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Comparative Environmental Assessment of a Gasoline and Fuel Cell Vehicle with Alternative Hydrogen Pathways in Iran

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A comparative full life cycle assessment of a gasoline vehicle and a fuel cell vehicle (FCV) with five different fuel cycles including steam methane reforming (SMR), coal gasification, photovoltaic (PV), solar thermal, and grid-based electrolysis is presented in this paper. The results show that the total greenhouse gas emissions (GHG) are mainly found in the materials production and the component manufacturing stages of the FCV. Among various hydrogen production methods, the FCV with PV electrolysis has the lowest GHG emissions of 0.13 kg CO2 eq./km. The total GHG emissions of the gasoline vehicle are estimated as 0.30 kg CO2 eq./km mainly from the operation stage. An uncertainty analysis is carried out to assess the effects of variations of different input parameters on the total emissions. With a 95% level of confidence, the total emissions of the FCV with PV electrolysis is 0.18±0.05 kg CO2 eq./km. The component manufacturing and assembly stage drives the total GHG emissions uncertainty the most.

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2. Introduction

Transport sector, with considerable energy consumption, is one of the major sectors of a country's economy. In Iran, the transport sector consumes 318 million barrels of oil equivalent per year which is over 17% of the country's annual energy demand [1]. Transportation accounts for approximately 24% of the total greenhouse (GHG) emissions of the country [2]. Therefore, for a cleaner future, the environmental issues regarding the transport sector should be addressed.

Hydrogen, as a clean energy carrier, is an excellent candidate for a more environmentally benign transport sector. Both fuel cells and internal combustion engines can use hydrogen to drive the vehicle. Proton Exchange Membrane (PEM) fuel cells are the most promising propulsion system due to their rapid startup time, high energy density, low weight and volume [3,4]. Hydrogen is mostly produced from fossil fuels currently. Therefore, it is required to investigate more sustainable pathways for hydrogen production.

Evangelisti et al. [4] performed a life cycle assessment of a fuel cell vehicle (FCV) and compared it with an internal combustion engine vehicle (ICEV). Honda FCX Clarity was selected, and the focus was on the manufacturing phase of the fuel cell system. It was shown that the total GHG emissions of the FCV was about 32% less than those of the ICEV [4].

Simons and Bauer [5] also conducted a life cycle assessment of a fuel cell vehicle. The total GHG emissions of the FCV was estimated as 0.296 kg CO2 eq./km considering hydrogen production through steam methane reforming (SMR) [5]. Bicer and Dincer [6] performed a comparative well to wheel life cycle analysis for methanol and hydrogen vehicles. It was shown that the GHG emissions of the hydrogen vehicle were 6 times lower than those of the methanol vehicle. Duclos et al. [7] presented an LCA of the recycling process of the platinum catalyst in the membrane electrode assembly of the proton exchange membrane (PEM) fuel cell. It was shown that about half of the environmental impacts could be avoided through platinum recovery at the end of life of the system.

Sharma and Strezov [8] conducted a life cycle assessment of diesel, gasoline, liquified petroleum gas, bio-diesel and hydrogen vehicles in Australia. It was indicated that the hydrogen vehicles have the lowest environmental impacts. In another study, Elgowainy et al. [9] presented a comparative evaluation of gasoline, diesel, compressed natural gas, and hydrogen vehicles in the United States. It was shown that the manufacturing phase of the hydrogen fuel cell vehicle has the highest GHG emissions.

Yoo et al. [10] conducted a life cycle assessment of a hydrogen FCV in South Korea. Their results indicated that if hydrogen is produced via water electrolysis using the Korean grid electricity, the GHG emissions of the fuel cell vehicle are over two times those associated with a conventional gasoline vehicle. Various hydrogen production methods were considered by Pereira and Coelho in Portugal [11]. Their results showed that GHG emissions of the FCVs with wind-based hydrogen are less than 85% of those of a gasoline vehicle. On the other hand, if hydrogen is produced through water electrolysis with Portugal grid electricity, the total GHG emissions are 43% higher than those of a gasoline vehicle.

Life cycle assessment of a fuel cell vehicle for various Canadian provinces was conducted considering three hydrogen pathways including SMR, thermochemical, and electrolysis [12]. It was shown that the best scenario with the lowest GHG emissions is nuclear-based thermochemical hydrogen production in Ontario. In another study, real life parameters such as fuel cell deterioration, performance of the fuel cell, actual driving cycle, and regenerative braking were considered. It was shown that the fuel cell degradation led to an increase in the total life cycle GHG emissions of the FCV by 520 kg CO2 eq. [13]. Effect of various driving patterns was also studied and it was shown that the highway driving pattern is the most favorable driving pattern [14]. Changizian et al. [15] optimized the performance of a fuel cell vehicle under realistic driving condition and showed that by using ultra capacitors, 3.3% reduction in fuel consumption is achievable.

