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Comparing the costs of well- to- wheel and greenhouse gas emissions for the production and operation of a hydrogen fuel cell instead of ICE

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ABSTRACT

This study provides a comprehensive comparison of the well-to-wheel energy demand, emissions and costs of conventional internal combustion engine and hydrogen fuel cell passenger car propulsion systems. The use of fuel cells in the transportation industry is an important and well-known issue. Vehicle production, operation, repair, and decommissioning are considered, along with a wide range of processes for hydrogen production, electricity blending, and internal combustion engine fuel. Results are determined based on a reference vehicle, propulsion efficiency, life cycle estimation data, and cost estimation. Well-to-wheel results are sensitive to the electricity source used to compress or liquefy the hydrogen. In the category of fuel cell efficiency, the results are almost equal; obtaining hydrogen by water electrolysis and methane steam reforming have the same efficiency (75%), but in the biomass gasification method, a 26% decrease in efficiency is observedHydrogen fuel cell vehicles consume approximately 29–66 % less energy and cause approximately 31–80 % less greenhouse gas emissions than conventional vehicles.

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Introduction

Due to the increase in population, the demand for transportation has increased. The increase in the number of cars and the consequent increase in environmental pollution have increased the need for research on pollution control technologies. Increasing concern regarding energy supply, severe shortage of non-renewable energy sources, environmental harm, air pollution in urban areas and greenhouse gas emissions has led to the development of the transportation industry based on clean energy sources. Cars are a major part of daily life. Therefore, materials and gases released from the exhaust of internal combustion engine cars are the main source of urban pollution, which itself causes the greenhouse effect and ultimately leads to global warming. According to existing research, if the energy consumption trend continues in the current form, the amount of carbon dioxide in the environment will double its amount by 2050, which is unacceptable from the perspective of environmental issues and existing roadmaps. According to global plans, this amount should reach almost half of its amount in 2050. For example, the transport sector is the largest emitter of greenhouse gases (GHG) in Switzerland accounting for more than 30% of total annual emissions, followed by emissions from the industrial and household sectors (approximately 20% each) according to Federal Environment Office in Switzerland (2011. Passenger cars account for approximately 70% of the total greenhouse gas emissions in the transportation sector by the Swiss Federal Office for the Environment (2011). The large proportion of emissions from road transport in Switzerland offers an opportunity to reduce national greenhouse gas emissions through the adoption of alternative propulsion technologies and energy carriers in conjunction with urban planning and multimodal transport schemes [1]. This study aimed to identify power transmission and production routes that have significant potential to reduce WTW energy demand, GHG emissions and costs compared to gasoline ICEVs. This was achieved by determining the total primary energy demand of the WTW and the cumulative GHG emissions associated with the operation, production, maintenance and decommissioning of the engine. Relative costs were determined for key cost differentiators, including energy carrier and fuel cell system costs. Engines, energy carriers and production paths were selected for evaluation based on the potential shown in Yazdani et al [1]. Alternative engines included hydrogen fuel cell, battery-electric and hybrid-electric engines, and alternative energy carriers for gasoline and diesel which included hydrogen, electricity, biogas, and compressed natural gas, taking into consideration sensitivity analysis, driving range, and electrical and component costs. Infrastructure requirements and infrastructure costs were not the scope of this study. [2] .The scope of existing studies was also limited to conventional means of hydrogen production including electrolysis, steam methane reforming and coal gasification as exemplified by Campanari et al. The cost effects of alternative propellants were also considered. The novel feature of this study is that it provides a comprehensive comparison of key cost differences between propellants for a wide range of hydrogen and fuel production processes [2; 4]. The study draws on life cycle assessment data from the ecoinvent database of the Swiss Center for Life Cycle Inventories. Unlike other Life Cycle Assessment databases, it contains data specific to energy production pathways in Switzerland and Europe that are relevant to this study. The ecoinvent database applies Life Cycle Assessment (LCA) analyses according to the International Organization for Standardization (ISO) guidelines in International Organization for Standardization. It also follows the 2007 IPCC climate change guidelines, which use IPCC AR4 global warming appropriateness values. The following sections detail the approach and results presented for WTW primary energy demand, WTW emissions, and propulsion costs.

