Analysis of Hydrogen as Alternative Fuel for Passenger Cars in Brazil

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ABSTRACT

The pressure for mobility decarbonization has motivated discussions in Brazil about new technology routes and viable energy sources for passenger cars. Publications and presentations were made to advocate in favor of some of them. Hydrogen was cited several times, since its potential for almost zero pollutants and zero CO_2 emission according to tank to wheels concept. In gaseous form, it is an energy vector with a high heat value that can be produced from renewable sources and used efficiently in specially designed combustion engines or with different fuel cell technologies and topologies. These advantages come together with challenges, as the infrastructure for production and distribution, the storage and the cost. This article aims to review and discuss these conflicts, summarizing the main production processes and estimating its carbon footprint. Also, an energy and well to wheels CO_2e analysis, in comparison with Battery Electric Vehicle technology, together with the necessity of hydrogen for other industrial uses are shown. The results do not clearly demonstrate the advantages of considering this fuel in the passenger car way to zero road map for the Brazilian market.

INTRODUCTION

The commitment of the Volkswagen Group regarding climate changes is summarized in its decarbonization policy “Way to Zero”, that states carbon neutrality until 2050. Since the Group consists of different brands and subsidiaries with global presence, it is necessary that each region searches for the most adequate solutions, taking local characteristics (e.g. energy matrix) into consideration.

To achieve the “Way to Zero”, the defined scope for CO_2e measurement is the “Cradle to Grave”. This border encompasses the emission of greenhouse gases (GHG) from the raw material extraction, manufacturing of parts and their assembly, vehicle usage by customers along a standardized life mileage and, finally, disposal efforts [1]. It is worth mentioning that GHG emissions are converted to CO_2 equivalent (CO_2e) via “Global Warming Potential” (GWP) standard table.

Preliminary evaluations for Brazilian market show that use phase is the most relevant for a passenger car life cycle. Here, not only the exhaust CO_2 (called “Tank to Wheels”) is considered, but also the CO_2e related to production and delivery of the vehicle energy source (e.g., fuel, electricity), i.e. “Well to Tank” emissions. In this way, GHG from the whole use phase are designed as “Well to Wheels” (or WtW) CO_2e, which is the main context of in this study.

The reduction of GHGs from fossil sources includes the evaluation of alternative energy sources and carriers for vehicles. Among various options, the gaseous hydrogen (H_2) has attracted attention in several countries, such as Brazil. The expectation that OEMs can offer H_2 powertrains in vehicle models has been discussed and already appeared in legislation such as Rota2030, which encourages this energy carrier without mentioning its origin (fossil or renewable) [2]. Its “CO_2 free” combustion or oxidation in fuel cells contributes to its appearance in the media, though further analysis of this gas challenges is essential likewise.

The Brazilian Volkswagen subsidiary recognized that a long-term road map for neutrality (i.e. a “Way to Zero”) need to be developed. This roadmap needs to be regularly updated in order to include the contribution of new technologies, to adapt the portfolio to marketing trends and to consider external changes, such as the evolution of the country’s energy matrix. The use of gaseous H_2 technology for passenger cars and light commercials in this market was evaluated and is presented in this paper to technically support its presence or absence in the company’s current Way to Zero.

H_2 PROPERTIES, VALUE CHAIN AND CARBON FOOTPRINT

PHYSICAL PROPERTIES – One of the factors driving enthusiasm for hydrogen is a lower heating value (LHV) per mass of 120.10 MJ/kg, three times greater than gasoline. However, its volumetric properties make this substance less competitive than common fuels, as shown in Table 1.

Table 1. Hydrogen physical properties *[3] [4] [5]*.