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Only few studies in the past considered both fuel cycle and vehicle cycle in the life cycle assessment. Also, no publication has been found on an LCA of fuel cell vehicles specific to Iran. The main objectives of this paper are as follows:

- An Excel-based data-intensive LCA model is developed to determine the total GHG emissions of a fuel cell vehicle considering both fuel cycle and vehicle cycle.
- Various hydrogen production pathways including SMR, coal gasification, photovoltaic electrolysis, parabolic trough solar based electrolysis, and grid-based electrolysis are considered.
- The results for the life cycle GHG emissions are compared with those of an internal combustion engine vehicle currently used in transportation sector in Iran.
- Uncertainty analysis is performed using Monte Carlo simulation to investigate uncertainties LCA.

2. Approach and methodology

2.1. Life cycle assessment

Life cycle assessment (LCA) evaluates the environmental aspects of a product system from raw material acquisition to final disposal. It consists of four phases [16]:

- Goal and scope definition including the reasons for performing the study, the system boundary, and the functional unit

- Inventory analysis including data collection and quantifying inputs and outputs of each stage

- Impact assessment including evaluation of significance of potential environmental impacts

- Interpretation including considering the findings from the inventory analysis and the impact assessment phases to present consistent results with the goal and scope definition phase of study

The main life cycle stages and system boundary are shown in Fig. 1. The fuel cycle includes raw material acquisition, feedstock transport, fuel production, and fuel transportation and distribution. The vehicle cycle includes material production, component fabrication assembly, vehicle operation, and recycling. The functional unit is 1 km driven by the vehicle.

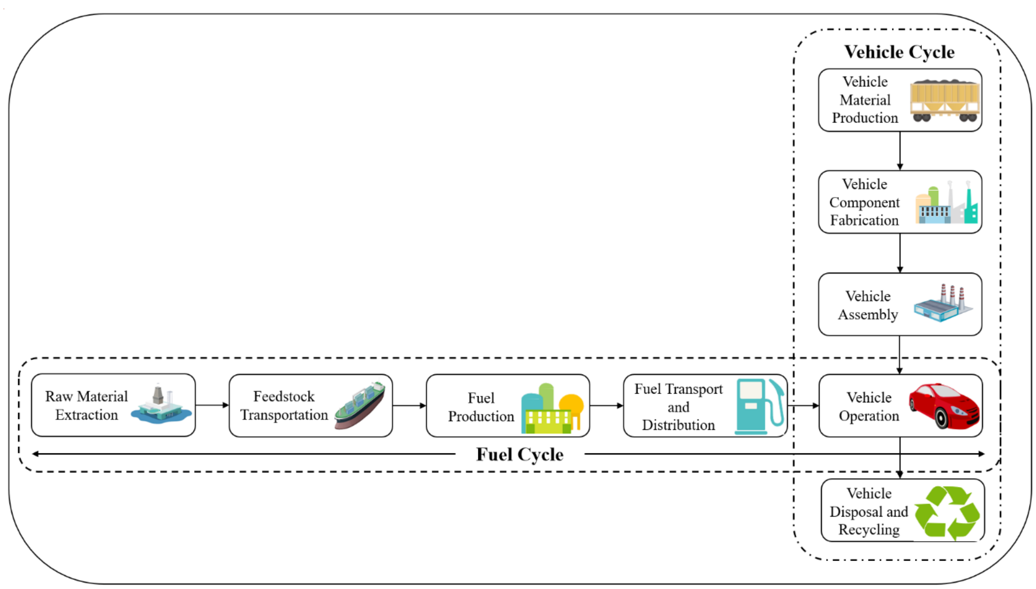

Fig. 1 Main life cycle stages considered in this study.