Necessity of doing research

Reducing greenhouse gas emissions (GHG) is an important global issue and the transportation sector is a highly important sector that can achieve the related goals. A committee has been formed in the European Union, whose goal is to reduce GHG emissions by 80% (based on 1990 levels) by 2050. The goal of this realization requires a 95% reduction in the emission of polluting gases from road transportation. Two key and important solutions to achieve these goals have been identified. The first is to increase the use of public transportation and the second is to upgrade the level of cars and provide cars with low pollutant emissions to cars without polluting gases. The use of fuel cells in the transportation industry is an important and well-known issue. Permanent customers of this technology in North America bought these systems for material handling vehicles without receiving government subsidies, and the number of fuel cell buses operating in cities around the world has increased, and for the first time, the mass production line of fuel cell vehicles has been launched. Therefore, the importance of producing these cars on a commercial scale in the fuel cell sector is an issue that cannot be disregarded. The mass production of these types of cars in the automotive industry sector can also bring economic benefits for this industry because it may lead to the production of components with higher quality and lower prices. The goal of car manufacturers is to reduce costs to the extent that the cost of these cars is equal to internal combustion engine cars. Therefore, reducing the costs of expensive catalytic materials such as platinum can be considered a great help in achieving this goal. One possibility is that platinum should no longer be used in fuel cell electric vehicles (FCEVs), but a catalyst can be used, such as catalytic converters installed in the exhaust of diesel vehicles. The existence of such efforts to reduce costs will benefit the producers and sellers of polymer fuel cells; thus, taking into account the volume of 88% of exchanges made for this type of fuel cell in 2012, it is obvious that fuel cell technology is currently booming. However, units still accounted for a small amount of exchanged power (41%) [5; 6]. Qian and Li [7] examined four types of logistics vehicles: hydrogen fuel cell vehicles, electric vehicles, LNG-fueled vehicles, and diesel-fueled vehicles. They analyzed and compared well-to-wheels energy consumption and emissions with the help of GREET software and conducted lifecycle assessments of the four types of vehicles to analyze their energy and environmental benefits. Yu et al. [8] investigated 17 major hydrogen pathways of fuel cell electric vehicles for their environmental impact, economic costs, and environmental efficiencies and compared with those of the energy pathway for battery-electric vehicles. Their results show that the pathways with hydrogen electrolysis from renewables have lower emissions and higher economic costs, which is contrary to the pathways with fossil-based hydrogen. Kuyumcu et al. [9] analyzed emissions and costs, considering both the entire energy production and consumption cycles for various vehicles. They showed that while fully electric vehicles currently have the lowest emissions, hydrogen-fueled vehicles can play a more prominent role in the near future with the increasing production of green hydrogen. Halder et al. [10] studied hydrogen fuel cell integration into vehicles, modelling and experimental investigations of hydrogen fuel cell vehicles with various powertrains. This study also reviews and analyzes the performance, energy management strategies, lifecycle cost and emissions of fuel cell vehicles. Previous literature suggested that the fuel consumption and well-to-wheel greenhouse gas emissions of hydrogen fuel cell-powered vehicles are significantly lower than those of conventional internal combustion vehicles. Hydrogen fuel cell vehicles consume approximately 29–66 % less energy and cause approximately 31–80 % less greenhouse gas emissions than conventional vehicles.

Well-to-wheel hydrogen fuel

Although the FCEV has no associated tailpipe emissions, the hydrogen stored inside the vehicle's tank may be associated with greenhouse gas emissions during the manufacturing and delivery/fueling stages. Emissions occur with the production of hydrogen from various raw materials. Emissions related to refueling occur during liquefaction or compression and pre-cooling in refueling terminals and stations. May estimated the greenhouse gas emissions associated with the hydrogen production and refueling route using WTW analysis. WTW analysis can be divided into well-to-pump (WTP) and pump-to-wheel (PTW) stages. As shown in Figure 1, The WTP stage includes the production of fuel from the primary source of energy (raw materials) delivered to the vehicle's energy storage system (fuel tank). The PTW stage includes fuel consumption during vehicle operation. The results of the WTP and PTW analysis for depicting WTW energy consumption and GHG emissions based on the fuel cycle is summarized. Life Cycle Analysis (LCA) is a standard tool for performing WTW analysis and assessing the environmental impact of a product "from cradle to grave" and it is already used for other types of transportation fuel [11].

