park Mainz. Coleman (2019:5128) shares that “for the current 6 MW PtG plant of Energiepark Mainz model results are extrapolated. This plant can reach approximately 1500 kgH2/d as a maximum amount”. This plant would suffice until 2022 in relation to being the sole source of H2 for buses as per the pro FC+ scenario. Coleman (2019:5129) shared that to match the increasing demand for H2, “a 14 MW or 18 MW PtG plant would be needed, and this would result in daily production of around 3000 kgH2/d. This is based on depreciation time of 20 years and at an interest of 5%, with operation expenditures of 4% of the investment cost and national electricity surcharges for Germany”. In Fig. 29, it can be seen that with a higher share of FCBs the most affordable plant production the daily required amount of H2 would be a 18 MW PtG plant.

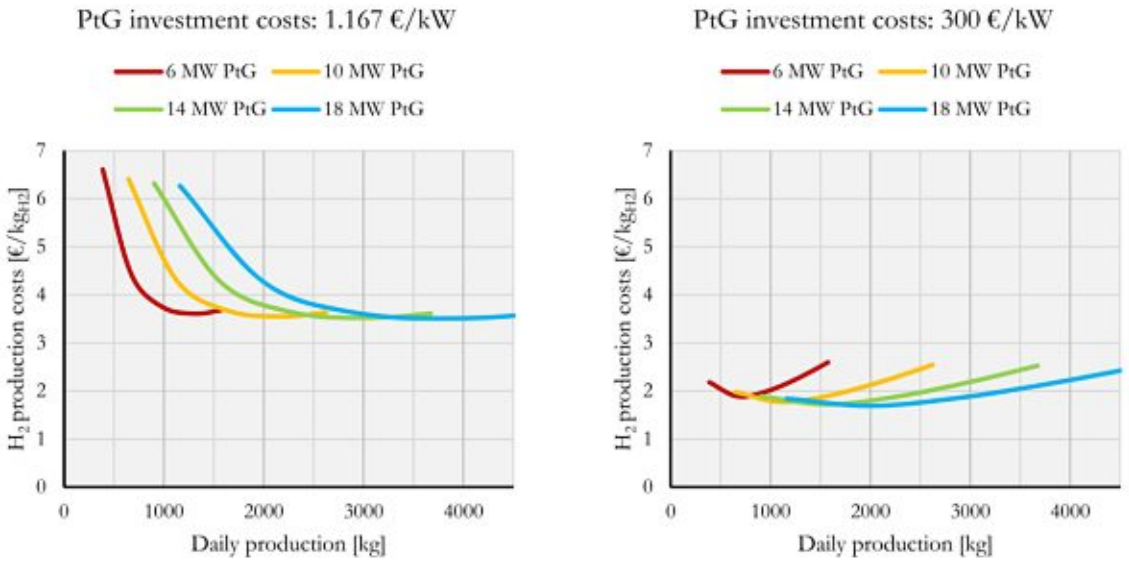

Fig. 29: H2 production costs in dependence on the daily production amount, Coleman (2019:5130).

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8.3. Tuscany, Italy

Various regions have been shared in this research to illustrate already performed pilot projects in European cities for H2 powered buses to illustrate future potential. In this section we look at Tuscany, Italy and the project shared by Bartolozzi et al. (2012:104) called 'Filiera Idrogeno (Hydrogen Chain)'. This project was supported by the region of Tuscany, and evaluates general objectives related to ecological, economical, social and technological features of the energy H2 chains, and its use as an alternative fuel. A LCA is used and to benchmark a H2 production based on Italian energy mix was assessed. The benchmarking further compared different technological alternatives, comparisons with EVs, based on renewables as well as on Italian electricity mix. "The different scenarios in this case study base the H2 produced via renewable energy sources such as biomass or wind. H2 was supplied to delivery vehicles (porter) equipped with either FCs or ICEVs. Based on the Italian electric mix, fuel production from renewables was benchmarked. This included benchmarking BEVs and H2 vehicles", Bartolozzi et al. (2012:104). Compared to other analysis we have seen so far, the example from Tuscany is not a bus for passengers as per the main theme of this research. However, to diversify we use this case study as the chosen vehicle in this study is a heavier vehicle than normal cars, and it's findings may lead to similar results as buses powered by H2.

- **Life Cycle Assessment of H2 Chain**

Bartolozzi et al. (2012:105) share that, "the objective of this LCA study is to evaluate the environmental impacts of H2 chain scenarios in Tuscany (Italy)", which include the following stages (Fig. 30):

- "H2 production chains, at regional scale.
- Storage, transportation and distribution of H2.
- Production, use and end-of-life of vehicle and components", Bartolozzi et al. (2012:105).

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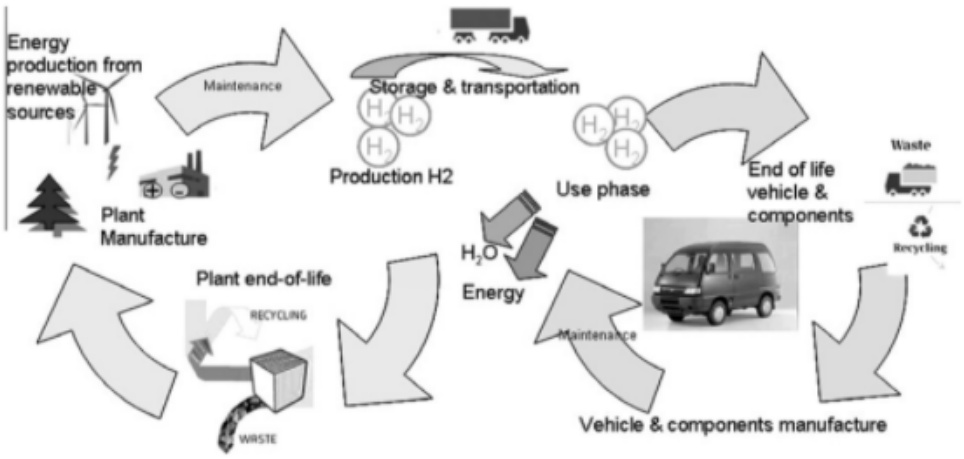

Fig. 30: General scheme of the investigated scenarios, Bartolozzi et al. (2012:106).

The lice cycle of products are very important as already shared in order to know the overall environmental impacts that are caused and can also facilitate TCO calculations. Bartolozzi et al. (2012:104) help to understand "the various processes within the life cycle phases; extraction of raw material, fuel production, transportation, manufacture, use, maintenance and end of life of plants. According to ISO 14040, the function unit describes the quantified performance of a product system for us as a reference in a LCA".

- **H2 and Electricity Production Processes**

Bartolozzi et al. (2012:105) shares that three renewable energy H2 production chains were considered:

- "H2 from electrolysis supplied by wind electricity (H2_WE): A local wind farm containing 4 turbines of 2MW each produced electricity. H2 was produced thereafter by coupling the wind turbine with an electrolyser with an output of 60 Nm3 H2/h, as described in Table 12", Bartolozzi et al. (2012:105).

Table 12: Characteristics of the electrolyzer, Bartolozzi et al. (2012:106).

Parameter	Unit	Value
Electricity	kW h/kg GH_2	62
Water required	L/kg GH_2	10
Storage pressure	bar	440
Production capacity	kg GH_2/yr	47250
Lifetime	yr	15
Area occupied	m^2	300
Output	60 Nm^3 H_2/h at 15 bar or 5394 kg/h which amounts to 180 kW/h	

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- “H2 from electrolysis supplied by biomass gasification (H2_BE): Short rotation forestry (SRF) is a vocation in the region of Tuscany. Biomass is gasified in a small gasification plant (1 MW/h), to provide electricity, as shared in table 13. As described before, H2 was produced by coupling the electrolyser”, Bartolozzi et al. (2012:105).

Table 13: Production of electricity from combustion of biomass gasification syngas, Bartolozzi et al. (2012:106).

Inputs	Quantity	Units
Biomass Poplar SRF (20% moisture)	40	kg/h
Water to scrubber	2390	kg
Electricity,	0.79	kW
Sodium hydroxide	0.041	kg
Outputs	**Quantity**	**Units**
Electricity	40	kW h
Water	16.2	kg/h
Air emissions		
O_2	20.1	kg/h
CO_2	55.8	kg/h
CO	1.21E−05	kg/h
N_2	215	kg/h
NO	5.87E−02	kg/h
SO_2	1.50E−03	kg/h
HCl	1.96E−04	kg/h
Solid waste		
Waste water (syngas purification)	2400	kg/h
Condensed water	11	kg/h
Ash	0.91	kg/h

- H2 from direct separation in the biomass gasification process (H2_BS): Here H2 is directly separated from the syngas manufactured in the biomass gasification process. The relevant information is reported in table 14 below.

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Table 14: H2 production from direct separation from biomass combustion syngas, Bartolozzi et al. (2012:106).

Inputs	Quantity	Units
Biomass Poplar SRF (20% moisture)	40	kg/h
Steam, for gasification (2 bar)	25	kg/h
Steam WGS (2 bar)	19.8	kg/h
O_2 (95%)	20	kg/h
Water to scrubber	2670	kg/h
Electricity	8.3	kW
Sodium hydroxide	0.05	kg
Outputs (120 °C)	**Quantity**	**Units**
H_2 (1.5 bar)	2.4	kg/h
Air emissions		
Water	5.43	kg/h
O_2	6.59	kg/h
CO_2	55.2	kg/h
CO	1.2E−05	kg/h
N_2	46.5	kg/h
NO	1.56E−02	kg/h
SO_2	1.44E−03	kg/h
HCl	1.93E−04	kg/h
Solid waste		
Waste water (syngas purification)	2710	kg/h
Condensed water	11	kg/h
Ash	1	kg/h

"Electrolysis was used to produce H2 form non- renewable sources which was supplied by electricity from the Italian power grid (benchmarking scenario). Electricity for the benchmarking process was manufactured from the same renewable sources applied for the H2 production", Bartolozzi et al. (2012:105).

- **H2 Storage, Transportation and Distribution**

A key item for the implementation for H2 powered vehicles, these topics cover some of the points related to needed infrastructure. Bartolozzi et al. (2012:105) shares that "H2 was compressed and stored in steel tanks at 200 bar, with an electricity requirement for gas compression of 8 kW h/kg CH2. Tanks were transported by truck to the H2 filling station. The network for the electricity distribution was excluded from the system boundaries".

- **Vehicle and Components**

As per table 15, the FCs and its components were described according to the prototype developed for this project. Bartolozzi et al. (2012:105) explains that "the vehicle was equipped with two H2 tanks at 35 MPa and with either FC ICE. In use phase, the fuel cell vehicle consumes 8.7 g/km of H2, with 78 g/km of vapour emission. The battery of the vehicle was 300 kg and 0.114 kWh/kg capacity with an electricity consumption of 17 kWh/km during the use phase".

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Table 15: Inventory data of the FC components of the prototype, Bartolozzi et al. (2012:107).

Components	Materials/energy	Quantity (kg)	Origin
Fuel cell stack	Graphite	14	Italy
	PTFE polymer	8	Italy
	Platinum (catalyzer)	0.006	Italy
	Steel, low-alloyed	29	Italy
	Chromium steel 18/8	7	Italy
	Electronic components	2	Italy
	Electricity, assembly (kW h)	40	Italy
Tank H_2	Aluminium alloy	10	Canada
	Glass fibre	18	Canada
	Steel, low-alloyed	2	Canada
	Electricity, assembly (kW h)	40	Italy
Battery	PEO polymer	37	Korea
	Electronic components	2	Italy
	Steel, low-alloyed	4	Italy
	Copper	1	Italy
	Electricity, assembly (kW h)	40	Italy
Electric machine	Ferrite	29.8	India
	Copper	4.6	Italy
	Permanent magnets	1.76	China
	Insulation material	0.3	Italy
	Steel Fe510	28.2	Italy
	Electricity, assembly (kW h)	40	Italy
Converters	Copper	2	Italy
	Insulation material	0.2	Italy
	Silica	0.5	Italy
	Ferrite	5	India
H_2 circuits integrated	Chromium steel 18/8	15	USA/ Italy

Seven scenarios were investigated with the data collected during the inventory phase by Bartolozzi et al. (2012:106):

- “H2 produced by electrolysis supplied with wind electricity (FC_WE).
- H2 produced by electrolysis supplied with biomass gasification electricity (FC_BE).
- H2 produced by direct separation in biomass gasification (ICE_BS).
- H2 produced from Italian electricity mix (benchmarking alternative) (FC_IT)”.