Property	Value	Unit	Comparison
Lower heating value (LHV)			
Gas (ambient pressure)	120.10	MJ/kg	3x of gasoline
	0.01	MJ/L	1/3 of natural gas
Gas (compressed, 700 bar)	5.6	MJ/L	~2/3 of natural gas at 250 bar
Liquid	8.5	MJ/L	1/3 of liquefied natural gas
Temperatures			
Boiling point (at 1 bar)	-252.76	ºC	90ºC below liquefied natural gas
Combustion			
Flame velocity	346	cm/s	8x of methane
Ignition range	4 – 77	% v. in air	6x wider than methane
Ignition energy	0.02	MJ	1/10 of methane
Stoichiometric air/fuel ratio	34.3	-	2x of natural gas

It should be noted that liquid hydrogen, already adopted as rocket propellant, requires cryogenic temperatures to be maintained in this physical state, since hydrogen has the second lowest boiling temperature of all substances. Consequently, most hydrogen applications adopt it as gas despite its lower volumetric energy density [6]. Therefore, greater pressures must be applied to the gas so as to achieve the same energy in an equal volume. For road transport applications, compressed hydrogen is usually stored in cylinders at 700 bar [7].

It is noteworthy that several precautions are necessary when handling hydrogen gas. Being a very light and small molecule, it escapes more easily through seals and can diffuse into certain materials, causing fractures and hampering the use of cylinders and pipes built for other gases [3]. Notwithstanding its non-toxicity, this gas is highly flammable due to a high flame velocity, wide ignition range and low ignition energy. Besides, its flame is colorless and odorless [3].

Hydrogen is already used industrially, so there are safety protocols and international experience on handling it. Still, 85% of hydrogen produced globally is consumed on-site [3]. In other words, only 15% of this commodity was commercialized and, therefore, had to be transported and handled by different agents.

PRODUCTION AND COLOURS – Hydrogen production routes are commonly color-coded, as illustrated in Figure 1 based on [7].

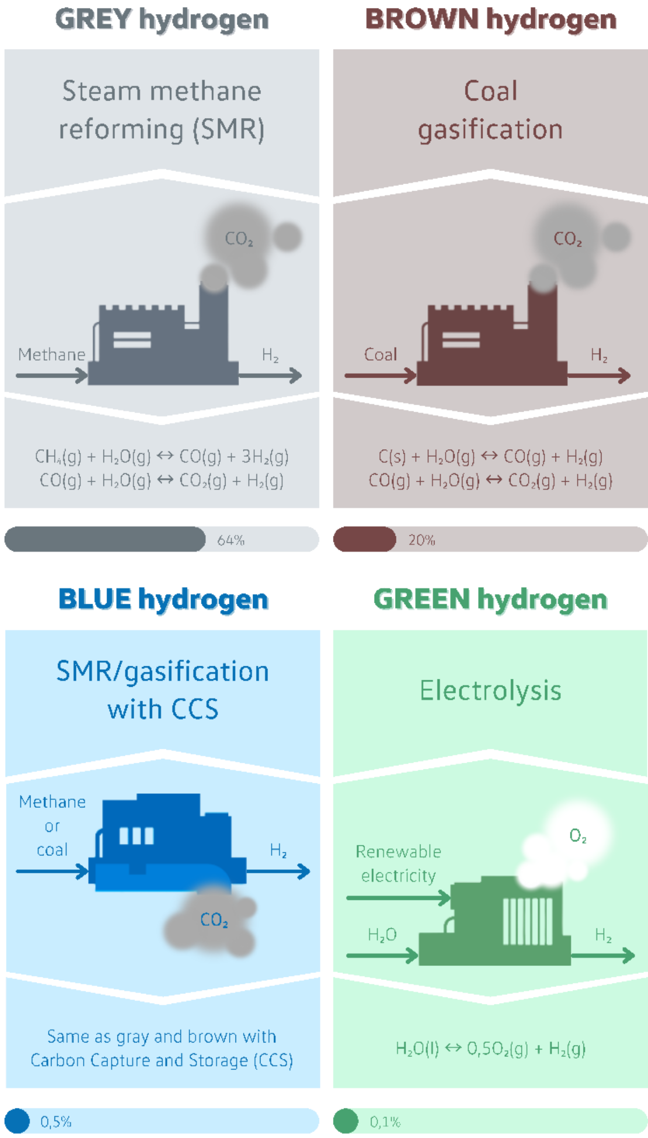

Figure 1. Grey, brown, blue and green hydrogen, describing their production routes, reactions and representation (%) in world production.