2.2. Uncertainty analysis

A major problem regarding LCA is the uncertainty in the data used in the inventory

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analysis. Various techniques are available to estimate uncertainties in LCA. A framework for data uncertainty analysis in an LCA was presented by Huijbregts et al. [17]. Data uncertainty is divided into two categories: absence of data, and inaccuracy of data. Applying uncertainty factors, and using input-output modelling and stochastic modelling, are potential options to deal with data inaccuracy for an uncertainty analysis [17]. Stochastic modelling done through a Monte Carlo simulation is a useful technique to deal with data uncertainty in LCA. Monte Carlo simulation is a computerized mathematical method based on repeated random sampling which by creating thousands of random scenarios accounts for future uncertainties. This simulation creates thousands of scenarios by randomly picking different values from a user-predefined probability distribution function to calculate the uncertain variables [17]. Among various available risk analysis add-ins, ModelRisk is selected and used in this paper.

3. Input data and assumptions

3.1. Fuel cell vehicle cycle

The fuel cell vehicle considered in this study is Toyota Mirai 2019 [18]. The fuel cell stack of the FCV has a power output of 113 kW and consists of 370 polymer electrolyte membrane cells. An average fuel consumption is 0.76 kg H_2/100 km [18,19].

Three main options are available for on-board hydrogen storage including storage of gaseous hydrogen in high pressure tanks, storage of liquified hydrogen in insulated tanks, and storage of hydrogen as protons in solids (metal hydrides) [18,20]. In the first case, hydrogen gas is compressed in vessels at the pressures up to 700 bars. This method is currently used in Toyota Mirai and Honda FCX clarity [4]. The second option is to use liquified hydrogen in insulated tanks. BMW uses this type of storage for their 7 series hydrogen ICEVs [18]. The liquefaction process requires about 40% of the total energy content of hydrogen. The last option is to use metal-hydrides for hydrogen storage which was demonstrated by Mercedes-Benz [18]. Weight of the vehicle is the main issue in this method. Therefore, in this study, the first method is considered for hydrogen storage. The FCV has two high pressure type 4 hydrogen storage tanks with normal operating pressure of 700 bar and storage capacity of 4.98 kg [19].

The fuel cell vehicle also has a high-voltage EV battery and a low-voltage auxiliary battery. The high-voltage EV battery consists of 34 Nickel-Metal Hydride batteries with a total voltage of 244.8 V [21]. An alkaline mixture of potassium and sodium hydroxide is used as the electrolyte. It powers the air compressors, converters, pumps, stack, inverters, and motor assemblies. Other devices including the radio, head lights and gauges are powered by a 12 V lead-acid auxiliary battery. The lead-acid battery is changed three times during the vehicle lifetime [22].

Electric traction motor and other components of the drivetrain except the fuel cell assembly is considered as the powertrain assembly. The FCV electric motor considered in this study is a 113kW permanent magnet AC synchronous motor [23]. Glider consists of body of the car, braking, steering, wheels, suspension systems and non-propulsion related electronics. Assembly, disposal and recycling (ADR), tire replacement, and vehicle fluids such as windshield, powertrain fluid, transmission fluid and powertrain coolant are also considered in this study.

Total weight of the vehicle is 1,848 kg. Weight distribution of various components of the fuel cell vehicle is shown in Fig. 2 [18,19]. Glider with the weight of 1,330 kg accounts for 71% of the total weight of the vehicle followed by fuel cell system with a weight of 225 kg [18,19]. Table 1 presents material and energy consumption for the fuel cell vehicle cycle.

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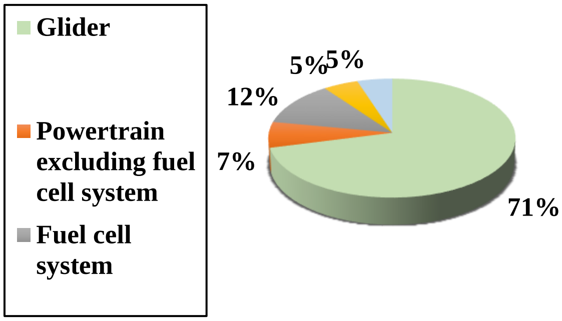

Fig. 1 Weight distribution of various components of the FCV.

Table 1 Material and energy consumption for the fuel cell vehicle cycle.

Material/Energy	Value
Steel and iron (kg)	1315.7
Aluminum and aluminum alloys (kg)	127.5
Copper and brass (kg)	79.4
Glass (kg)	53.6
Rubber/plastics (kg)	231
Others (kg)	40.6
Energy (kWh/km)	2.71×10^{-1}

Data sources: [4,5,18,19,24,25]

3.2. Hydrogen Production Pathways

Schematic of alternative hydrogen production pathways considered in this study are shown in Fig. 3. Hydrogen production plant is located in Tehran. Natural gas is transported from Asaluyeh natural gas field in Bushehr to the hydrogen production plant in Tehran through a 0.6m pipeline. The length of the pipeline is 1,250 km with a lifetime of 50 years [26]. The SMR plant produces hydrogen at a rate of 140,000 tonnes per year with thermal efficiency of 76%, capacity factor of 85% and lifetime of 20 years [27-29].