The benchmarking analysis with EVs was carried out with the following scenarios and presented by Bartolozzi et al. (2012:106):

- “Electric Porter with wind electricity (BEV_W)
- Electric Porter with electricity from biomass gasification (BEV_B)
- Electric Porter with electricity from Italian electricity mix (BEV_IT)”
- Life cycle impact assessment”.

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In this section the most important points relations to the LCA assessment are highlighted with context provided to this case study. In table 16, the environmental flows of the seven scenarios with ten midpoint impact categories are shor. “The environmental impacts of each scenario are referred to the functional unit of 200 km”, Bartolozzi et al. (2012:106-107).

Table 16: Impact assessment results of the 7 analysed scenarios, Bartolozzi et al. (2012:107).

Impact category	Units	BEV_B	BEV_W	BEV_IT	FC_BE	FC_WE	FC _IT	ICE_BS
Abiotic depletion	kg Sb eq	0.17	0.19	0.27	0.36	0.23	0.67	0.38
Acidification	kg SO_2 eq	0.19	0.16	0.21	0.42	0.19	0.49	0.25
Eutrophication	kg PO_4^{3} eq	0.10	0.09	0.10	0.12	0057	0.12	0.08
Global warming (GWP100)	kg CO_2 eq	22.07	24.24	35.65	53.32	33.77	96.38	50.6
Ozone layer depletion (ODP)	kg CFC-11 eq	1.78 E−05	1.84 E−05	1.86 E−05	1.38 E−04	1.35 E−04	1.40 E−04	2.04 E−05
Human toxicity	kg 1,4-DB eq	68.66	66.62	69.79	53.71	41.54	57.28	40.85
Fresh water aquatic ecotoxicity	kg 1,4-DB eq	23.24	21.90	24.13	20.89	14.63	23.69	13.09
Marine aquatic ecotoxicity	kg 1,4-DB eq	56382.3	53214.7	58685.3	43554.7	29006.2	50859.2	28719.2
Terrestrial ecotoxicity	kg 1,4-DB eq	0.22	0.22	0.29	0.26	0.19	0.47	0.26
Photochemical oxidation	kg C2H4 eq	−0014	0008	0010	−0056	0009	0021	0006

Bartolozzi et al. (2012:107) further explains the findings to share that “the FC_BE scenario that includes biomass gasification and electricity production has a large impact on most of the categories. For example, eutrophication (0.12 kg PO3 4 equivalent), GWP (53.3 kg CO2 equivalent) and acidification (0.42 kg PO3 4 equivalent)”, Bartolozzi et al. (2012:107). “On the other hand, FC_WE has the lowest impacts for eutrophication (0.057 kg PO3 4 equivalent), GWP (33.7 kg CO2 eq) and acidification (0.19 kg SO2 equivalent)”, Bartolozzi et al. (2012:107) . “In the BEV_IT scenario larger impacts are visible compared to the renewable energy scenarios”, Bartolozzi et al. (2012:107). In Fig. 31, below the results of the LCA of all the 7 categories are presented.

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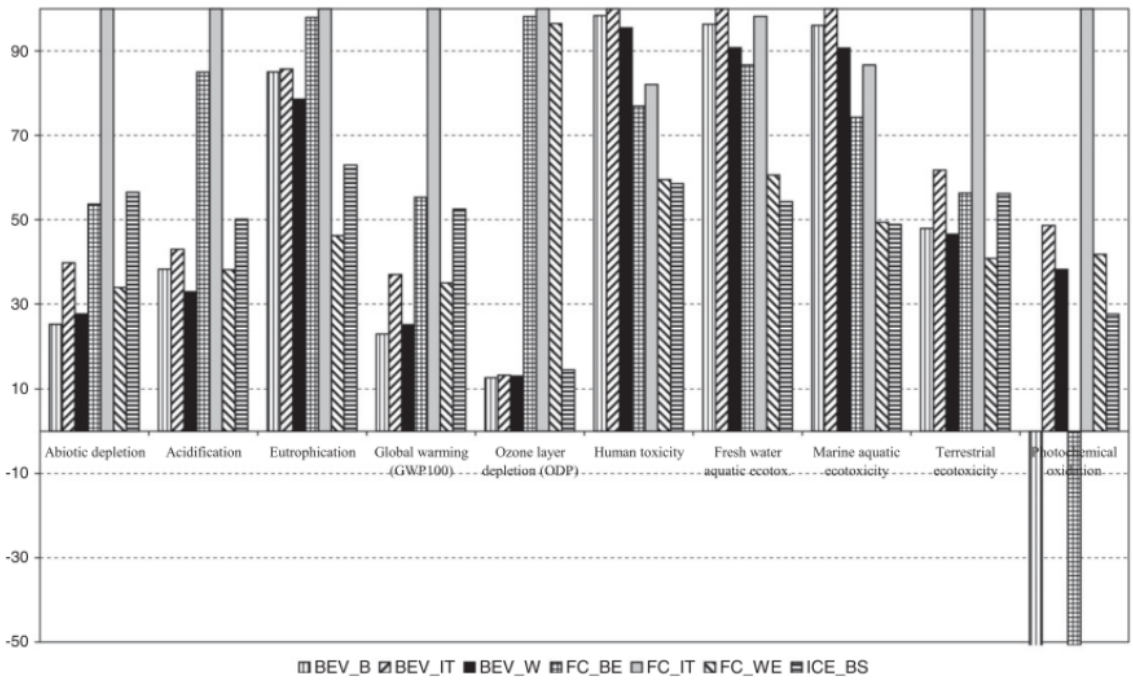

Fig. 31: Life cycle impact assessment results for the 7 analysed scenarios, Bartolozzi et al. (2012:108).

8.4. Valencia, Spain

Valencia is a city in Spain located on the Mediterranean coast. The population in 2018 amounted to just about 800,000 inhabitants and is the third most populated city in Spain. Salazar et al. (2020:4) in his study shares that "in 2018, there are 43 HEB and 2 BEVs in the bus fleet in Valencia. Compared to other Spanish cities (see Table 17), Valencia is clearly behind. So there is room for improvement in Valencia regarding HEB buses even though they currently have around 8.7%, but compared to the large share (75.4%) of diesel buses, there is clearly room for improvement".

Table 17: Bus fleet composition (number and %) in major cities in Spain (Year, 2018), Salazar et al. (2020:4).

	Diesel	CNG	Hybrid	Full Electric	Total
Madrid	981	930	53	18	1982
	49,50%	46,92%	2,67%	0,91%	100,00%
Valencia	372	75	43	2	493
	75,46%	15,21%	8,72%	0,41%	100,00%
Seville	179	230	1	0	410
	44,63%	55,13%	0,24%	0,00%	100,00%
Barcelona	447	365	309	2	1123
	39,80%	32,50%	27,52%	0,18%	100,00%

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Salazar et al. (2020:4) explains that the data for this study that is analysed comes from "survey questionnaires shared to college students from Valencia. This group of dataset is a main user of public transport in Valencia and the use of convenience surveys can help preliminary testing of future generation public acceptance of eco-friendly public transport modes". The survey was done on the internet via google forms, which is a good tool to finally download the responses on the survey into a consolidated spreadsheet. "The sample included 427 students from various backgrounds, in 2017-2018. As shown in Table 18, the respondents had to choose their answers from; completely disagree (1) to completely agree (5). The information gathered helped to use LCA to classify the respondents 3 different classes (low, medium or high level of engagement)".

Table 18: Statements for measuring environmental concern used in the Latent Class model, Salazar et al. (2020:5).

Variable	Description of the statement (From 0 = completely disagree to 5 = fully agree)
FUT_GEN	I am afraid when I think about environmental conditions for future generations
RESPONSIBLE	The great majority of people do not act in an environmentally responsible way
CATASTROPHE	If we continue our current style of living, we are approaching an environmental catastrophe
GROWTH_LIM	There are limits of economic growth which the industrialized countries have already reached or will reach very soon
ECOL_EXAGER	In my opinion, environmental problems are greatly exaggerated by proponents of the environmental movement
POLITICIANS	It is still true that politicians do much too little to protect the environment
STANDARD_LIV	To protect the environment, we all should be willing to reduce our current standard of living
LOOSE_JOBS	Environmental protection measures should be carried out, even if this reduces the number of jobs in the economy
CLIMATE_REAL	Climate change is already a reality as average temperatures have increased and climate catastrophes are becoming more common
NEWS	When I watch TV or read news about environmental issues, I sometimes feel ashamed and even angry
HEALTH_RISK	With regard to the consequences for human health of air pollution in the city of Valencia, do you think that there is a high risk for your health?
ENVIRONMENT	Importance they give to the conservation and protection of the environment

The questionnaire included 3 sections and Salazar et al. (2020:4) summarised them below:

- "First section- included attitudinal questions aimed to find out the respondents' environmental awareness. The questionnaire asked for information on the respondent's perception on recycling habits, main mode of transport used, air quality in the city, human health and pro-environmental behavior", Salazar et al. (2020:4).
- "Second section- described the policy changes that would be needed to improve air quality through the gradual introduction of HEB. In specific, respondents were asked if they were willing to pay more for this technology. The acquiring cost would be around 40 and 70% more costly than conventional buses", Salazar et al. (2020:4).
- "Third section- focus was put on the socio-econmoinc questions such as age, sex, degree of study, family size, household,personal income etc", Salazar et al. (2020:4).

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- **Latent Class Analysis**

Salazar et al. (2020:2) shares that for the latent class analysis to further break down and analyze the responses “the three latest classes model was selected. In table 19 and its plot in Fig. 32, each response to the twelve questions about environmental concern were described in 3 cases. The average membership probability of class 1, class 2 and class 3 were 32%, 50% and 18%, respectively”.

Table 19: Three-class solution: cluster size and conditional probabilities, Salazar et al. (2020:6).

	Class 1 Highly env. concerned	Class 2 Medium env. concerned	Class 3 Low env. concerned
Cluster Size	0,3222	0,5006	0,1772
Statements			
FUT_GENERAT			
1 strongly disagree	0	0,0004	0,0406
2	0,0001	0,0067	0,1341
3	0,0048	0,0895	0,3654
4	0,1477	0,4595	0,384
5 strongly agree	0,8474	0,4439	0,0759
RESPONSIBLE			
1 strongly disagree	0	0	0
2	0,0061	0,0143	0,046
3	0,0743	0,1223	0,2302
4	0,3189	0,3706	0,4074
5 strongly agree	0,6007	0,4928	0,3163
CATASTROPHE			
1 strongly disagree	0	0,0013	0,0799
2	0	0,0094	0,1405
3	0,0012	0,086	0,3122
4	0,0648	0,4077	0,3606
5 strongly agree	0,934	0,4956	0,1068
GROWTH_LIM			
1 strongly disagree	0,002	0,0389	0,1094
2	0,0117	0,0881	0,1617
3	0,095	0,2758	0,3301
4	0,3124	0,3487	0,2722
5 strongly agree	0,579	0,2485	0,1265
ECOL_EXAGER			
1 strongly disagree	0,7176	0,3008	0,1307
2	0,2584	0,4568	0,3714
3	0,0216	0,1609	0,2448
4	0,0023	0,0729	0,2077
5 strongly agree	0,0001	0,0085	0,0454
POLITICIANS			
1 strongly disagree	0,0041	0,0357	0,0587
2	0,0066	0,0302	0,0421
3	0,0473	0,114	0,1354
4	0,3097	0,3946	0,3984
5 strongly agree	0,6324	0,4255	0,3654
STANDARD_LIV			
1 strongly disagree	0,003	0,0306	0,0891
2	0,039	0,1803	0,3254
3	0,1092	0,2323	0,2601
4	0,331	0,3239	0,225
5 strongly agree	0,5178	0,2329	0,1004
LOOSE_JOBS			
1 strongly disagree	0,0047	0,0333	0,1482
2	0,0507	0,1678	0,3394
3	0,2556	0,3969	0,3648
4	0,4298	0,3133	0,1308
5 strongly agree	0,2592	0,0887	0,0168
CLIMATE_REAL			
1 strongly disagree	0	0,0022	0,0216
2	0,0003	0,0091	0,0434
3	0,0103	0,0913	0,2111
4	0,1771	0,4092	0,4586
5 strongly agree	0,8123	0,4882	0,2652
NEWS			
1 strongly disagree	0	0,0003	0,0826
2	0,0001	0,0102	0,2775
3	0,0109	0,1481	0,4535
4	0,2088	0,5046	0,1734
5 strongly agree	0,7801	0,3368	0,013
HEALTH_RISK			
1 strongly disagree	0,0028	0,0061	0,0475
2	0,0606	0,1001	0,3176
3	0,2373	0,2953	0,3785
4	0,4531	0,4247	0,2199
5 strongly agree	0,2462	0,1739	0,0364
ENVIRONMENT			
1 not all important	0	0	0
2	0	0,0011	0,0387
3	0,0018	0,0408	0,2853
4	0,1011	0,3815	0,5217
5 extremely important	0,897	0,5766	0,1542