According to [7], most of the world's hydrogen production (64%) is via a process called steam methane reforming (SMR), whose raw material is natural gas. This path is followed by coal gasification, which accounts for around 20% of the market and is located mainly in China (currently the largest producer of hydrogen). Other less common paths are natural gas reforms adopting oxygen from air as oxidizing agent (partial oxidation, POx) instead of steam or adopting both (autothermal reforming, ATR). Approximately 15% of the hydrogen currently generated is a co-product of industries with other purposes.

Currently, essentially all coal and methane consumed is of fossil origin. An option with less impact on the environment is electrolysis, but it only adds up to 0.1% of production today. Electrolysis corresponds to the reaction of breaking down water molecules using energy, a mechanism comparable to the reverse process of a fuel cell. The process is performed by an equipment called electrolyzer, consisting of an anode and a cathode separated by an electrolyte. Changes in the composition of these components lead to different electrolyzer technologies [8], with those commercially available being alkaline (ALK) and proton exchange membrane (PEM) [9]. With a technology readiness level (TRL) of 9, ALK cells have a basic aqueous solution as an electrolyte, while this item is a solid proton-permeable membrane in the case of PEM [9]. A technology that is gaining maturity and approaching commercialization is the solid oxide electrolysis cell (SOEC), having a TRL of 8 [9].

Another alternative is the operation of fossil process with carbon capture and storage (CCS), representing 0.5% of market [7]. In Brazil, "moss" hydrogen has gained prominence. It comes from the conversion of biomass, biofuels or organic matter co-products through chemical processes such as catalytic reforming, gasification, pyrolysis, and anaerobic bio digestion [6].

CARBON INTENSITY – It is important to emphasize that color nomenclature, even though widely used, does not follow any standard. Furthermore, this classification does not explicitly state the environmental impacts involved in obtaining hydrogen. Thus, it has fallen into disuse and has been replaced by a carbon intensity identification [10]. Figure 2, created by [10], shows examples of emissions per kilogram of hydrogen depending on the pathway.

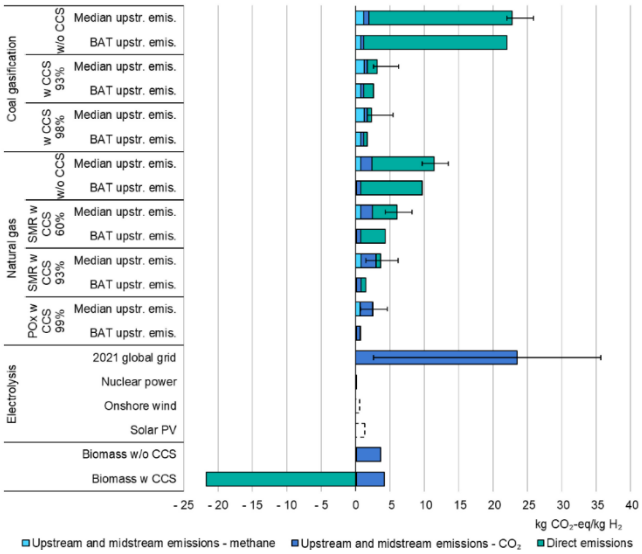

Figure 2. Carbon intensity of different hydrogen production routes in 2021 (BAT = best available technology) [10].