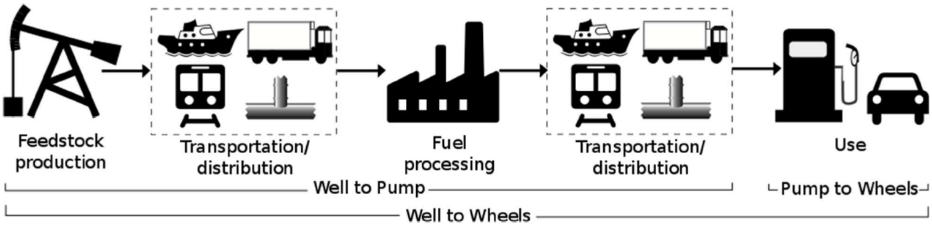

Figure 1: Well-to-wheel fuel cycle.

Hydrogen delivery routes

The hydrogen delivery route starts through the production plant and ends at the FCEV storage tank. The delivery route includes various processes such as liquefaction or compression at the distribution terminal, transportation and distribution, as well as compression, storage, pre-cooling and distribution at a fuel station. H_2 is produced at low pressure (~20 bar) from SMR and electrolysis processes and may be compressed for transport from the production plant to the distribution terminal through pipelines. However, in early FCEV deployment markets, the demand for H_2 may not justify the establishment of a dedicated H_2 pipeline network. Therefore, in the present study, it was assumed that the central H_2 production plant is adjacent to the distribution terminal. At the distribution terminal, H_2 is either compressed or liquefied so that it can be loaded into compressed gas pipe trailers or cryogenic liquid tankers for transport to fueling stations, as shown in Figure 2. [3].

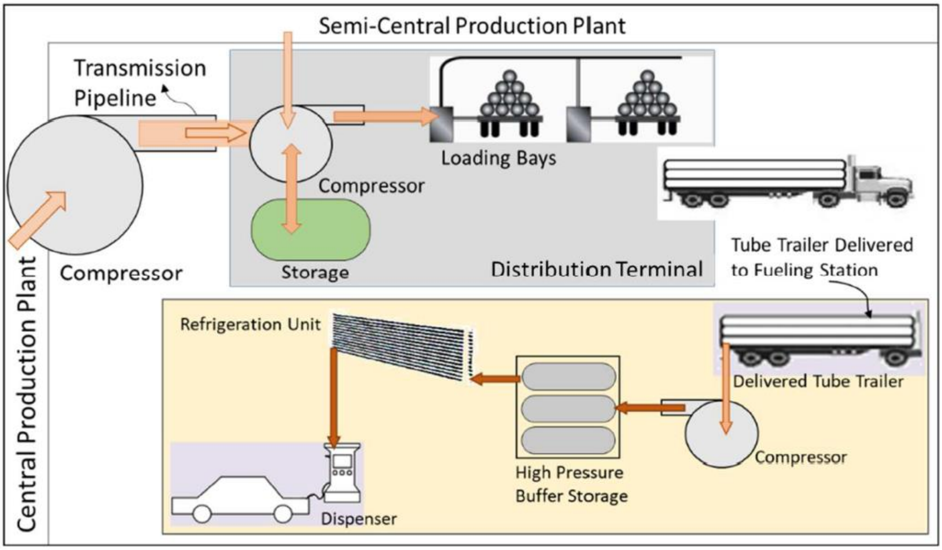

Figure 2. $G.H_2$ truck delivery schematic.

Gas transfer path

To deliver H_2 gas to refueling stations, H_2 may be compressed to a pressure between 200 and 500 bar and loaded onto gas pipe trailers for transportation and distribution (Figure 2). Pipe trailer payload depends on pipe volume, number of pipes, and loading pressure, and is limited by the US Department of Transportation to a gross vehicle weight limit of 80,000 pounds (36,287 kg). Currently, tube trailers are configured to carry between 300 and 1100 kg of compressed hydrogen gas ($G.H_2$), which can be unloaded or replaced with an "empty" tube trailer on demand. A pipe trailer at a gas station delivers H_2 to a gas compressor that compresses the H_2 up to 1,000 times and stores it in a high-pressure buffer storage system for distribution to vehicle tanks. The diffuser controls the flow from the high-pressure buffer tank into the vehicle tank using a cooling system that pre-cools the H_2 to -40°C to prevent overheating of the FCEV tank.