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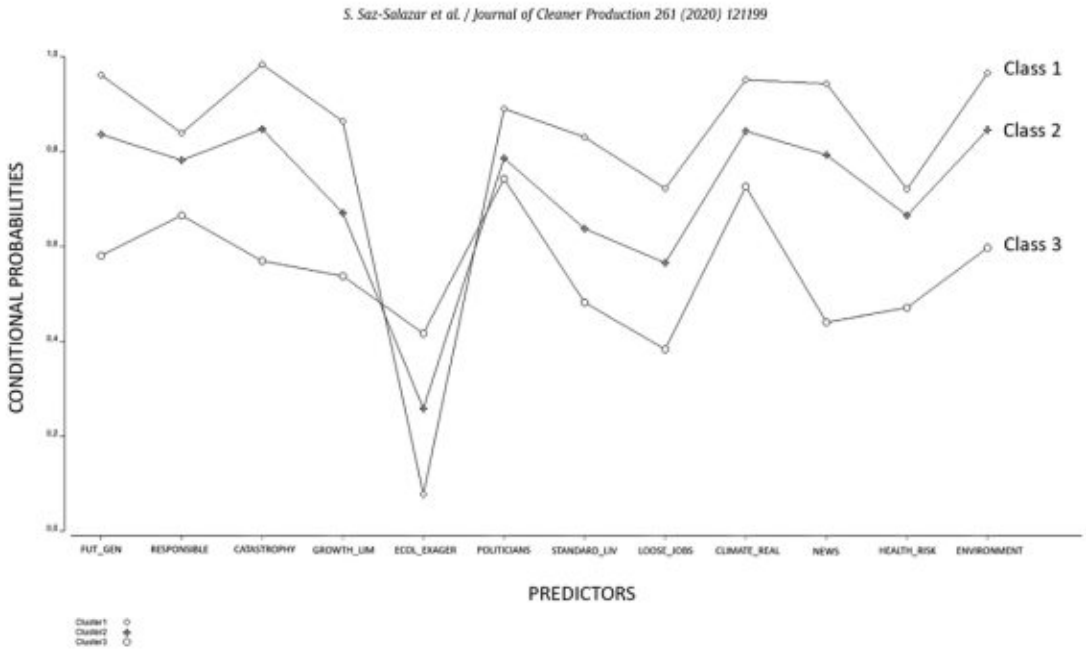

Fig. 32: Class conditional outcome probabilities for the 3-class model, Salazar et al. (2020:7).

Salazar et al. (2020:5) explains that “class 1 was named as the highly environmentally concerned class. Out of the 89% respondents who responded to the importance given to the protection of the environment, 81% answered as strongly agree, and believe that climate change is a reality. 93% of the respondents also strongly agree that if we do not change our current style of living, we will have environmental catastrophe”. “Class 2 was named as medium environmentally concerned. For the protection of the environment, 57% responded as very important. For the class 3, this was named as the low environmentally concerned class, and only 15% of the respondents answered that the protection of the environment is very important”, Salazar et al. (2020:5).

- **Contingent Valuation**

Within the questionnaire, respondents were asked to answer if they are willing to pay extra cost per single bus fare to support the further implementation of HEB in Valencia. Those who answered yes, were asked how much as an open ended question. Salazar et al. (2020:7) shares table 20 to show the statistics summary for the estimated WTP by class. Salazar et al. (2020:8) presents the results and shares that “the respondents willing to pay more depends on the class type that they are in and in class 3 the lowest number of people are willing to pay more. Surprisingly class 2 (76%) of the respondents are willing to pay more than the class 1 respondents (65.4%). The resulting hypothetical increase would be between 17% to 22%”.

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Table 20: Mean WTP extra per single bus fare by class, Salazar et al. (2020:7).

	All	Class 1	Class 2	Class 3
% respondents WTP>0	67.5	65.4	76.2	51.9
% protest responses	25.0	24.4	21.9	32.1
Mean WTP (€) excluding protest responses and outliers. Stand. Dev. in parenthesis	0.33 (0.29)	0.32 (0.30)	0.38 (0.30)	0.25 (0.26)
Hypothetical increase in single bus fare (%)	22	21	25	17

Note: the current price of a single bus fare is €1.50.

8.5. Porto, Portugal

Frey et al. (2007:282) in their study to assess differences between diesel and H2 and FCEBs show a very good analysis to depict key factors for FCEBs in the market for Portugal. Frey et al. (2007:282) "assess at a micro scale the fuel consumption for diesel buses in the United States of America (US) and Portugal vs. H2 FCEBs operate on the same routes, and estimated changes in emissions by substituting to H2 fueled buses are assessed. The findings of the research is to compare the H2 FCEB in Porto vs. the diesel bus in Porto and US, hence the case study is prioritised for H2 buses in Porto, Portugal".

- **Database for Case Study**

- **Ann Arbor Transportation Authority A database (US)**

The environmental protection agency in 2002 reported on board data for diesel transit buses in Ann Arbor using PEMS on 12 diesel transit buses. Frey et al. (2007:283) shares additionally "the tested buses were equipped with Detroit Diesel Series 50 engines and all buses weighed 12 tonnes and had a 8.5 litre engine. Sensors Inc. produced the SEMTECH-D which was used as the PEMS, which includes an engine scanner for measuring data from the buses' electronic control module (ECM)". "A GPS for recording vehicle position and altitude, exhaust probe and sample hose, gas analysers for measuring pollutant concentrations in the exhaust, weather probe and a computer for combining these data streams into one file and estimating emission routes on a mass per time basis", Frey et al. (2007:283). "Real time volumetric fuel consumption rate data converted into mass flow rate is provided by the ECM. The fuel based pollutant emission rates can be estimated from the exhaust concentration data", Frey et al. (2007:283).

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- **Porto Database**

Along with the above data from the US, it was important to also use a diesel source from Porto, first off to show the differences or similarities between the diesel options of US and Porto vs. the FCEB option in Porto. Frey et al. (2007:283) mention that “for both diesel and FCEBs, the tested bus routes in Porto have substantial road grades (up to 10%) and low average speed”. The add that, “the route is entirely urban and has a length of 7.8km, it is circular without any terminal stop. The data was collected from one bus line of the Sociedade de Transportes Colectivos do Porto (STCP) network. One FCEB and one diesel bus travelled on this route in the same direction for 1 day from around 6.30 a.m. to 6.00 p.m”. Frey et al. (2007:283) explains that “the Porto diesel bus was tested in 2004, weighing 11.5 tonnes. A 2002 Mercedes Citaro with a 12L engine, with 14 measured trips. Secondly data was collected via a fuel flow meter, a data acquisition board, a command display unit and a laptop. Vehicle dynamics including fuel consumption and speed were recorded and passenger counts were made manually”.

As mentioned the FCEB bus was the major change for a city like Porto to assess versus diesel options. Frey et al. (2007:283) shares that “the testes Porto FCE bus weighed 14 tonnes and was a small series Mercedes Citaro. With a combined power of 300 kW, two FC stacks were fed from 350 bar compressed H2 storage. A conventional gearbox was driven by a 200 kW electric engine”. “The minimum power output of the FCs was approximately 25 kW. The bus used was a pure FCEB and not a hybrid. Eleven measured trips were taken and for each trip; fuel consumption rate, vehicle speed and controller area network (CAN) motor RPM were recorded twice per second”, Frey et al. (2007:283). Frey et al. (2007:283) further explains this study by mentioning that, “each bus was divided into a calibration and validation database. The calibration database was used to develop the vehicle specific power (VSP) based modal fuel consumption models. The models were applied to the activity data of the validation datasets to predict fuel consumption”. “To make the comparison, for the AATA diesel database, eight buses were selected for the calibration database and four buses for the validation database. For the Porto diesel bus, nine trips were selected for the calibration database and five trips for the validation database. For the Porto FCEB, eight trips were selected for the calibration database and three trips were selected for the validation database”, . Frey et al. (2007:283)

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- **Concept for Study**

Passenger load on transit vehicles and various other trip based factors can affect the amount of fuel that is consumed during the operation in a real life duty cycle. Frey et al. (2007:284) shares an important concept about is, “VSP that is defined as power per unit mass of the vehicle and is a function of vehicle acceleration, speed and road grade. The VSP for transit buses is estimated based on the typical coefficient values that represent the types of buses that analysed in this study, see below eq. 7”:

$$\mathrm{VSP} = v \times (a + g \times \sin(\varphi) + 0.092) + 0.00021 \times v^3$$

Eq. 7: Calculation of VSP, Frey et al. (2007:284).

“where VSP (m2/s3); v is speed at which the vehicle travels (m/s); a is acceleration of the vehicle (m/s2); u is road grade (decimal fraction); 0.092 is rolling resistance term coefficient; and 0.00021 is the drag term coefficient”, Frey et al. (2007:284). In table 21, Frey et al. (2007:284) show the definition of VSP modes. “When determining the number of VSP modes, 2 considerations were used: (i) each mode should produce an average fuel consumption rate which is numerically different from any other mode, and (ii) no single mode should dominate the estimate of fuel consumption”. Frey et al. (2007:285) shares that, “variability and magnitude in average fuel consumption between the Poro and AATA diesel buses, and between the Porto diesel and H2 FCEB are compared. To compare fuel consumption between diesel and H2, the diesel fuel consumption was converted to an H2 equivalent basis. To do this,a lower heating value of 120 MJ/kg for H2 and 35.7 MJ/l for diesel is used”.

Table 21: Definition of VSP modes, Frey et al. (2007:284).

VSP mode	VSP range (m^2/s^3)	VSP mode	VSP range (m^2/s^3)
1	$\mathrm{VSP} \leqslant 0$	5	$6 \leqslant \mathrm{VSP} < 8$
2	$0 < \mathrm{VSP} < 2$	6	$8 \leqslant \mathrm{VSP} < 10$
3	$2 \leqslant \mathrm{VSP} < 4$	7	$10 \leqslant \mathrm{VSP} < 13$
4	$4 \leqslant \mathrm{VSP} < 6$	8	$\mathrm{VSP} \geqslant 13$

- **Exploratory Analysis**

Frey et al. (2007:285) share table 22 which is the “Spearman correlation coefficients for fuel consumption rate and selected explanatory factors for the tested vehicles. All correlation coefficients are numerically significant due to all p values being less than 0.05. For both diesel and H2 FCBs, the acceleration and speed is highly correlated”. In Fig. 33 Frey et al. (2007:285) shows the “effects of the on- board passenger load, where at the middle and high speed ranges, the passenger load has a significant impact on the fuel consumption, and during low speed or idling there is almost no effect”.

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Table 22: Rank correlation, fuel consumption rates vs. factors based on trip database, Frey et al. (2007:285).