The global average carbon intensity for hydrogen production was 12 – 13 $kgCO_2e/kgH_2$ in 2021 [10]. Nonetheless, according to [7], to achieve the net-zero emissions scenario this value must drop to 5.5 $kgCO_2e/kgH_2$ in 2030 and be less than 1 $kgCO_2e/kgH_2$ in 2050. Currently, hydrogen has the average impact of 10 – 14 $kgCO_2e/kgH_2$ from SMR and 22 – 26 $kgCO_2e/kgH_2$ from coal gasification [7]. Emissions from electrolysis vary greatly depending on the source of electricity, and it is common not to include embedded capital expenditure (CAPEX) emissions (i.e. electrical infrastructure) as stated in ISO/TS 19870 guidance. This premise, however, may underestimate the real impact of electricity generation, even if the energy is renewable.

Thus, new legislation and certification methodologies have adopted terms such as "low-emission hydrogen" to classify the sustainability of the gas [10]. Each certification scheme may present a specific emission limit for hydrogen to carry this label. Brazilian law 14.948 was approved in August 2024, establishing a maximum intensity of 7 $kgCO_2e/kgH_2$ for hydrogen to be considered low carbon regardless of the production route [11]. This substance has gained attention in the country as opportunities for reducing emissions arise due to the large share of renewables in the electricity matrix and the availability of biomass. The latter can be used both to generate biogas (precursor or possible substitute for natural gas) and to directly obtain "moss" hydrogen.

CURRENT AND FUTURE APPLICATIONS – Most of the hydrogen requested by the market is in its pure form (~77%), while the remainder is mixed with other gases such as carbon monoxide (mixture called syngas) [7]. Nowadays, hydrogen is demanded practically by industry, the main sectors being ammonia (45%), oil refining (34%), methanol (15%) and iron/steel (6%) [12].

New applications for hydrogen are projected to emerge in the coming years and their share in global demand is expected to rise from less than 1% in 2024 to 40% in 2030 [7]. This substance is seen as a strategic energy vector for several economies to reach net-zero, focusing mainly on hard-to-abate sectors. These sectors include energy intensive activities, in which the direct use of electricity is not a technically and economically viable solution [3].

In addition to new uses in steel production, examples of other sectors that may substantially consume this gas in the future are heat/electricity, synfuels and transport. Hydrogen can replace natural gas in industrial stationary power generation. In the production of hydrogen-based fuels and feedstocks, it can be adopted as the main raw material (e.g. using syngas), or as an input in different industrial stages (e.g. hydrocracking, hydrogenation, hydrotreatment).

Regarding the transport sector, the gas can be burned directly in combustion engines (H_2-ICE), consumed in fuel cell electric vehicles (FCEV) or generated in ethanol reforming electric vehicles. The latter will be explained later in this article. Trucks represent the fastest growing demand for FCEV, followed by buses. Together, their sales increased by 25% in 2022 and 50% in 2023 [7]. Meanwhile, sales of FCEV light vehicles have been growing, but at an increasingly slower pace (35% in 2022 and 15% in 2023) [7].

Still, hydrogen for road transport currently accounts for less than 0.1% of global demand [7].

H_2 INFRASTRUCTURE AND FUELING STATION CHALLENGES

In order to provide hydrogen for passenger cars and light commercials, this fuel should arrive at stations near to the customers through, for example: centralized production with further distribution via pipelines and production near or at the fuel station, using an electrolyzer system. Both are briefly discussed in the next sections.

CENTRALIZED PRODUCTION – Centralized production via SMR can offer efficiency advantages due to, for example, scale and thermal energy recovery (i.e., capturing heat from high-temperature streams and using it to preheat reagents). Nevertheless, the distribution of hydrogen for fueling stations remains a challenge, since it requires the development of infrastructure.

One possibility for H_2 distribution is its mixture in the natural gas network, separating it near to end use point via purification technologies [13]. Separation techniques include pressure swing adsorption (PSA), membrane separation and electrochemical hydrogen separation (EHS, or hydrogen pumping). The first has higher TRL, being used to remove contaminant gases (especially CO_2) coming out of the SMR process. This equipment could be used in fuel stations, requiring additional CAPEX. These costs could increase even more when different technologies are combined to obtain high hydrogen purity demanded by FCEV with PEM.