Liquid delivery route

H_2 can usually be converted to liquid using liquid nitrogen, which pre-cools H_2 from ambient temperature to 80 K, followed by a series of compression and expansion processes to reach the required temperature of 20 K. This is carried out to liquefy H_2. Liquid hydrogen ($L.H_2$) is then loaded into large cryogenic storage tanks at the adjacent distribution terminal and subsequently distributed into cryogenic liquid tankers for delivery to fueling stations. A liquid tanker carries approximately 4 tons of L.H_2 close to atmospheric temperature to be discharged in refrigerated tanks at one or more fueling stations. A refueling station's cryogenic tank stores H_2 at a pressure of 2-8 bar and delivers it to a high-pressure pump, which increases the H_2 pressure to over 700 bar, heats the pressurized H_2 through a heat exchanger to -40°C (known as a vaporizer) and distributes it in the tank of the vehicle (Figure 3). Alternatively, a cryogenic pump may be used to directly pump cryogenic H_2 into a compressed vehicle tank at 350 bar and -230°C (Figure 3). Usually, compressed cold is distributed in the proving phase which increases the energy storage density of FCEVs, thus improving the driving range of FCEVs [12].

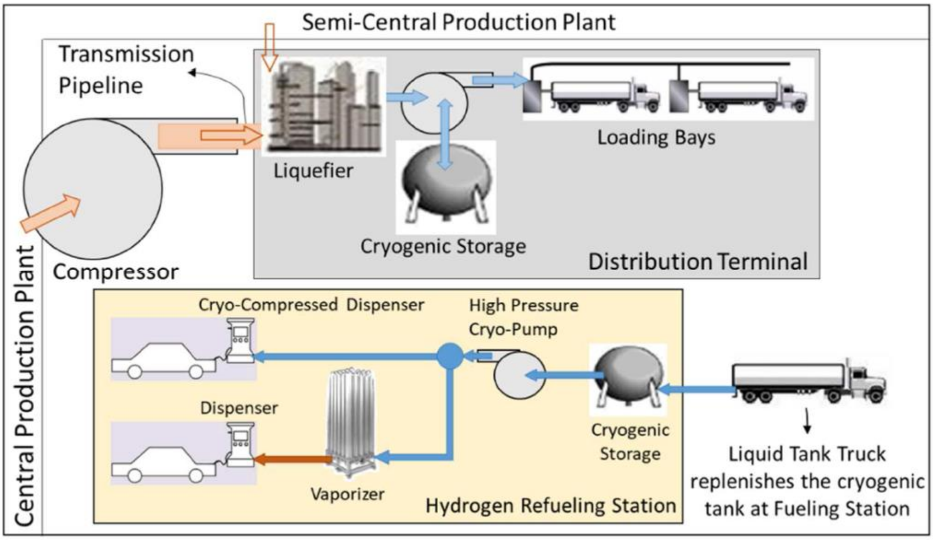

Figure 3. Schematic of L.H_2 delivery route.

Delivery of L.H_2 is generally more cost-effective compared to transporting compressed H_2 gas in tube trailers, especially for long transportation distances due to their higher load (4 vs. 1 metric ton). However, the H_2 liquefaction process is energy-intensive, consuming between 11 and 15 kWh per kg of H_2, depending on the H_2 supply pressure and the energy efficiency of the compression and expansion processes during liquefaction. Therefore, the electricity used for liquefaction must be low-cost and from low or zero-carbon sources. [13].

Table 1 . Estimation of energy consumption for H_2 delivery routes.

	L.H2 via Cryogenic Tanker Truc		G.H2 via Tube-Trailer Truck	
مشخ	4000(kg)	Payload	1000(kg)	Payload
	-	Working Pressure (bar)	500	Working Pressure (bar)
	90	Delivery Distance (mi)	90	Delivery Distance (mi)
در پایا	12	Liquefaction (kWh/kg H2)	2.58	Compression (kWh/kg H2)
	0.08	Pumping (kWh/kg H2)		
در حین	1.21	Fuel Use (MJ/kg H2)	3.64	Fuel Use (MJ/kg H2)
در جایگا گیر	0.55	Pumping (kWh/kg H2)	1.21	Compression (kWh/kg H2)
			0.63	Pre-Cooling (kWh/kgH2)

Production of PED energy carriers and GHG emission factors

PED and GHG emission factors for each hydrogen production route have been calculated in Yazdani et al. [1]. All PED and GHG emission factors of hydrogen and electricity are summarized in Figure 4. It is noteworthy that these factors account for all upstream processes and energy-carrying inputs except for hydrogen propellant manufacturing, maintenance, and disposal due to a lack of available data [1]. A detailed discussion of these values and calculations is presented in Yazdani et al. (2014) [1; 2].