Data source	Fuel type	Speed	Acceleration	Road grade
AATA	Diesel	0.59	0.66	0.11
Porto	Diesel	0.79	0.32	0.10
	Hydrogen	0.49	0.40	0.21

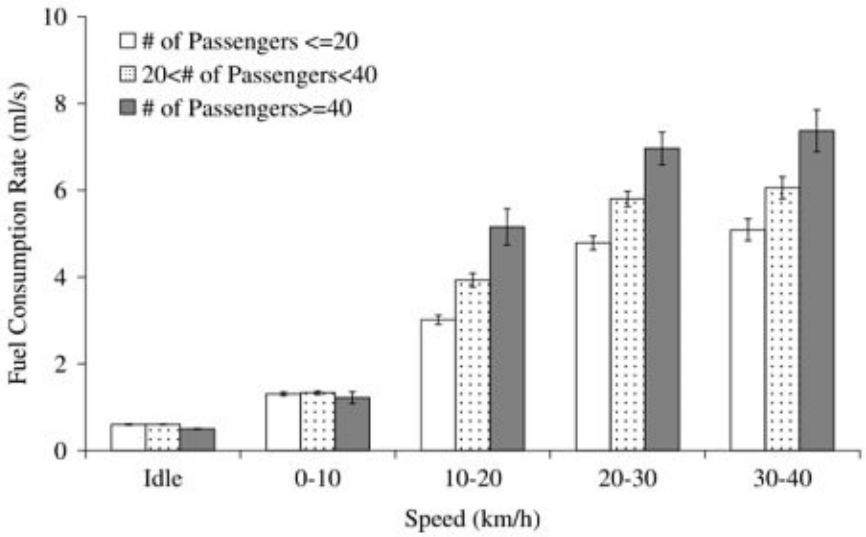

Fig. 33: Effect of on-board passenger load on mean fuel consumption rate, with 95% confidence intervals for Porto diesel bus, Frey et al. (2007:286).

- **Fuel consumption modeling results using VSP approach**

In the above eq. 5, real life speed profiles including vehicle acceleration were combined with road grade data from the vehicle to estimate second by second VSP. Frey et al. (2007:286) explains that, “in Fig. 34 and 35, the average fuel consumption rates are similar when the VSP values are less than zero. But a monotonic increase in fuel consumption is noted for both FCEBs and diesel”.

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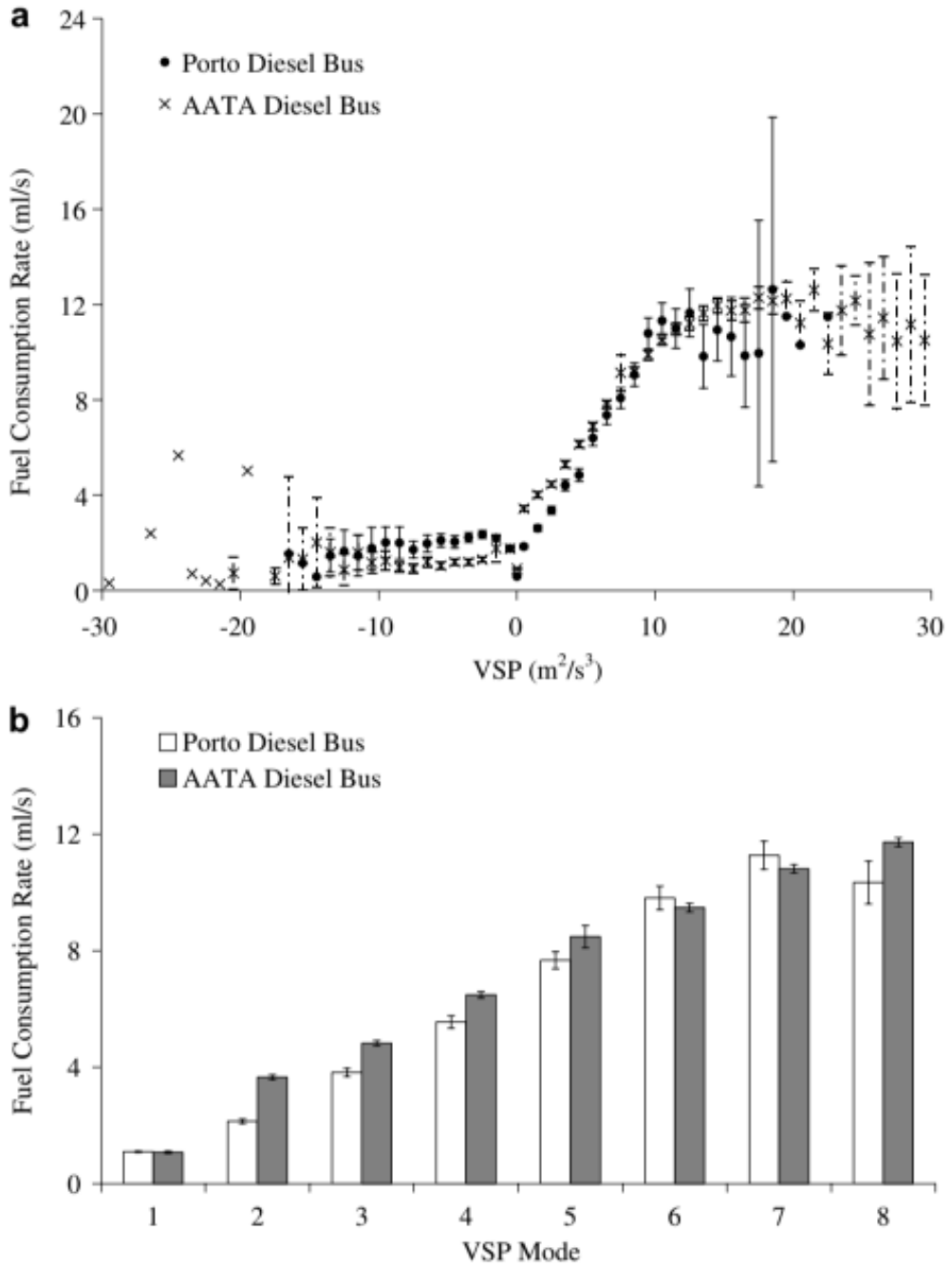

Fig. 34: Fuel consumption rate by VSP mode for Ann Arbor and Porto diesel buses: (a) diesel buses VSP and average fuel consumption, with 95% confidence intervals and (b) VSP modal average fuel consumption rate, with 95% confidence intervals, for diesel buses, Frey et al. (2007:287).

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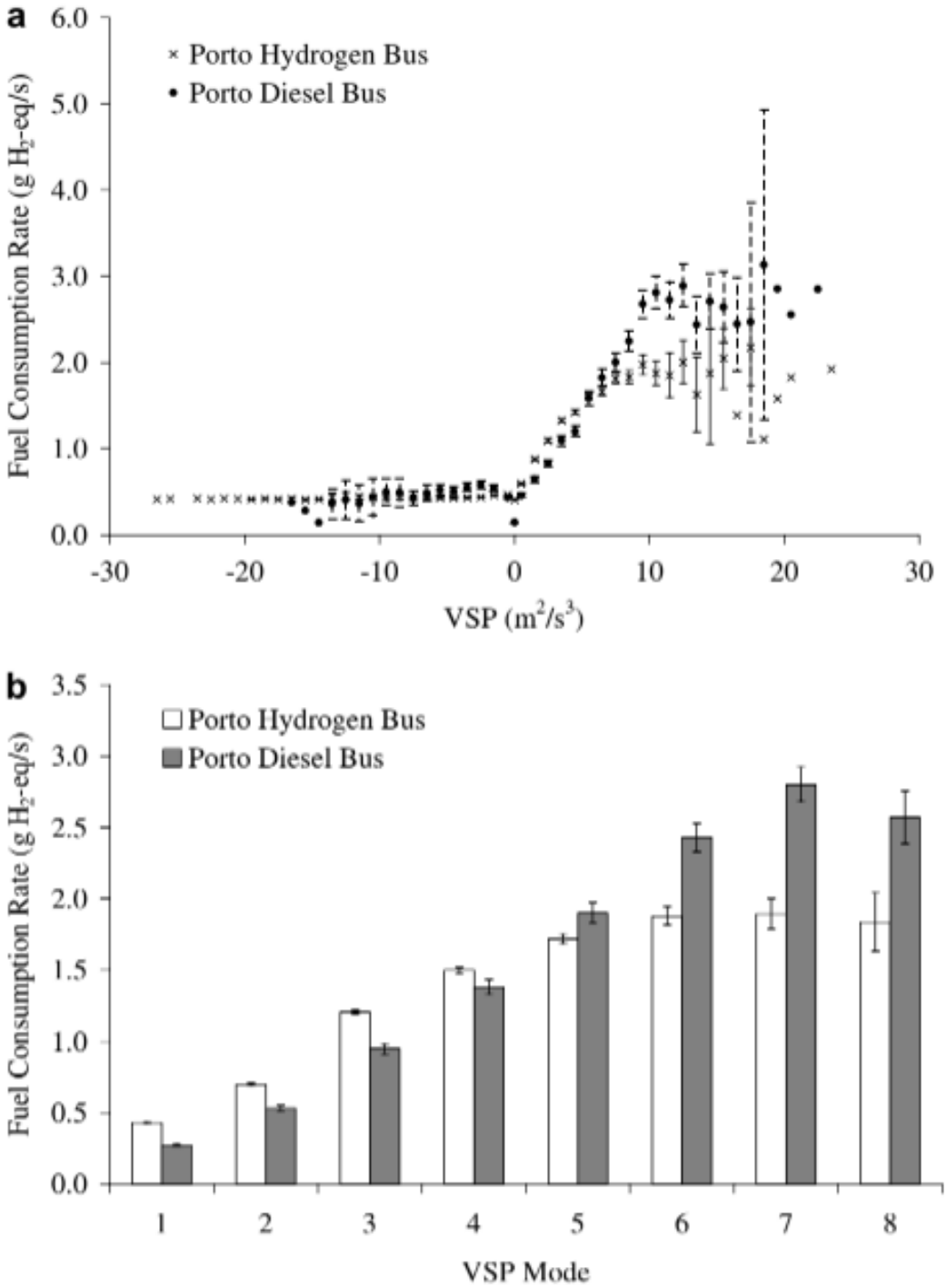

Fig. 35: Fuel consumption rate by VSP mode for Porto diesel and H2 FCEBs: (a) VSP and average fuel consumption, with 95% confidence intervals and (b) VSP modal average fuel consumption rate, with 95% confidence intervals, for Porto buses, Frey et al. (2007:288).

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“For the 2 FCEB, the VSP modal average fuel consumption rates are statistically indistinguishable for modes 6 and higher. The VSP approach is able to show a substantial portion of short term variability in fuel consumption. The ratio of the highest to lowest mean value among the modes is 10.8, 10.3 and 4.4, for AATA diesel buses, the Porto diesel bus, and the Porto FCEB”,Frey et al. (2007:287-288). Total trip fuel consumption was estimated based on the time spent in each of the VSP modes. In table 23, the prediction errors between predicted and measured total trip fuel consumption are summarised. “For AATA diesel buses, the errors range from 9.5% to 10.6%. For the Porto diesel bus, the errors range from 8.7% to 9.0%, whereas for the H2 FCEB, the errors range from 0.8% to 2.6%”, Frey et al. (2007:287). The low rate of errors of the 2 FCEB buses can be classified as a unique selling point as per this study. Frey et al. (2007:288) further shows in Fig. 36, “higher passenger loads result in higher fuel consumption (except for modes 1 and 2). The total trip fuel consumption was estimated on the passenger load mode and the fraction of time spent in each VSP”.

Table 23: Summary of trip fuel consumption prediction errors for the validation data sets, Frey et al. (2007:289).