Moreover, current natural gas pipelines and gas fired appliances are not adequate to transport blends with more than 20% vol. of hydrogen [13]. As mentioned before, this stems from its permeability through the elastomeric sealings, polymeric pipes and metallic treads of pipe junctions. Leaks pose risks, especially in closed spaces, because of the high inflammability range of its air/fuel mixtures. Additionally, hydrogen emission into the atmosphere can diminish its decarbonization capability, since this gas has a global warming potential approximately 12 times greater than CO_2 over a 100-year period [14].

Lastly, centralized hydrogen production with distributed infrastructure seems to be not adequate in short/ medium term for typical Brazilian cities and calls for particular attention to the risks of installing gas pipelines in populated areas.

LOCAL PRODUCTION – Local production usually uses water electrolysis, illustrated along with its downstream and upstream processes in Figure 3. The calculation presented was based on the water demand of [15] and data from [16].

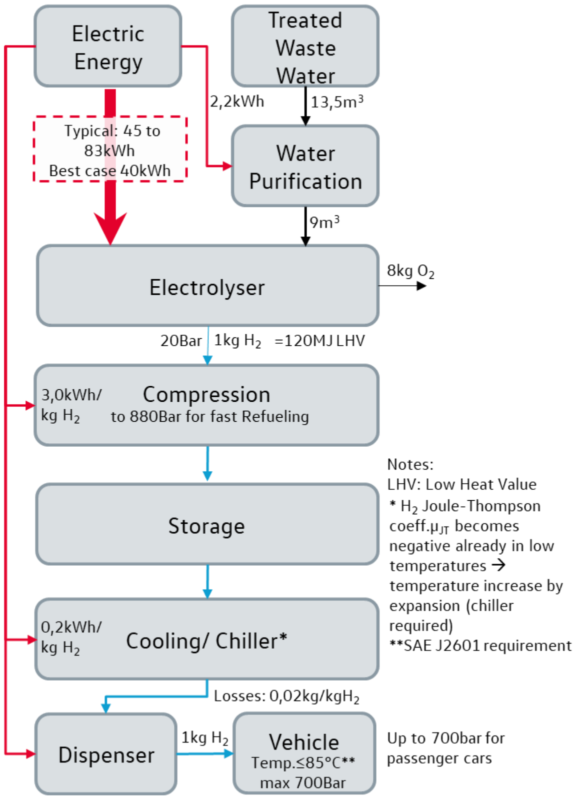

Figure 3. Flowchart from the production of electrolytic hydrogen to its delivery for vehicles, describing energy and water consumptions.

This production requires a considerable investment for the electrolyzer itself and its auxiliary system. Currently, ALK cells are the most mature, presenting a lower initial investment (ca 500 to 1,000 US$/kW) and achieving efficiencies of up to 70%. PEM reaches costs of 700 to 1,400 US$/kW with maximum efficiency of 83%. SOEC is a more expensive technology (2,000 US$/kW) and its efficiency is still in range of 50%. Taking the PEM as an example, its average CAPEX is 1,050 US$/kW. Assuming that its cost is given by energy (kW) of hydrogen, a power of 1 kW for one hour would generate approximately 0.03 kgH_2 and would generate an expense of 35,000 US$/$kgH_2$. Therefore, a fuel station capable of producing 100 kgH_2/h would require an investment of ca. US$ 3.5M. This represents a major challenge for implementing H_2 fueling stations in Brazil.

Regarding operation expenses (OPEX), the largest contributor is the cost of renewable electricity demanded by the electrolyzer. As stated in Figure 3, the energy ratio between this electricity and the hydrogen produced is 83%, considering an optimistic scenario. This would lead to a consumption of 40 kWh per kgH_2, added to 2.2 kWh required for water purification. It is also assumed that oxygen is not sold as a co-product on account of required purification and compression costs. Instead, it is released into the atmosphere.