The coal from an underground coal mine is transported to the hydrogen production facility in 900 km of distance by rail. The hydrogen production plant has a lifetime of 20 year and efficiency of 64% [29-31].

The photovoltaic electrolysis plant consists of 464,000 mono-crystalline photovoltaic modules and produces hydrogen at a rate of 4,600 tonnes per year and. Each module has an aperture area of 1.6 m^2. The solar-to-electricity efficiency of the plant is 16% and the capacity factor is 24% [32,33]. Alkaline water electrolyzers are selected for hydrogen production in this study. Each electrolyzer has a production capacity of 600 kg/year, an efficiency of 68.5% and a lifetime of 15 years [34]. Total solar irradiance is 2200 $kWh/m^2/year$ in Tehran.

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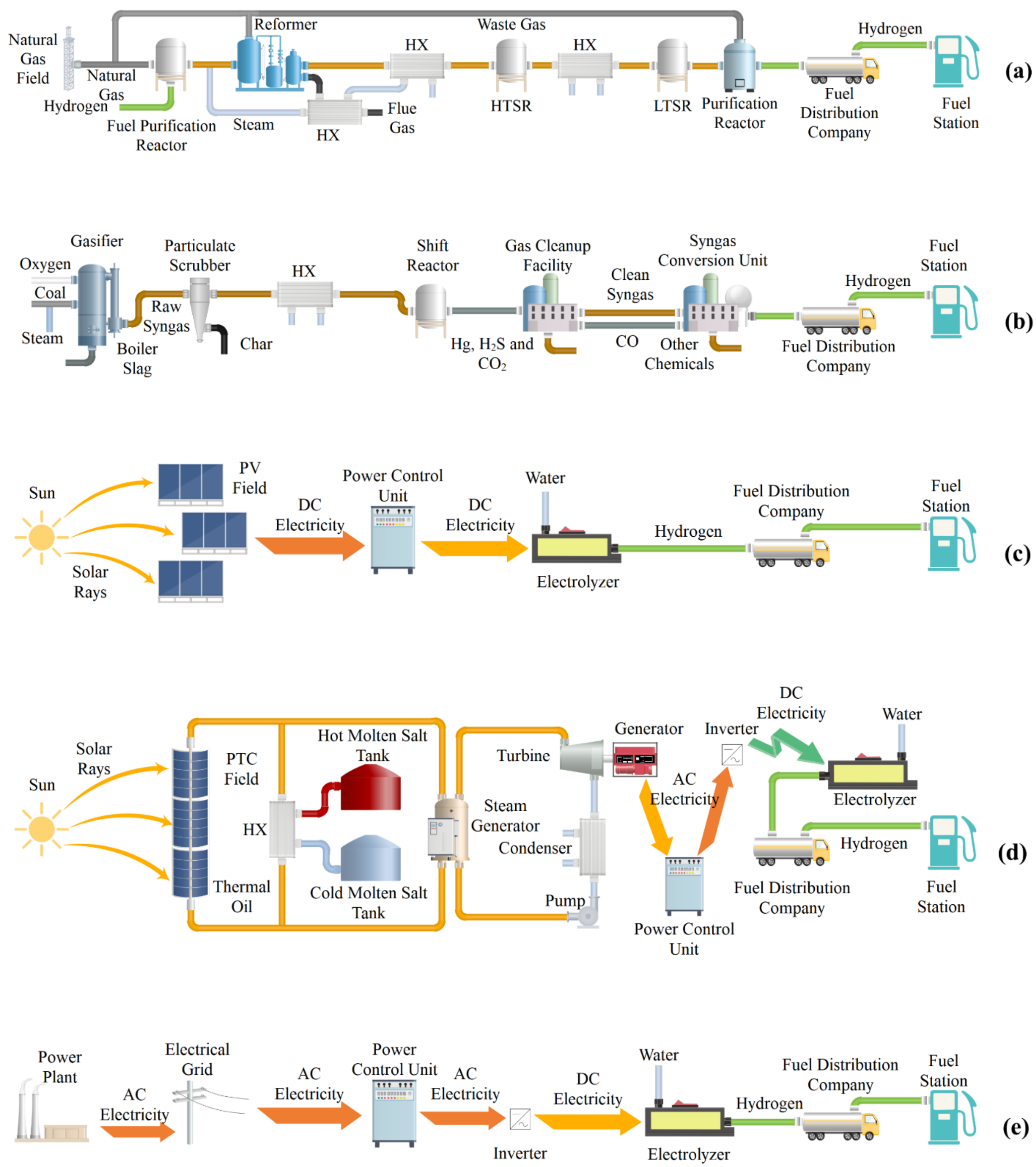