Data source	Fuel type (units)	Trip code	Measured trip fuel consumption	Fuel consumption prediction error	
				VSP approach (%)	VSP and passenger load approach (%)
AATA	Diesel (l)	1	13.09	0.8	N/A
		5	26.05	10.6	N/A
		8	31.19	−9.5	N/A
		14	19.37	3.4	N/A
Porto	Diesel (l)	3	3.96	9.0	0.6
		6	5.45	−7.3	0.3
		9	5.82	−8.7	−6.4
		12	5.85	−2.3	4.4
		14	4.67	2.2	0.04
	Hydrogen (kg)	3	1.89	−0.8	N/A
		6	1.66	2.6	N/A
		9	1.86	−0.8	N/A

Note: “–” represents underestimate and “N/A” represents no data available.

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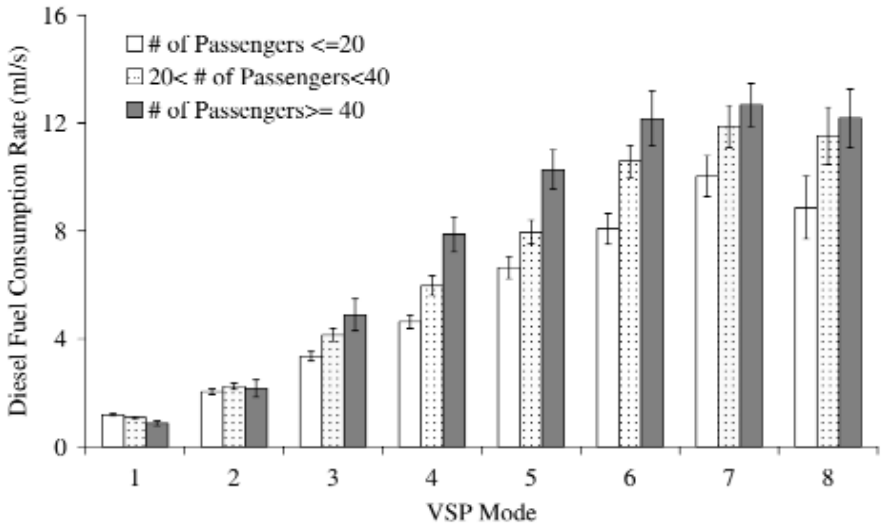

Fig. 36: VSP and passenger load modal average fuel consumption with 95% confidence intervals for the Porto diesel bus, Frey et al. (2007:289).

To summarise this study, Frey et al. (2007:290) finds that "as shown in table 23, the trip prediction errors range from 4.4% to 6.4%, which are consistently lower than the range of errors obtained by the VSP only approach (upto 9%). In Fig. 34 it can be seen that the AATA diesel bus and the Porto diesel bus show similar trends in relation to modal fuel consumption. The H2 bus fuel consumption rates are less sensitive to high VSP values". The larger size of the H2 buses, makes their fuel consumption higher as well and the purpose of the FCBs was to show system and component reliability rather than optimised efficiency on all areas.

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9. Results

The results of this research are presented in the below section where an overall result from the study is presented and thereafter the individual results of the case study are explained.

9.1. European Cities Case Studies Results

Within this section the below individually assessed results of the provided case study are summarised below:

- In Stockholm even though the respondents are willing to learn more about FC technology, they are not willing to pay a higher bus fare. This is the opposite in the case for Valencia, where the respondents are willing to pay a higher bus fare to see more implementation of FCBs. This result can be differentiated due to the age group of the respondents, where in Stockholm the average age was 40 and in Valencia the average age was 27 (college students).
- Feedback was only received from the bus drivers in Stockholm, which was very positive towards this technology, and then promoted the further use of it.
- The Rhine Main area shows the importance of having a H2 production source close to the final area of operational usage. In case, this region wishes to include more buses in the coming years, a significant upgrade of the current power plant will be needed. This is applicable to all regions, and a clear demand hike will need supply to match the needs.
- In the case study from Valencia, several short term and long terms scenarios are shown. In the short term (until 2030) it can be proved that the costs of battery EVs will be more competitive than FCVs in comparison to ICEVs.
- For Porto, it can be concluded that the fuel consumption of both the diesel buses (from US and Porto) is the same. However the fuel consumption for the H2 bus is higher than diesel which is a limitation.

A further review into the results of each case study is provided.

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- **Stockholm, Sweden**

Passenger Survey Results

Haraldsson et al. (2005:320) in Fig. 37, share the responses of the passengers to reflect their age distribution. The average age noticed is 46 years, however as it can be seen from the numbers, 140 (27%) of the passengers were 60 years or above and only 40 (8%) were under 20 years of age. This is a slight imbalance within the demographics, and furthermore, it can be seen that 63% of the passengers were women.

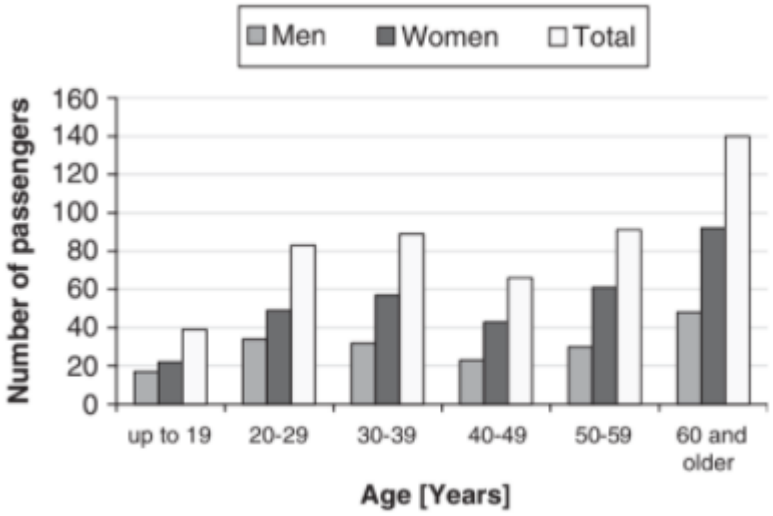

Fig. 37: The age distribution among the passengers responding to the survey, Haraldsson et al. (2005:320).

Haraldsson et al. (2005:320) share that, “77% of the respondents were aware of the CUTE FCEB project, with the newspapers (55%) and bus stops (26%) being the highest source of information as shown in Fig. 38”.

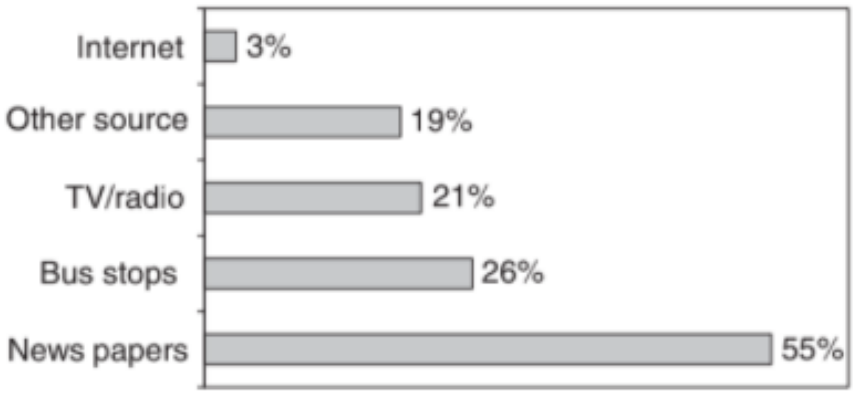

Fig. 38: Information sources on the FCEB project, Haraldsson et al. (2005:320).

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“Regarding the question of safety about H2 and fuel cell technology (refer Fig. 39), the majority (74%) of the passengers felt that the technology was safe (with a response of 5,6 or 7 in the questionnaire), and a small (3%) of passengers thought it was unsafe. 23% of the passengers indicated that they did not have any opinion”,Haraldsson et al. (2005:320).

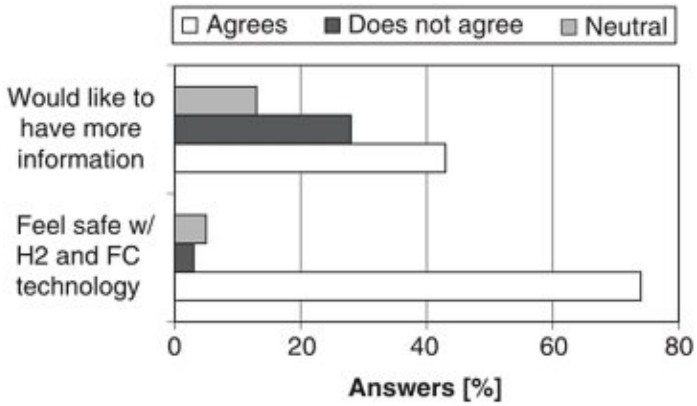

Fig. 39: Respondents’ attitudes towards information and safety of H2/ FCs technologies, Haraldsson et al. (2005:320).

In relation to the question about wanting to learn more about H2 and FC technology, Haraldsson et al. (2005:320) shapes Fig. 40 with the response. As visible, there is a strong correlation between age and wanting to learn more. The older groups of the passengers feel that they want to have more information whereas the younger generation did not feel the need to have as much information. This is opposite to what would have been normally anticipated for this question.

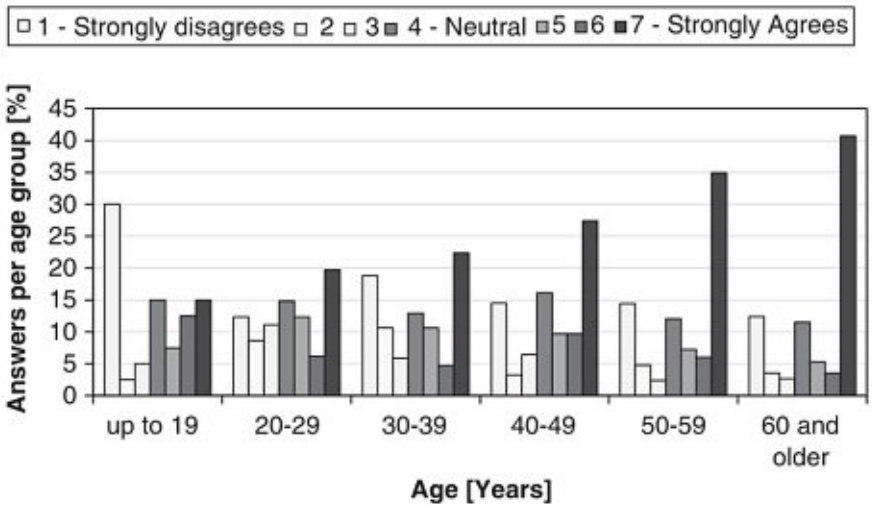

Fig. 40: The respondents’ attitudes about the need for more information, Haraldsson et al. (2005:321).

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In Fig. 41, Haraldsson et al. (2005:321) depicts the results of the question related to noise and comfort of the FCEBs in comparison to ICE buses. The results show that most passengers believed that the FCEBs were less noisy and more comfortable than conventional buses. Haraldsson et al. (2005:320) shares that “in relation to the noise question, many responded with a 7”. Also most people answer that the comfort is also better in FCEBs compared to conventional buses, however this answer is not as clear as the noise answer. Also important to note that passengers over 40 mainly answered that the FCEBs were more comfortable, and this is the same age group of passengers that wanted to learn more about the technology.

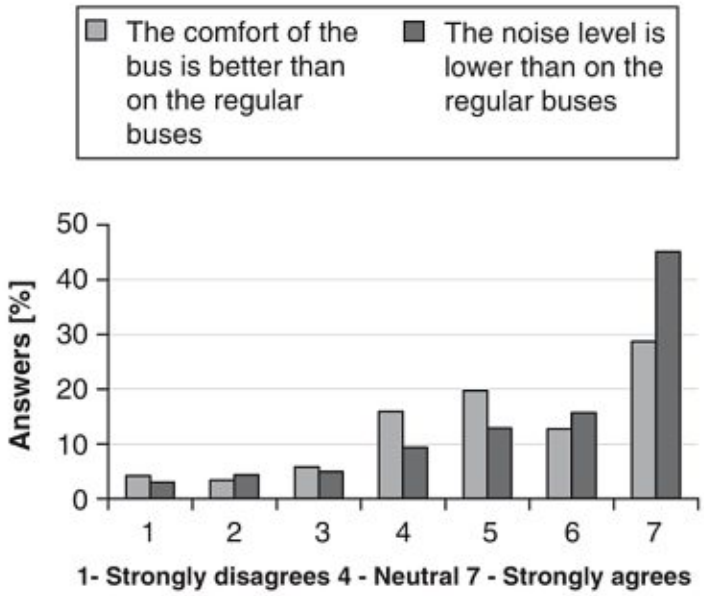

Fig. 41: The FCEB characteristics versus a conventional bus, Haraldsson et al. (2005:321).