Since the electrolyzer produces hydrogen at 30 - 40 bar, the fueling station also needs to compress this gas to 700 bar demanded by the FCEV. The most common compressor type is the mechanical diaphragm, whose sealing performance ensures no contact between gas and lubricants [17]. Thus, compression purity can reach 99.999% [18]. The power required for process is proportional to the isentropic efficiency, the mass flow rate and the difference between discharge/suction temperatures [17]. As a result of hydrogen low molecular weight, more energy is consumed at this stage when compared to other gases.

Given a fast-fueling station, compression from 20 to 880 bar would be necessary, bringing about a theoretical energy demand of 1.47 kWh/kgH_2 [19]. Since diaphragm compressors are a mature technology, their isentropic efficiencies range from 80 to 95% [20], being 88% the average efficiency. Considering a mechanical efficiency of 56%, an overall efficiency of 49% can be achieved. This leads to the use of 3.0 kWh per kgH_2, mentioned by [19]. [21] states reference values for the energy consumption of other mechanical and non-mechanical compressor technologies: ca. 10 kWh/kgH_2 for metal hydride, max. 4 kWh/kgH_2 for electrochemical, max. 5 kWh/kgH_2 for pistons or diaphragm and 2.75 kWh/kgH_2 for ionic liquid. Therefore, the demand calculated seems plausible.

Likewise pressure, hydrogen temperature calls for adjustments. According to norm SAEJ2601, the maximum temperature of vehicle H_2 is restricted to 85 ºC. Unlike other gases, hydrogen expansion can increase its temperature, disregarding heat exchanges with the environment (adiabatic process). This phenomenon depends on the substance's Joule-Thomson thermodynamic coefficient, the ratio between temperature and pressure variations at constant enthalpy. For hydrogen, this assumes a negative value under fueling station conditions. Ergo, a controlled cooling is required via chiller [21]. [21] assumes that hydrogen pre-cooling needs approximately 4% of compression's energy demand, near to 0.2 kWh/kgH_2 estimated by [19].

Ultimately, this electrolytic fueling station also engenders hydrogen losses. [22] researched the reduction of this mass loss from 35 to 2% on the California State University campus. Assuming an optimistic scenario, 2% (ca 0.9 kWh) was adopted as the basis for this study. A total demand of 46.3 kWh/kgH_2 was found when joining all processes: electrolysis (40 kWh/kgH_2), water purification (2.2), compression (3.0), cooling (0.2) and losses (0.9). Considering an electricity cost of 0.9 R$/kWh in São Paulo, this system would spend 42 R$/kg$H_2$ or 7 US$/kg$H_2$. This result does not consider profit margin or capital cost payment.

Hence, costs arising from local production becomes a challenge for its implementation in Brazil. Its commercial viability depends on the amount of hydrogen sold, proportional to the number of FCEVs in the market, and/or public incentives for private initiatives. At the same time, increased infrastructure is also essential for higher FCEV sales, creating a "chicken and egg" problem.

LOCAL PRODUCTION WITH BIOETHANOL – Recently, the University of São Paulo (USP) started a project to obtain hydrogen using bioethanol as raw material instead purified water. Pilot experiments (5 kgH_2/h) include campus transportation with FCEV buses and cars [23] powered with hydrogen from bioethanol steam reform. This process consists in the reaction between ethanol and superheated water in the presence of catalyst: $C_2H_6O + 3H_2O \rightarrow 2CO_2 + 6H_2$ [24].