Fig. 3 Schematic of alternative fossil fuel-based pathways for hydrogen production: (a) steam methane reforming, (b) coal gasification, (c) solar photovoltaic electrolysis, (d) solar parabolic trough electrolysis, and (e) grid-based electrolysis.

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A parabolic trough concentrating solar power (CSP) plant with 7.5 hours of thermal storage and lifetime of 30 years is considered for solar thermal hydrogen pathway. Thermo-oil is used as the heat transfer fluid and molten salt is used as the thermal storage fluid. The molten salt is binary mixture of 60% sodium nitrate and 40% potassium nitrate. The solar field consists of 297 collectors with an aperture area of 1,720 m^2 each [32]. The thermo-oil passes through a heat exchanger to produce superheated steam for a Rankine cycle used for electricity generation. The solar-to-hydrogen efficiency is 11%, on a higher heating value basis [34].

Fig. 4 shows the electricity generation mix in Iran. Over 90% of grid power is produced from fossil fuels [35]. The electricity-to-hydrogen efficiency of the electrolyzer is 68.5%. Transmission losses of 11.5% are considered in this study [36]. The upstream emission here is 0.65 kg CO_2 eq./kWh [35,36].

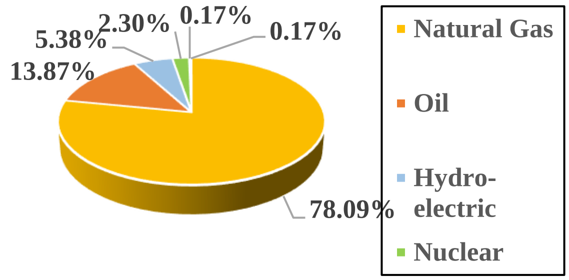

Fig. 4 Electricity generation mix in Iran. Data source: [36].

Material and energy consumption for alternative hydrogen production pathways is presented in Table 2 [30-35,38,39].

Table 2 Material and energy consumption for alternative hydrogen pathways.

Material/Energy	Steam methane reforming	Coal gasification	PV electrolysis	Parabolic trough electrolysis	Grid electrolysis
Steel and iron (kg/km)	2.75×10^{-5}	3.12×10^{-5}	12.46×10^{-4}	26.95×10^{-4}	12.07×10^{-4}
Concrete (kg/km)	8.52×10^{-5}	10.26×10^{-5}	25.28×10^{-4}	58.51×10^{-4}	18.06×10^{-4}
Aluminum and aluminum alloys (kg/km)	2.24×10^{-7}	3.14×10^{-7}	41.67×10^{-5}	60.53×10^{-5}	1.49×10^{-6}
Glass/silicon (kg/km)	-	-	47.46×10^{-5}	51.07×10^{-5}	1.86×10^{-5}
Energy (kWh/km)[a]	3.86×10^{-1}	4.25×10^{-1}	9.74×10^{-3}	9.48×10^{-4}	3.69×10^{-1}
Synthetic Oil (kg/km)	-	-	-	15.97×10^{-5}	-
Molten Salt (kg/km)	-	-	-	20.49×10^{-4}	-

[a] *Includes electricity, natural gas, and coal.*

3.3. Hydrogen compression and distribution

Hydrogen leaves the hydrogen production facility at a pressure of 10 bars and is compressed to a pressure of 200 bars at the hydrogen distribution facility for transportation by tube trailers. The transportation distance is about 30 km. Hydrogen is then compressed to a

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pressure of 820 bars at the fueling station. The compressor has an efficiency of 91% and lifetime of 25 years [10].

3.4. Gasoline vehicle

Iran Khodro Samand LX EF7 is selected for the comparison. Its specifications are shown in Table 3 [40]. The lifetime of the vehicle is about 8 years or 150,000 km which is similar to the FCV studied [41].

Table 3 Specifications of the gasoline vehicle considered in this study.