A key question was to understand the willingness of the passengers to pay more if a higher number of FCEBs are introduced in Stockholm. See Fig. 42 and 43.

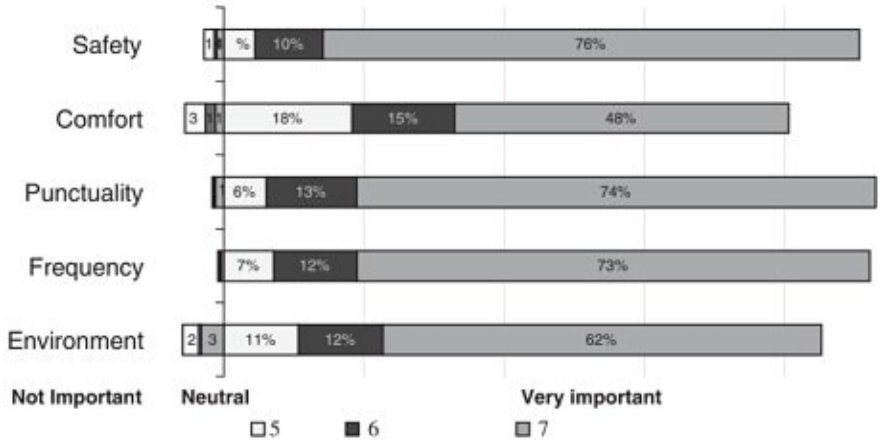

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Fig. 42: Key factors for the choice of public transportation means. Not important (1–3) to the left of the axis and important (5–7) to the right, Haraldsson et al. (2005:322).

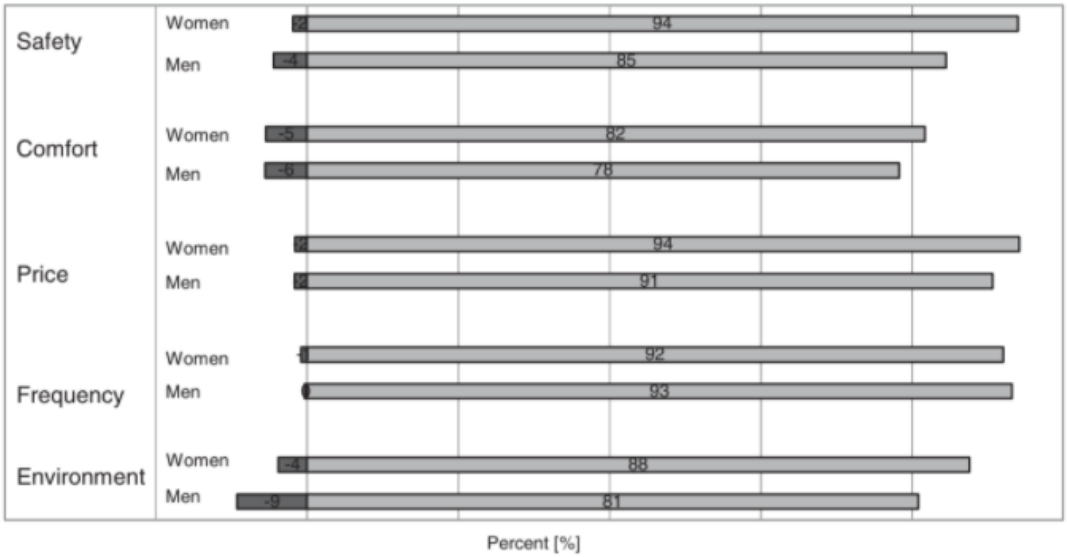

Fig. 43: The difference in gender concerning the importance of key factors in transportation, Haraldsson et al. (2005:322).

Haraldsson et al. (2005:322) explains that “as seen from Fig. 42, the passengers rate punctuality, safety and frequency as the most important facts in selecting the type of transport mode, comfort and environmental aspects are also rated as high but not to the same extent”. “The results also show that the female portion of the passengers seem to value safety more than men. In Fig. 44 the WTP more by passengers is shown, which displays very negative responses from passengers with a majority (64%) not willing to pay more”, Haraldsson et al. (2005:322).

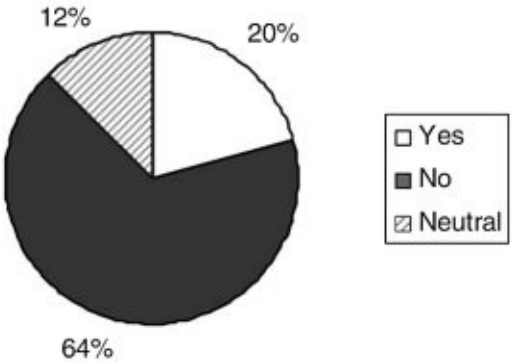

Fig. 44: WTP a higher fee to enable more FCEBs, Haraldsson et al. (2005:322).

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Bus Driver Survey Results

After we have reviewed the results of this study for the passengers, another key stakeholder group is the bus drivers who would play a massive role in the attitude shift to a H2 economy as the operators of FCBs. Haraldsson et al. (2005:323) share that “most of the drivers have positive results towards FCEBs, and majority (65%) were positive during the test period. In Fig. 45, the responses of the drivers are very positive; as they recognise FCEBs to be better than diesel buses in relation to emissions from the smell, exhaust and passenger comfort”. “The driving experience, general comfort and acceleration were reported as better or similar to diesel buses. One- third of the drivers felt that exhaustion of drivers from driving the FCEBs was higher than conventional buses”, Haraldsson et al. (2005:323).

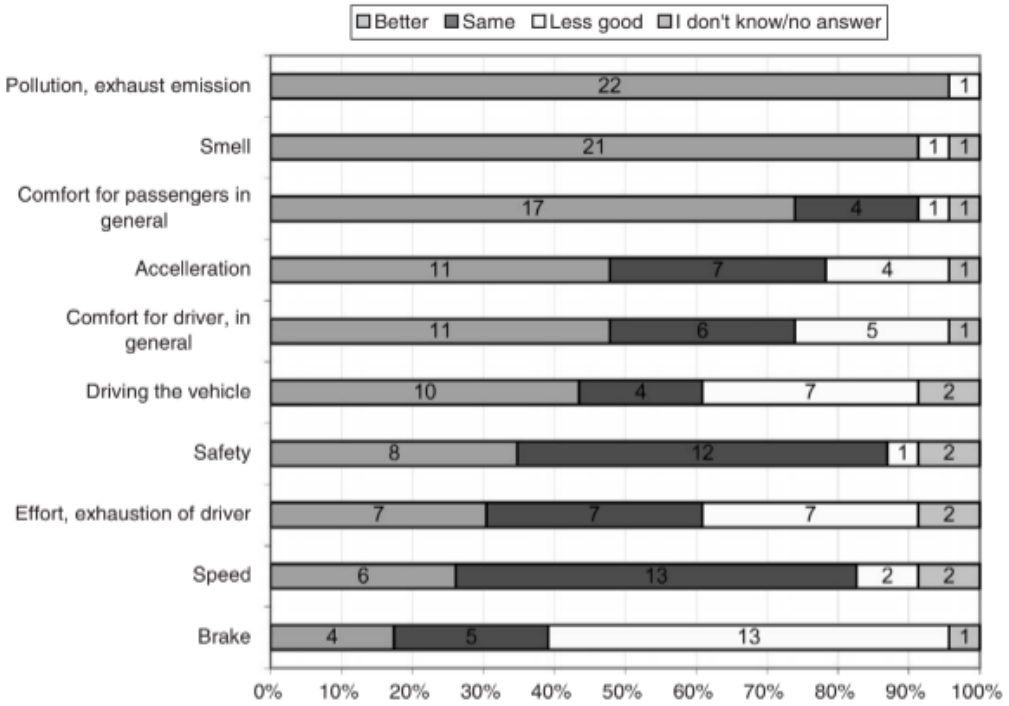

Fig. 45. Summarised results from the bus driver survey in CUTE Stockholm, Haraldsson et al. (2005:323).

One of the low performing points was that most drivers agreed that the performance of the brakes of the FCEBs were worse than conventional buses. Haraldsson et al. (2005:324) shares that, “more than half (57%) of the respondents thought the brake was worse than a diesel bus”. Finally, Haraldsson et al. (2005:324-325) summarises the main conclusions of the CUTE project in Stockholm:

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- “Newspapers and bus stops are the major source of information on the FCEBs.
- Passengers are positive towards the FCEBs and feel safe while in the buses.
- Passengers above the age of 40, want to have more information.
- Respondents are not willing to pay a higher fee if more FCEBs are introduced.
- The drivers show an overall positive feedback to the FCs bus project”.

Fuel consumption values were a key finding to understand the difference between conventional vehicles. Saxe et al. (2007:701) shares that, “drive cycle tests were performed in all the 9 cities of the CUTE project. A special gear shifting scheme as earlier explained was used to make the beginning and end of a drive cycle so that data for the different drive cycles could be identified and retrieved in order to further assess”.

- **Rhein-Main area, Germany**

The Rhein Main area is a very resourceful area for H2 powered vehicles and can show signs of a strong ecosystem that can be duplicated. Huge targets on a national level at Germany allow a shift in behaviour from various stakeholder groups, and the efforts are put more in the direction to understand the best possible options rather than assessing if it is an option in the first place. Reduce GHG emissions act as a driver for traffic transition globally and urban areas act as a strong location to implement larger vehicles with battery electric and FC electric applications. Hence public transport is a very interesting area of deployment and bus transport is also very popular. The substitution scenarios presented in the study of Coleman (2019) for the Rhein- Main area, show that the operational requirements of public transport can be met by a transition fleet combined with electric and FCBs.

Coleman (2019:5131) explains the key results of this study by sharing, “in the pro-battery scenario, even a small fleet of FC buses can show a restriction of GH2 200 supply. The FC+ scenario excludes GH2 200 from the beginning, followed by GH2 500 reaching a fleet of 23%, meaning 30 articulated FC and 35 standard buses. For 60 articulated FC and 60 standard buses, there would be a need for 1 delivery per day of LH2”. From an operational point of view, on site and near site electrolysis with the construction of designated H2 pipeline infrastructure will be promising. “The results also show that from an economical point of view, H2 production in PtG plants can meet demand of projected bus fleets with a rated electrolysis power of 18 MW. Finally, the GIS analysis shows that the Rhine-Main area is a very suitable place for a decentralised installation of PtG plants to demonstrate large scale H2 supply chain”, Coleman (2019:5131).

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- **Tuscany, Italy**

For the study in Tuscany, a LCA was used to compare and evaluate environmental impacts of alternative scenarios for H2 chains proposed. In the Bartolozzi et al. (2012:110) study, benchmarking with a set of electrical vehicle scenarios was done, and also the benchmarking of the renewable energy sources with the Italian energy mix were provided. The key findings from the study of Bartolozzi et al. (2012:110) are:

- "For the Italian national electricity mix, the use of renewable energy sources (for H2 production of electricity production) has a better performance on most of the impact categories", Bartolozzi et al. (2012:110).
- "Compared to H2 scenarios, BEV scenarios have better environmental performance. However BEV does not include storage and distribution, which gives significant importance to the H2 scenarios", Bartolozzi et al. (2012:110).
- "Biomass based H2 scenarios, in the operational phase, have larger impacts compared to FC_WE scenarios. For this scenario, the impacts are shifted to the vehicle manufacturing and the H2 storage and distribution phases. In the electric scenario, the impacts shift to vehicle manufacturing and maintenance phases, hence having a small impact on the operational phase", Bartolozzi et al. (2012:110).