Available information from companies [25] and [26] suggests that around 7.65 L of ethanol, 30 L of water and 2.35 kWh of electricity are necessary for 1 kgH_2. The equipment and installation investments are unclear, but [25] estimates US$ 250k for the first, reaching US$ 1M when infrastructure for installation is added. Raw material expenses can yet be evaluated through ethanol (3.73 R$/L [27]) and electricity (0.79 R$/kWh [28]) costs in São Paulo, reaching 30.39 R$/kg$H_2$ or 5.47 US$/kg$H_2$. Although the value is to be lower than the electrolysis estimation, challenges as infrastructure and vehicles market remain the same.

FUEL CELL VEHICLES ENERGY EFFICIENCY

An internal combustion engine (ICE) converts, via fuel combustion, chemical energy into thermal energy and uses fluid expansion to produce mechanical power. In the meantime, fuel cells are devices that convert fuel chemical energy into electricity via an electrochemical process. Electricity is then delivered to an electric motor that converts it into mechanical power. This powertrain is not subject to the inherent thermal and friction losses present in ICE and can achieve higher fuel use efficiencies. It features greater efficiencies at partial loads as well [29]. Conventional ICE only surpasses it at high loads, when, for example, pumping losses in spark ignition engines is reduced [30].

PEM fuel cell is the most commercially available technology for vehicles nowadays. This cell operates at low temperatures (below 100 °C) determined by the polymer, which necessitates high purity hydrogen to avoid cell poisoning and durability issues [29].

A schematic view of H_2 fuel station and vehicle electric motor (eMotor) is depicted in Figure 4. Electricity coming, for example, from the grid is transformed into chemical energy in the form of hydrogen, filling up the vehicle's tank. Once inside the vehicle, the hydrogen is converted back into electricity through the fuel cell and supplied to the eMotor.

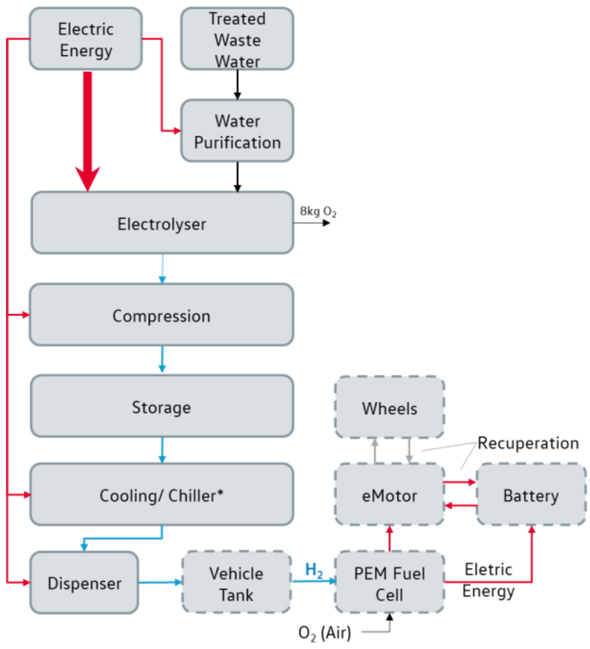

Figure 4. Schematic view of filling station and vehicle (dashed blocks).

This configuration differs from a battery electric vehicle (BEV), presenting the fuel cell instead of part of the batteries. As mentioned before, PEM's theoretical efficiency for converting H_2 into electricity is 83% [29], which can decrease to around 60% in real cases [31]. So, to provide 1 MJ to the eMotor, 1.67 MJ is consumed from the H_2 fuel tank. To provide this high purity gas, it was estimated previously in this study that 46.3 kWh (167 MJ) per kgH_2 (120 MJ) would be requested, an efficiency of 72%.

For 1 MJ of electricity to be delivered to FCEV's eMotor with this efficiency, 2.32 MJ (ratio between 1.67 and 0.72) would be purchased. Meanwhile, BEV losses are mostly related to the charging system, ranging from 83 to 94% [32]. Considering the average value of 89%, charging the batteries with 1 MJ would require purchasing 1.12 MJ, a more competitive result than FCEV.