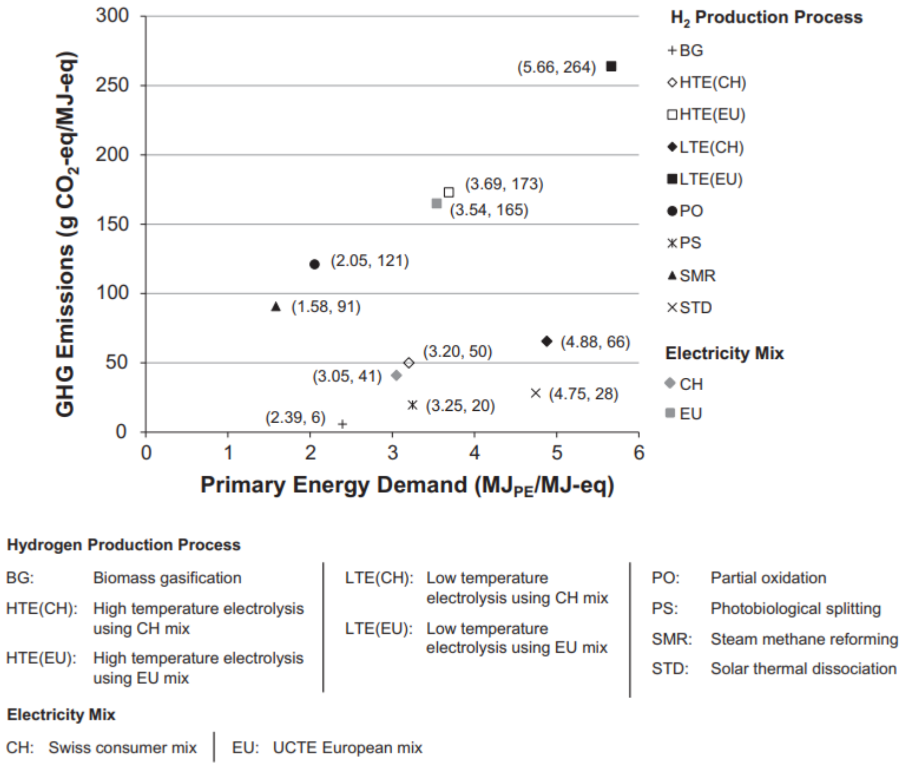

Figure 4. Hydrogen and electricity compare primary energy demand and GHG emission factors.

Energy carrier consumption rates

The consumption rate of the power plant is determined based on the method explained in the research of Yazdani et al. [1]. That is, the consumption rate of the reference vehicle based on the manufacturer's specifications calculated according to the European Union Vehicle Directive, using the New European Driving Cycle (NEDC) (Council of the European Communities, 1980). This cycle is a combination of urban and suburban driving conditions with a maximum speed of 120 km/h. Note that the increase in mass due to energy carriers, storage tanks, fuel cells and battery systems (including auxiliary battery systems such as casing, conductors, cooling and battery management system) is considered. All cars maintain the same power-to-mass ratio to ensure comparable performance across engines [1]. In the category of fuel cell efficiency, the results are almost equal; obtaining hydrogen by water electrolysis and methane steam reforming have the same efficiency (75%), but in the biomass gasification method, a 26% decrease in efficiency is observed. The compression efficiency is the same in all 3 methods [14].