Category	Details
Number of cylinders	4
Power	85 kW
Vehicle weight	1,274 kg
Fuel consumption	7.49 l/100 km
Emissions standard	Euro IV

4. Results and discussion

Fig. 5 shows the GHG emissions associated with the manufacturing stage of the FCV vehicle cycle. It is shown that the glider production has the highest contribution to the GHG emissions. This is due to the steel and iron materials required for its manufacturing stage. The manufacturing of the glider, hydrogen tank and fuel cell stack emits 0.034, 0.015 and 0.013 kg CO_2 eq./km, respectively.

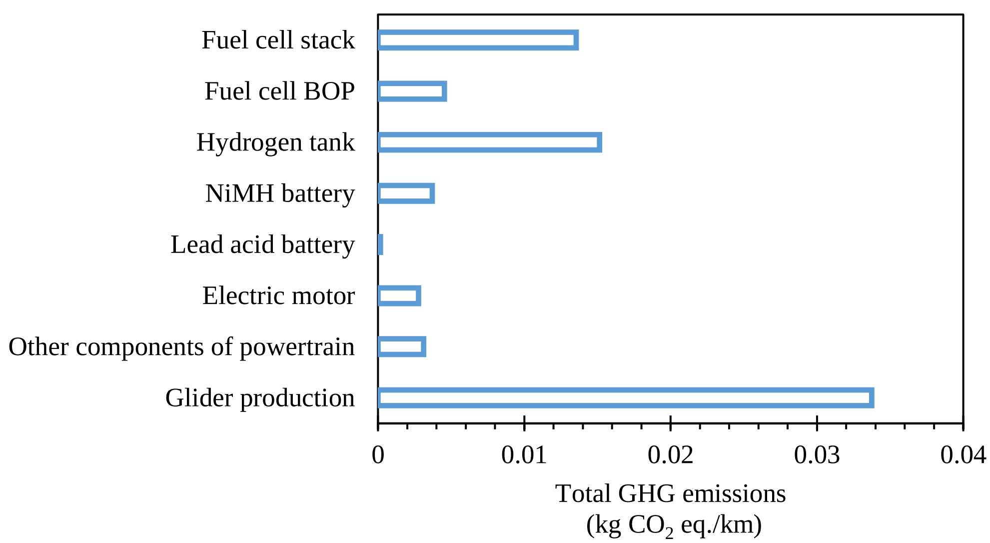

Fig. 5 GHG emissions of the manufacturing stage of the fuel cell vehicle cycle.

As shown in Fig. 6, total GHG emissions of the vehicle cycle of an FCV are 0.094 kg CO_2 eq./km. The material production and component manufacturing contribute about 81% of the total GHG emissions of FCV. The manufacturing stage of a gasoline vehicle emits 0.030 kg CO_2 eq./km which is significantly less than those of a fuel cell vehicle. The operation phase of the gasoline and fuel cell vehicle emits about 0.21 and 0.01 kg CO_2 eq./km, respectively.

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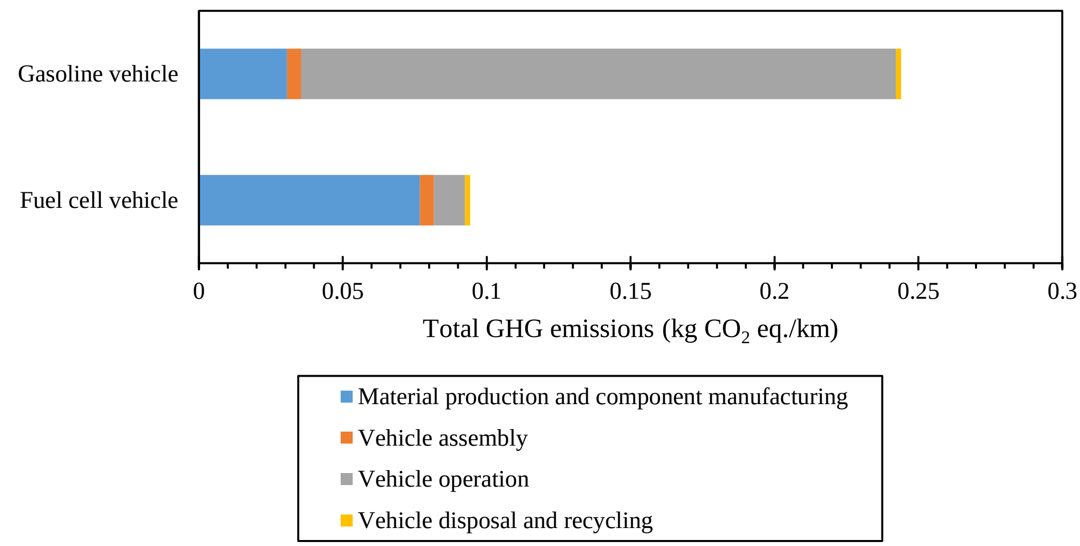