WELL TO WHEELS EVALUATION

From the bottom to up of Figure 5, the PEM fuel cell stack converts, with 60% efficiency [31], 1.67 MJ of H_2 from high pressure tank into electric energy to eMotor. The compression phase, with 91% efficiency considering 3 kWh (10.8 MJ) compression power spent per kg of H_2 (120 MJ), as shown in Figure 3, demands 1.84 MJ to deliver 1.67 MJ to PEM. The anhydrous ethanol electrolysis with electricity performed in the Stationary Reformer produces hydrogen with 71% efficiency [26]. Following [26], it is necessary 0.116 L of anhydrous ethanol, with 2.45 MJ [33], and 0.128 MJ of electricity, totalizing 2.58 MJ to produce 1.84 MJ of Hydrogen (0.015 kg). The WtW results 39% overall energy efficiency, optimistic and still plausible according to value considered by [29] when converting natural gas to hydrogen, from 22 to 33%.

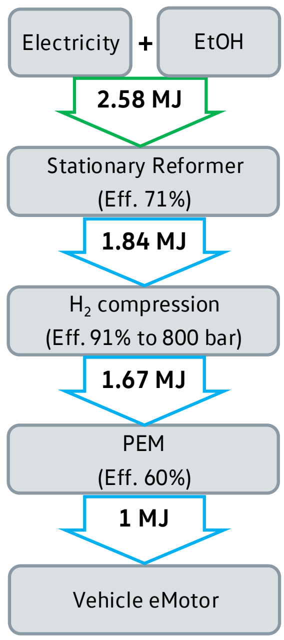

Figure 5. Flowchart of energy consumption and efficiency of the hydrogen production stages through ethanol reforming to supply an eMotor.

The hydrogen carbon intensity results in 73.7 gCO_2e/MJ, that is the sum of ethanol and electricity consumed by reformers. The anhydrous ethanol intensity was considered 26.9 gCO_2e/MJ [34] and Brazilian electricity carbon intensity of 31.8 gCO_2e/MJ [34]. Comparing a hydrogen fuel cell vehicle to a battery electric vehicle (BEV), the carbon intensity to deliver 1 MJ energy to vehicle battery results 35.3 gCO_2e/MJ calculated by Brazilian electricity grid and 90% efficiency of vehicle recharger [35].

The cost of 1 MJ of energy from H_2 can be estimated by the ethanol cost of 3.73 R$/L [27] for 0.116 L consumed, added by Brazilian electricity cost of 0.79 R$/kWh or 0.22 R$/MJ [28] for 0.128 MJ consumed, which result in 0.46 R$/MJ of hydrogen. The cost of electricity to recharge a BEV result in 0.24 R$/MJ for 90% recharging efficiency.

COMMENTS AND CONCLUSION

Hydrogen has an undoubtful energetic importance for the economy. It is necessary in many industrial processes and, when produced through renewable sources, can be used to decarbonize hard-to-abate segments in the Way to Zero path. However, this study showed disadvantages for considering hydrogen as a road map measure for future passenger cars when compared to other fuel alternatives. Examples of challenges are high powertrain/vehicle initial cost, fueling infrastructure investment and maintenance cost, hydrogen production prices and safety risks. Since CO_2e emissions reduction can be achieved in other ways, these expenses make it less viable. It is important to note that this scenario may change overtime and is different for transport other than light vehicles (e.g., trucks and buses).

Therefore, academic decarbonization research and funding/legislation benefits should focus on the production of low carbon hydrogen, its transportation without losses and its use as a basic chemical feedstock. In a continental country with strong agriculture and metallurgy, the demand for local production of fertilizers and green steel can consume low carbon H_2. Also, this gas can assist in reducing carbon intensity of fossil-based fuels, producing synthetic fuels for long haul jets and ships or even improving fuels as a drop-in additive. Finally, research for evaluating the benefit of on-board ethanol reforming for efficient Auxiliary Power Unit devices or for combustion and internal combustion engine efficiency improvement should also be considered.

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