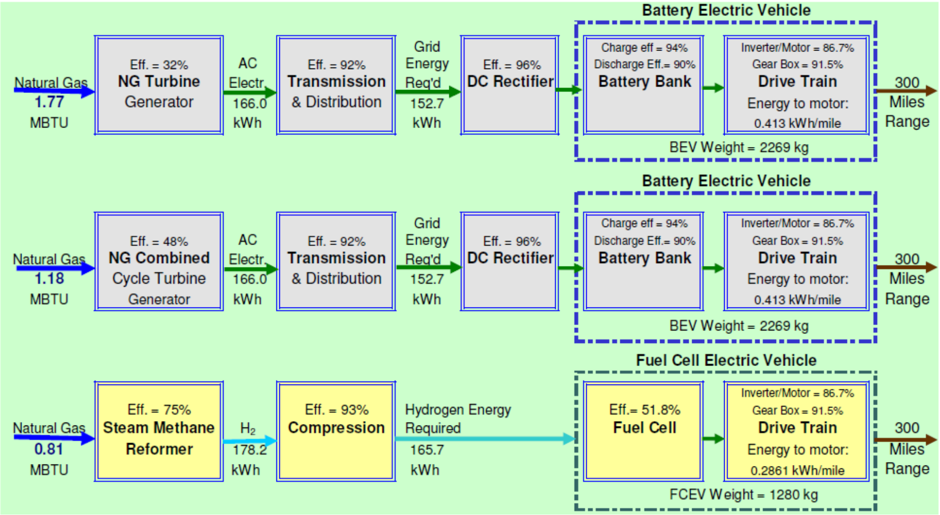

Figure 5. Comparing the efficiency of hydrogen production methods and fuel cell efficiency.

Production, maintenance, and disposal of primary energy demand and vehicle greenhouse gas emissions

The primary energy demand and GHG emission factors for the production, maintenance and disposal of the base ICE vehicle body were taken from the ecoinvent database of the Swiss Life Cycle Inventory Center (Swiss Center for Life Cycle Inventories, 2011). These factors are summarized in Table 9 and assumed for each type of engine. Car maintenance includes regular washing (every 833 km), service checks (every 15,000 km), and replacement of non-repairable parts. It assumes full recycling of steel, aluminium and copper and partial recycling of tires.

Table 2. Primary energy demand and greenhouse gas emission factors for the production, maintenance and disposal of the car body.

GHG emissions (kg CO_2-eq/kg)	Primary energy demand (MJ PE/kg)	Component
3.15	63.10	Body production
0.58	16.54	Maintenance
0.31	1.78	Disposal

Primary energy demand for power plant production and greenhouse gas emissions

The specific primary energy demand and greenhouse gas emissions for each type of engine are summarized in Table 10 [4]. These values include the contribution of machines, engines and gearboxes, and are based on the ecoinvent database. [1].

Table 3: Specific demand for primary energy and greenhouse gas emission factors for engine production.

GHG emissions (kg CO_2-eq/kW)	Primary energy demand (MJ $_{PE}$/kW)	Vehicle
4.2	93	ICEV
10.8	214	HEV
42.9	812	PHEV
9.1	166	EV/FCV

PED and GHG emission factors of the fuel cell

The specific primary energy demand and greenhouse gas emissions for fuel cell production and the hydrogen storage tank are provided in Table 4 [4; 15]. Fuel cell production data is based on the Ecoinvent database while the production of the reservoir uses data from the APME database and Boustead Model v.4.4.

Table 4: Specific demand for primary energy and greenhouse gas emissions for fuel cell system production.

GHG emissions	Primary energy demand	
18.2 kg CO_2-eq/kW	251 MJ $_{PE}$/kW	PEM fuel cell production
7 g CO_2-eq/kg $_{tank}$	251 MJ $_{PE}$/ kg $_{tank}$	H_2 storage tank production

Cost calculations

Costs are determined before tax for cost differentiators only. This includes the demand for energy carriers and the generation of batteries or fuel cell systems. All other vehicle costs are assumed to remain roughly the same across powertrains, which is a reasonable assumption given that electric motor and ICE prices are similar [4]. Infrastructure costs are not considered in the present study. Fuel cell cost estimates vary according to the reference source and time frame. Fuel cell costs based on the source are summarized in Table 5. The prices of diesel, CNG and biogas are considered in relation to these three gasoline reference prices according to the trends of Ref. [14]. The range of fuel prices is summarized in Table 13 in €/petrol l-eq [14].

Table 5. Fuel cell cost estimation.