Fig. 6 GHG emissions associated with the vehicle cycle of a fuel cell and a gasoline vehicle

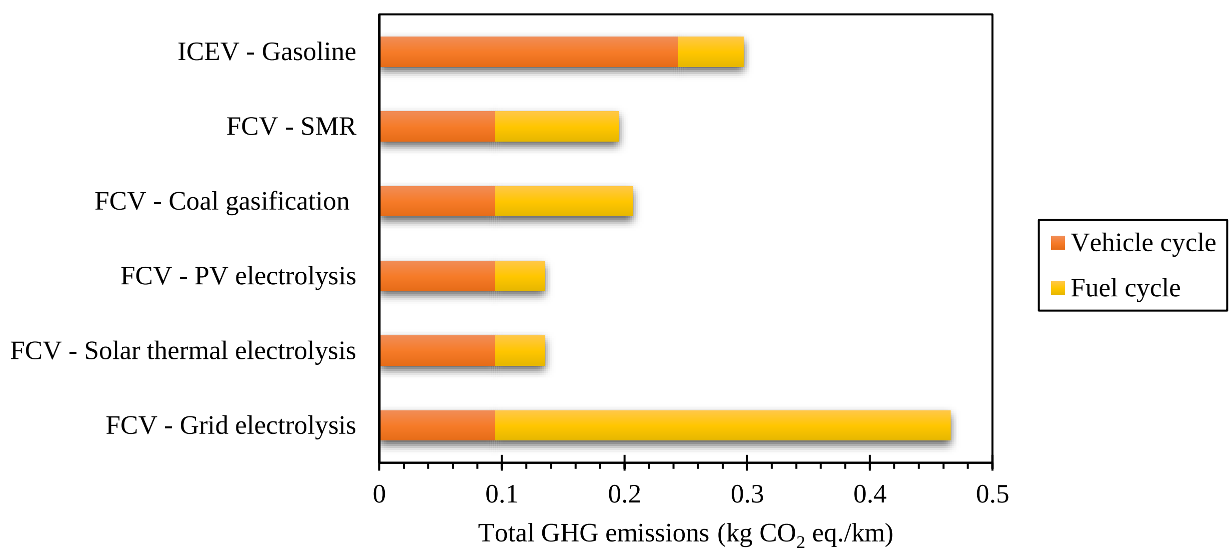

Fig. 7 Total life cycle GHG emissions of the gasoline vehicle and FCV with alternative hydrogen pathways.

Fig. 7 shows the total life cycle GHG emissions of the fuel cell and gasoline vehicles considering both vehicle cycle and fuel cycle. FCV with grid electrolysis has the highest total GHG emissions which are 0.465 kg CO2 eq./km. This is 56% higher than that of the gasoline vehicle. As stated earlier, over 90% of grid electricity in Iran is based on fossil fuels.

The most environmentally benign cases are the FCV with PV based electrolysis and solar thermal based electrolysis with the total GHG emissions of about 0.135 kg CO_2 eq./km, respectively. Although the material consumption of the PV electrolysis is less than that of the solar thermal electrolysis, the total GHG emissions of PV electrolysis and solar thermal electrolysis are

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almost the same due to the large energy consumption of photovoltaics in the manufacturing of mono crystalline cells. Also, total GHG emissions of the FCV with hydrogen from SMR and the gasoline vehicle are 0.19 and 0.30 kg CO_2 eq./km. Our results show that FCV with grid electrolysis is not suitable for Iran. However, fuel cell vehicles have less emissions than gasoline vehicles even if SMR is used for hydrogen production. FCVs with renewable-based hydrogen can reduce the total GHG emissions significantly.

Currently, the hydrogen production cost in Iran is about \$2/kg H_2 for SMR and \$40/kg H_2 for PV electrolysis [42,43]. It is expected that by decreasing the cost of renewable energy in near future, the solar-based hydrogen pathways will be competitive.

The results for GHG emissions of FCVs are compared with those reported by previous studies for different hydrogen production methods in Table 4. Our results are in good agreement with past studies. Simons and Bauer [5] considered European electricity mix with an emission factor of 0.35 kg CO_2 eq./kWh. Burnham et al. [24] considered U.S.electricity mix in their study with an emission factor of 0.45 kg CO_2 eq./kWh. Also, Yang et al. [44] used China electricity mix with an emission factor of 0.72 kg CO_2 eq./kWh which is higher than that of Iran.