- **Valencia, Spain**

For the study in Valencia, the sample of college students used helped to analyse the WTP scenarios for HEB in Valencia. Salazar et al. (2020:4) in this study, used the "Latent Class model that allowed to identify 3 latent classes for the respondents (high, medium and low environment concern). The results show that there is a positive WTP to support the introduction of HEB in Valencia and 67% of the respondents are willing to pay a higher bus fare to make this happen". This is a very different finding to the results in 9.1.1. As in Stockholm, the respondents were not willing to pay a higher bus fee. However the sample group is also important, and the younger group of respondents in Valencia might understand the reasons to pay a higher bus fee more than the older (over 40 years of age) respondents in Stockholm, who also asked for more information on H2 and fuel cell technology, which inclines to not knowing enough about the subject.

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Salazar et al. (2020:9) also share that “the respondents willing to pay a higher bus fare in Valencia are in favour of a 22% increase of the current bus fare (2020) and shows that this level of public acceptance is vital. Also in class 2, the respondents are willing to pay more, and even a higher percentage (76%) than class 1 regarding this point. Even with the high environmental concern of class 1 respondents, the result would have been expected to be opposite compared to class 2 respondents”. However, looking at the Fig. 32, “it is also visible that the 11 predictors considered the conditional possibilities as very similar between class 1 and class 2, so this could explain the point on the bus fare. For class 3, the results are more conclusive as their low environmental concern is a clear reflection of them not willing to pay extra for the bus fare”, Salazar et al. (2020:9).

- **Porto, Portugal**

A substantial amount of variability in fuel consumption can be explained by, “the VSP approach, that integrates the effects of acceleration, speed and roade grade into 1 parameter”, Frey et al. (2007:290). In this study a rela comparison was made in the same period of operation between diesel buses (from US and Porto) and the FCB (from Porto). This unique type of research can help to understand particular areas of interest to further investigate the development of H2 powered vehicles. Frey et al. (2007:290) shares that, “the modal average fuel consumption for the AATA buses and the Porto diesel bus were found to be similar. The Porto FCB was not optimised for fuel economy and also showed this as the VSP based modal average fuel consumption for the Porto FCB had smaller relative variability when compared to the diesel buses’”. The VSP approach is a practical way to evaluate the effects of driving patterns on total fuel consumption and could help policy makers to take action in order to support fuel alternatives and improvement of air quality. However it can be argued that the results found in this study are based only on 3 buses and a larger number of buses might be needed to understand industrial scale operations. Here the case studies in the other cities of Europe help to facilitate an understanding for larger scale deployment that the study of Porto does not fully do. Frey et al. (2007:290) adds to the conclusion of this study by sharing, “overall vehicle energy consumption and fuel cycle may increase if diesel fuel is replaced by H2 obtained from steam reforming of methane”.

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10. Discussion

The CUTE project was key for a range of stakeholders to have first hand feedback for the operation of FCEBs and perception of passengers. Since the start of the project, “around thirty H2 powered buses have been commissioned in nine European cities,providing 12 million passengers with pollution- free transport with no major incidents reported so far”. It is important to highlight that the lack of incidents also validates the technology is operated with the right guidelines. Air Liquide (2018:10) “have installed a H2 station to recharge five buses in Rosenholm, Norway. Other stations have also been built in Rotterdam, Netherlands and Versaille, France. This will help to recharge FCVs in the region and in Versaille particularly, with their H2 station plan to serve France’s first H2 bus service for the Vélizy-Villacoublay to Versailles line from 2019”.

10.1. Need for Market Creation: Five Enablers to Establish

The Hydrogen council help to further add, five levers with which stakeholders can create demand for H2 and establish a market:

- “Look to renewable energy for inspiration and reduce market uncertainty. For example, making a shift to zero emission fleet logistics with recurrent usage”, Hydrogen Council (2020).
- “Work on scaling technologies and applications that generate the best improvement for investment. For example, scaling FC production from 10,000 to 200,000 units can reduce the unit cost by 45%. Scaling of 70 GW for electrolysis plants can lead to lower costs of upto 330 EUR per kW”, Hydrogen Council (2020).
- “Development of H2 solutions can create more usage of H2 with viable applications. For example around airports, for heating, local industry feedstock and, refueling of buses and airplanes”, Hydrogen Council (2020).
- “Increasing utilisation rates in distribution networks to be prioritised. For example, moving from 20% to 80% utilisation rates in refueling networks and tanks can slash distribution costs by up to 70%”, Hydrogen Council (2020).
- “Investing in renewable H2 production with low or no carbon. Low cost H2 will be the single most important factor to accelerate the H2 economy and is one of the top three cost reduction criterias for H2 applications”, Hydrogen Council (2020).

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10.2. Need for Deployment of H2 Infrastructure in Europe

It is important to understand the current H2 refuelling stations available in the world in order to understand the next stage of growth. Ajanovic and Haas (2020:8) in their study explain that "worldwide there are 376 HRS as of 2018. As shown in Fig. 5, there are only five countries with over 20 HRS. In the future, around 2500-3500 FCVs per station are expected", which might not be enough to cover the growing number of H2 vehicles in the market, hence needed for further development. This further helps to justify why at this stage (upto 2050) it makes more sense to commercialise larger vehicle types such as buses in cities as there are set driving routes and central fueling locations (can be done at night when during the non-operating hours of the bus). It is also possible to build cross country projects as standardisation for the market of buses can be easily duplicated. However common standards and regulations will be needed to make all of this happen. As discussed by Ogden (2018:9), H2 refuelling infrastructure should offer:

- "Coverage of sufficient numbers of stations to enable convenient travel.
- Capacity to match growing H2 demand.
- Positive cash flow for station owners and network-wide supply.
- Cost competitiveness with gasoline (on an EUR per km basis)", Ogden (2018:9).

Private organisations such as Air Liquide are leading the way to provide infrastructure along with the product H2 to fuel their stations, examples across European geographies is shared below by the Hydrogen Council (2020):

- "Germany- In total 43 HRS exist in 2020 in Germany. Air Liquide owns 12 HRS as part of various partnerships, including the H2 mobility Deutschland joint venture operated between Air Liquide, OMV, Linde, Stell and Total. These companies plan to increase the number for HRS to 400 units with the support of the German government", Hydrogen Council (2020).
- "Northern Europe- Copenhagen H2 Network (CHN), a subsidiary of Air Liquide, has 5 HRS installed in Denmark, out of which 3 are in Copenhagen, 1 in Vejle and 1 in Aalborg. Air Liquide also opened their first station in Rotterdam, Netherlands in 2014", Hydrogen Council (2020).
- "France- Hyway is a key project, co funded by the Auvergne-Rhône-Alpes regional council, ADEME, and the European Union (as part of the ERDF, European Regional Development Fund program) operating in France. It aims to use captive fleets to trial and verify the technical and economic justification for a 'hydrogen kit' to extend the range of hybrid EVs", Hydrogen Council (2020). "In January 2015, Air Liquide opened a H2 charging station in Saint-Lô, on behalf of the Manche Departmental Council. Air Liquide has also opened a station on the GEG site in Grenoble, to fuel the company's vehicle fleets", Hydrogen Council (2020).

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10.3. Policy Framework Considerations

Currently there are a very low number of policies and regulations applied to H2 and FC technologies. Ajanovic and Haas (2020:8) share that, “policies today are only indirectly supportive of H2 and FC technologies, as there are strong ambitions to reduce CO2 emissions and banning ICE vehicles”. But as there are no directly linked policies related to promotion of H2 and FC technology the fast and broad implementation of this technology is a major issue. For any society, it is important to have sustainable means to develop and hence long term visions and a stable policy framework is needed. In Fig. 46, the major elements of the required policy framework are shared:

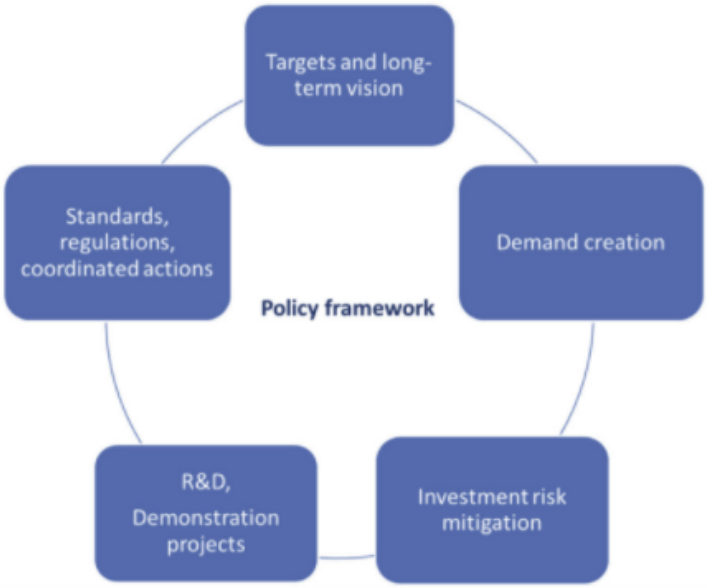

Fig. 46: Policy framework required for a further uptake of FCVs, Ajanovic and Haas (2020:8).

Further to policy making, it is also recommended to understand enablers from the government to accelerate deployment from industry. To this effect, the Hydrogen Council (2020) share six ways in which governments can level the playing field:

- “National strategies. Governments have a role to play a role in setting national targets, as they have done already through 18 H2 roadmaps developed across the globe”, Hydrogen Council (2020).
- “Coordination. Governments are well positioned as neutral conveners of industry stakeholders to mediate potential local investment opportunities”, Hydrogen Council (2020).

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- “Regulation. Governments can help remove barriers that may exist to invest in the H2 economy today, e.g. by facilitating the process to obtain permits for new refuelling stations and developing internationally consistent regulation to limit market specificity”, Hydrogen Council (2020).
- “Standardisation. Governments can also support industry to coordinate national and international standards, e.g. around pressure levels and safety”, Hydrogen Council (2020).
- “Infrastructure. Governments can choose to invest in the deployment of new infrastructure and re-use, where relevant, of existing networks (e.g. natural gas networks)”, Hydrogen Council (2020).
- “Incentives. Finally, governments could decide to apply incentives, e.g. tax breaks or subsidies to encourage the initial acceleration of H2”, Hydrogen Council (2020).

10.4. Collaboration between Organisations / Future Investments

Private organisations, as shared previously, play a significant role to promote mass deployment for a new technology capable of industrialisation globally. In order to support a common cause, the Hydrogen Council was born. “It includes Air Liquide, Alstom, BMW Group, Daimler, ENGIE, Honda, Linde, Total, and Toyota among other well known companies. As of mid-2020, the Hydrogen Council includes over 90 multinational companies from the automotive, energy, and manufacturing sectors”, Air Liquide (2021). Throughout this research, it has been established that further investments will be needed for H2 and FC technology to become more cost competitive than today (2020). The Hydrogen council (2020) share some areas where investments in the next decade (until 2030) can make a difference:

- “H2 production- to have competitive costs for renewable H2 from electrolysis an aggregate deployment of 70 GW of electrolysers capacity is needed. This could mean an overall investment of EUR 16.5 billion”, Hydrogen council (2020). After 2030, when economic competitiveness is reached by applying the aforementioned, the costs of H2 will further decrease (for example until 2050). For other complementary technologies such as implementation of low- carbon H2 from natural gas with CCS, approximately EUR 5 billion would be required”, Hydrogen council (2020).
- “Transport sector- The infrastructure of HRS and distribution networks required a cost differential for FCs and H2 tanks compared with low carbon substitutes, which implies an additional anticipated investment of EUR 24.7 billion to cover the economic gap”, Hydrogen council (2020).
- “Heating sector- For industries and buildings, to repurpose fist gas pipeline networks for H2, is anticipated at EUR 14 billion investment by 2030”, Hydrogen council (2020).

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10.5. Drivers and Obstacles for Electrolytic H2 from Renewable Resources

Maggio et al. (2019:11379) shares the main drivers and obstacles are summarized in Table 24.

Table 24: Main drivers and obstacles for the RES-based 'hydrogen economy', Maggio et al. (2019:11379).