Source	Assumptions	Fuel cell cost \kW$_{el}$€
Thomas, C. E. (2009)	Current state of technology with a platinum content of 0.189 g/kW, high volume production (HVP), and a platinum cost of 34 €/g	38
Thomas, C. E. (2009)	Doubling the amount of platinum (or assuming an increase in platinum cost), HVP	44
Thomas, C. E. (2009)	Long-term cost which assumes, among other improvements, a reduction in the amount of platinum to 0.125 g/kW	29
Thomas, C. E. (2009)	Current state of technology and HVP; H2 storage tank cost included	41

Hydrogen storage tank costs are estimated at 463 €/kgH_2 if fuel cells are not included in the cost estimate.

Table 6. Range of gasoline, diesel, CNG and biogas prices before taxes in €/l-eq.

Reference	Upper estimate	Mid-range estimate	Lower estimate	Fuel
[13]	0.90	0.80	0.70	Gasoline
[12]	0.87	0.78	0.68	Diesel
[14]	0.63	0.56	0.49	CNG
[14]	1.21	1.07	0.94	Biogas

A range of hydrogen cost estimates for each hydrogen production process is considered based on international sources. High and low cost estimates by process are summarized in Table 6. These estimates reflect large-scale hydrogen production and are applied in the case of Switzerland assuming technical similarities. A summary of energy carrier costs is shown in Figure 6 in terms of GJ/€ for ease of comparison.

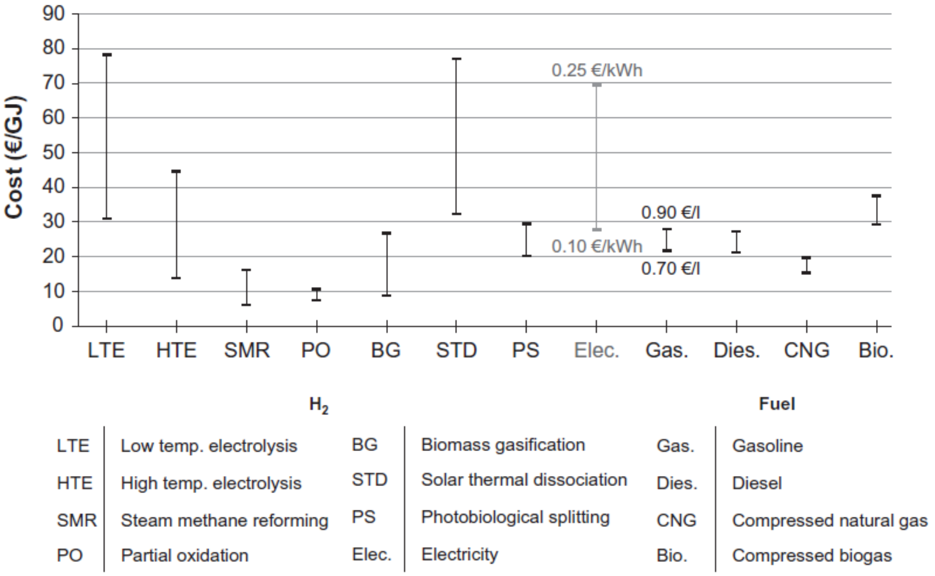

Figure 6. Comparative range of energy carrier cost estimates before tax.

In a paper by Lohse-Busch et al., fuel consumption and operating vehicle emissions (ie, PTW) data for a HFCEV (Toyota Mirai) and a comparable conventional gasoline ICEV (Mazda 3) are reported. In the present paper, the system boundary has been extended to include the effects of fuel production and delivery steps (ie, WTP). The argon GHG model was used, and adjusted emissions and energy use in transportation to perform WTW analysis for various H2 production and delivery routes and compared it to conventional gasoline-based ICEVs. The fuel cycle was exclusively focused on. However, the vehicle manufacturing cycle, including material extraction, vehicle component manufacturing, vehicle assembly, and vehicle recycling steps, was outside the scope of this analysis.

Conclusion

Based on the comparison of costs and greenhouse gas emissions for the production and operation of a hydrogen fuel cell versus an ICE, it is evident that hydrogen fuel cells offer a more sustainable and environmentally friendly option. Despite potentially higher costs associated with initial production and infrastructure development, the long-term benefits of reduced greenhouse gas emissions and improved energy efficiency make hydrogen fuel cells a promising alternative for the future of transportation. As technology continues to advance and economies of scale are achieved, the costs of hydrogen fuel cells are likely to become more competitive with ICE, making them a viable solution for reducing the carbon footprint of the transportation sector.

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