Drivers	Obstacles
Favourable policy framework that creates a market pull	High costs of hydrogen and fuel cell technologies
New regulatory frameworks – at national and international level – concerning finance, tax, environment, and safety	Lack of subsidies to support market competitive conditions for hydrogen technologies. Absence of a common regulatory framework.
Engagement of stakeholders, public and private, to establish the roadmap	Lack of investments in the hydrogen infrastructure
Energy security and reduction of GHG emissions	Electricity price
Need of energy storage and electric grid balance	Current socio-economic context

- **Drivers:** H2 by electrolysis and especially using renewable energy during the electrolysis process is a massive improvement to the world's ecosystem in an environmentally beneficial way. Maggio et al. (2019:11380) shares, "that from several researches it has been stated that for consumers the need for a well-structured refuelling system is not as important as increasing money savings". This can be summarized from the findings of Ball and Weeda (2015:7909), for conditions they deem necessary for electrolysis to become an economically viable option for electricity storage:

  - "Surplus of tens of TWhs around 3000- 4000 FLH annually from electricity generation by renewables.
  - Low electricity prices during a significant part of the year.
  - Sustainable and favourable policy frameworks for H2 and FC technology".

  To enable the above mentioned drives and solutions, the following would be needed:

  - "Reduction of capital and fixed costs.
  - Realization of cost premiums, in particular in the mobility sector.
  - A regulatory framework aimed to decrease or delete the payable surcharges", Ball and Weeda (2015:7909).

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- **Obstacles:** Maggio et al. (2019:11380) express that “absence of a proper HRS network which requires high investment cost is a big obstacle. Many barriers exist today, however broadly 2 main obstacles have been observed; the lack of demand for H2 and FC technology, and the prohibitive costs”. Some other barriers that have been highlighted are:

  - “Safety related barriers for production and consumption.
  - Lack of subsidies and regulatory policy framework from governmental bodies.
  - The cost of electricity from the grid for powering the electrolyser.
  - Low investments currently compared to the real requirements for production”,Maggio et al. (2019:11380).

Andreasen and Sovacool (2014: 894), in their stakeholder analysis tried to find the most important factors for H2 deployment in Denmark, and their findings help to understand some real life issues that should be foreseen; a low number of subsidies received (for example in the case of biogas in the past) can hinder the equal competitive conditions to implement H2 in markets. Removing subsidies on the other hand would point towards a backward pull of society and non-taxing or dis-incentivised behaviours would not be sustainable for regulating policies.

10.6. Optimization of Renewable Resources Input

Optimisation of the production, storage and usage of renewable energy will become more and more important for the future. Ramesohl and Merten (2006:1256) explain that, “1 kWh of renewable electricity can substitute public grid generation to prevent emissions of around 590 g CO2eqv/kWh. The use of renewable eneroduce H2 which would be further used as fuel for vehicles can result in a reduction of emissions by 191 g CO2 eqv/kWh”. An illustration of such an operating model with high reductions of emissions is shown in Fig. 47 below:

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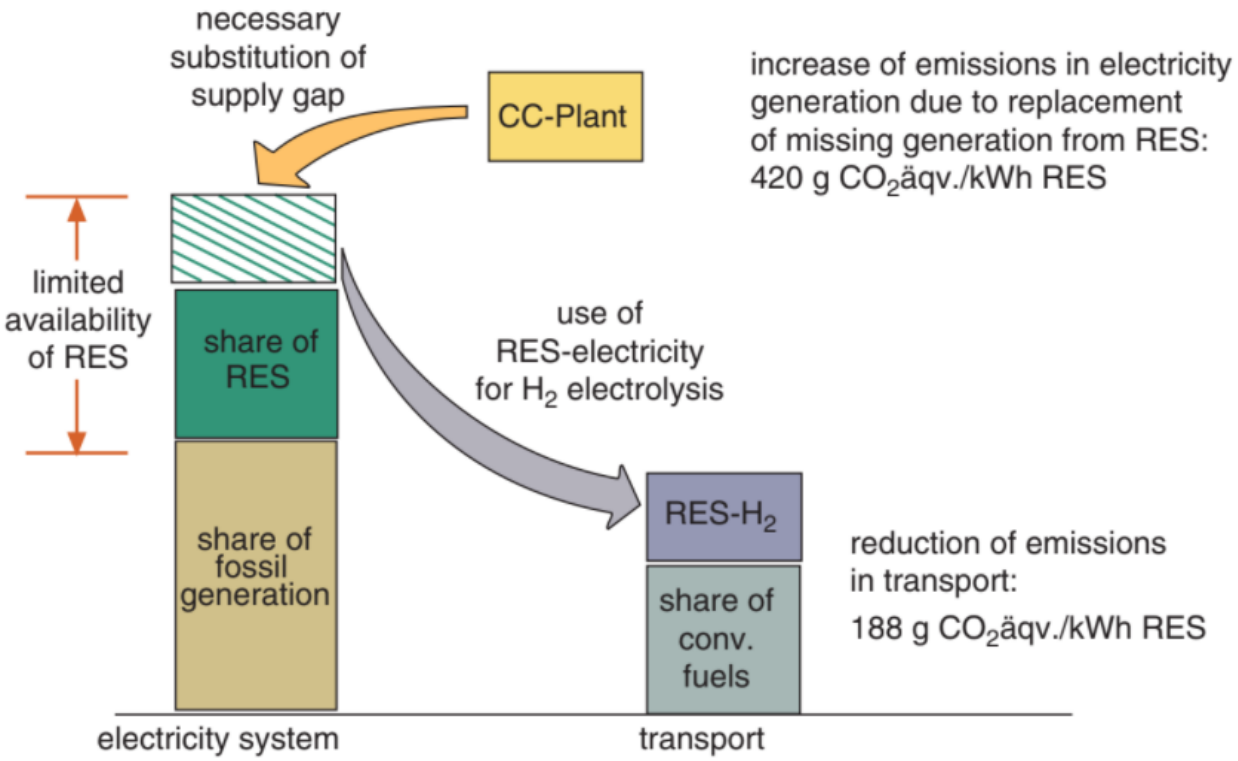

Fig. 47: Holistic assessment of the specific emissions of H2 production from renewables, Ramesohl and Merten (2006:1256).

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11. Summary and Conclusion

Several studies have been presented to show the current trials for H2 fuelled buses around Europe within this study. Different regions in Europe might have different priorities when implementing an alternative fuel within the market. Infrastructure to produce, deliver and store H2 has been highlighted as a key growth market. It has been shared numerous times in this research that if the infrastructure and technology matures, cost savings will be identified from different angles. In this research, the transition in the transport sector and more particularly the inter city operated buses is shown as an area of immediate implementation to a sustainable alternative to conventional buses and fuel. The policy decision makers have been given high importance for the future development of the market as well and social and institutional factors have been presented to share the perception of the public and local communities.

Elhajj and Ochieng (2020:12) share that “the population of the world is predicted to grow and by 2050, urban cities' population will be 5.9 billion people, comprising 68% of the world’s population in 2020. To this effect, the popularisation of H2 fuelled intercity buses is considered as an economic and ecological improvement”. “Within cities, depending on the size of a bus, a fully occupied bus can replace between 5 to 40 cars with a high fuel saving potential. In 2015, in the European Union around 57 billion passenger journeys were made using public transport of which 56% used buses”, Elhajj and Ochieng (2020:12). Today we also see bus shelters being equipped with CCTV cameras and real time displays to show bus schedules and emergency calling options to increase service reliability. Many roads in Europe are also being converted to only public transportation and cycles, reducing emissions and avoiding traffic congestions.

This work indicates that H2 buses in Europe have the chance to become a serious alternative to conventional buses due to the presented results. The education of local communities is vital to share knowledge and avoid confusion for the mass public. The sustainable development of transport highly depends on the innovative implementation of a H2 economy. It goes without saying, that this will lead to jobs in the local cities to be able to operate and maintain the H2 economy. Turon (2019:840) additionally shares, “it should be remembered that all activities aimed at popularization and education in the field of new mobility require the effort to change the attitude of society”. The acceptance of the public, not just in the short term, which may include paying a higher ticket fee compared to what they pay in conventional buses today will be needed. The insights provided in this research help to understand that patience withH2 technology and mass deployment will help to reduce costs and also reap environmental benefits which are needed to meet GHG emission goals.

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To this effect, the Hydrogen Council (2020) provide possible scenarios which assess the next years to come:

- "2020-2025: H2 expected to become competitive for larger vehicles (buses, trains, coaches, forklifts). Pure EVs are not competitive when looking at the TCO", Hydrogen Council (2020).
- "2030: Reduced costs of H2 production and distribution, will reduce costs for other vehicle ranges, such as compact cars", Hydrogen Council (2020).
- "2050: In the 2 °C scenario, total CO2 emissions need to be 90% lower than today, which can only be achieved by having a stable H2 economy along with other renewable technologies in industrial mode", Hydrogen Council (2020).

Moving towards a sustainable environment and renewable resources is the goal for mankind and the next years will define our resilience to achieve this. However all support offered for this cause is valuable and governments around the world play a huge role in relation to policy and framework. Köhler et al. (2009:2994) helps to summarise the three recommended policy implications that are also relevant for the application of this research.

- "Strong and large scale preference shifts for consumers is needed together with relevant policy actions for communities to move to a sustainable system for mobility", Köhler et al. (2009:2994).
- "The best alternative for the upcoming 10 years, might not be a long term option. It is important to keep investigating to understand alternative technology niches. An energy mix is always advocated as a good option in order to lower dependency", Köhler et al. (2009:2994).
- "A radical behaviour change will be required, with support from grassroot stakeholders to support implementation of new changes (parking restrictions, fuel tax increases)", Köhler et al. (2009:2994).

This research is however not exhaustive and there can be further research considered for the future to know more about; maturity of water electrolysis technology, wider research on larger vehicles (airplanes, ships, trucks), development of pipelines for H2 supply, government policy implications and related studies. Indeed several areas of research to further understand the H2 technology and benefits for the transport industry are needed. Today, we are still a long way from having comparable costs of private owned cars between H2 and diesel engines, and hence the luxury to justify this investment is not available to all. The economy of scale for this technology will show the long term benefits, and it might be only until 2050 that we start seeing more companies produce H2 cars, so that they can market their environmental benefits along with cost parity versus conventional vehicles.

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List of Abbreviations and Symbols

AWE	Alkaline water electrolysers
BEVs	Battery electric vehicles
CCS	Carbon capture and storage
CF	Carbon fiber
CO	Carbon monoxide
CUTE	Clean urban transport for Europe
cH2	Compressed hydrogen
CNG	Compressed natural gas
CSP	Concentrated solar power
°C	Degree celsius
ECM	Electronic control module
EUR	Euros (€)
Eq.	Equation
EVs	Electric vehicles
Fig.	Figure
FC	Fuel cell
FCB	Fuel cell bus
FCBs	Fuel cell buses
FCEBs	Fuel cell electric buses
FCs	Fuel cells
FCVs	Fuel cell vehicles

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FLH	Full load hours
GH2	Gas hydrogen
GIS	Geographic information system
GWP	Global warming potential
GHG	Greenhouse gas
He	Helium
HEB	Hybrid Buses
H2	Hydrogen
HRS	Hydrogen (H2) refueling stations
ICE	Internal combustion engine
ICEVs	Internal combustion engine vehicles
km	Kilometers
LCA	Life cycle analysis
LH2	Liquid hydrogen
MC	Master controller
CH4	Methane
O2	Oxygen
%	Percentage
PFSA	Perfluorinated sulfonic acid
PED	Primary energy demand
PEM	Proton exchange membrane
PEMWE	Proton exchange membrane water electrolysis

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POCP	Photochemical ozone creation potential
PtG	Power to gas
SCFD	Standard cubic feet per day
SMR	Steam methane reformation
SOEC	Solid oxide electrolyser cell/solid oxide electrolysis
TCO	Total cost of ownership
US	United States of America
VSP	Vehicle specific power
Vs.	Versus
H2O	Water
WTP	Willingness to pay

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