Table 4 Comparison between our results for GHG emissions[a] and previous studies.

Study	Location	FCV - SMR	FCV – Coal gasification	FCV – PV electrolysis	FCV – Solar PTC electrolysis	FCV – Grid Electrolysis
Present study	Iran	0.195	0.207	0.134	0.135	0.465
Simons and Baur [5]	Europe	-	-	0.155	-	0.454
Burnham et al. [24]	United States	0.178	-	-	-	-
Yang et al. [44]	China	-	-	-	-	0.491

[a] *All the emissions are in kg CO_2 eq./km.*

4.1. Uncertainty analysis

An uncertainty analysis is conducted using a Monte Carlo simulation model through ModelRisk. Table 5 shows the variations in key input parameters. It is noted that the fuel cell stack is replaced once the vehicle lifetime exceeds 150,000 km.

The results for the total GHG emissions of the FCV with PV electrolysis are shown in Fig. 8. As can be seen, with a 95% level of confidence, total GHG emissions range between 0.13 and 0.23 kg CO2 eq./km. It is important to know which life cycle stage causes this uncertainty. The tornado chart in Fig. 9 shows the degree that the mean of the total emissions is affected by each stage distribution. It is observed that the component manufacturing and assembly drives the total GHG emissions uncertainty the most. The total emissions range from 0.15 to 0.21 kg CO2 eq./km depending on the emissions from the manufacturing and assembly stage. This range is 0.145-0.206 kg CO2 eq./km for hydrogen transportation and distribution, 0.156-0.195 kg CO2 eq./km for vehicle operation, and 0.167-0.183 kg CO2 eq./km for hydrogen production. The total GHG emissions are estimated to be 0.18±0.05 kg CO2 eq./km

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Table 5 Variations in key input parameters for the Monte Carlo Simulation.

Parameter	**Baseline**	**Range**
Vehicle lifetime (km)	150,000	100,000-200,000
Solar hydrogen plant lifetime (a)	30	25-35
Fossil fuel hydrogen plant lifetime (a)	30	25-35
Annual solar irradiance (kWh/m^2/year)	2,200	2,000-2,400
Solar-to-hydrogen efficiency (%)	11	7.5-14.5
Transportation distance to the fueling station (km)	30	500-0
Compressor efficiency (%)	91	87-95
FCV fuel consumption (kg H_2/km)	0.76	0.56-0.96
Gasoline vehicle fuel consumption (l/km)	7.49	5-10

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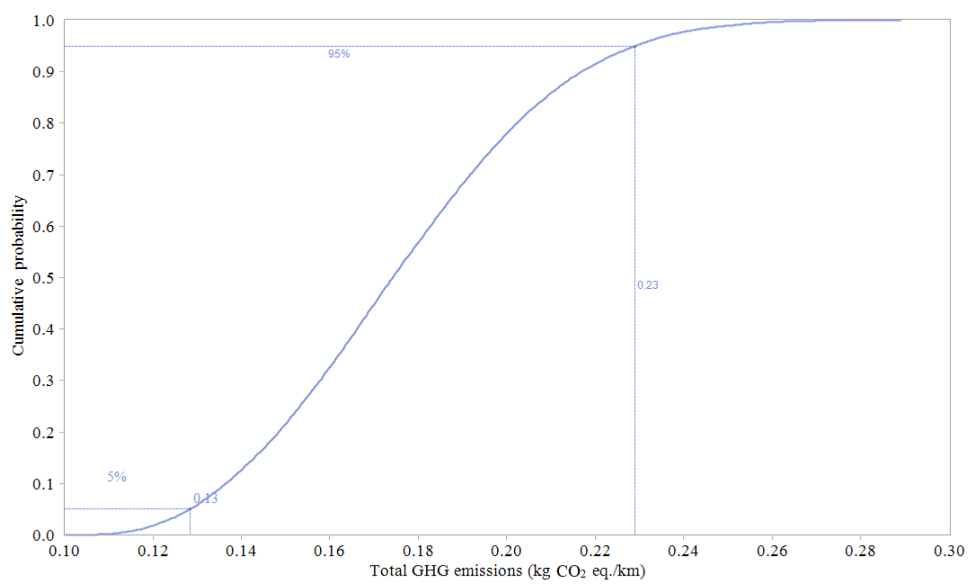

Fig. 8 Uncertainty analysis with Monte Carlo simulation.

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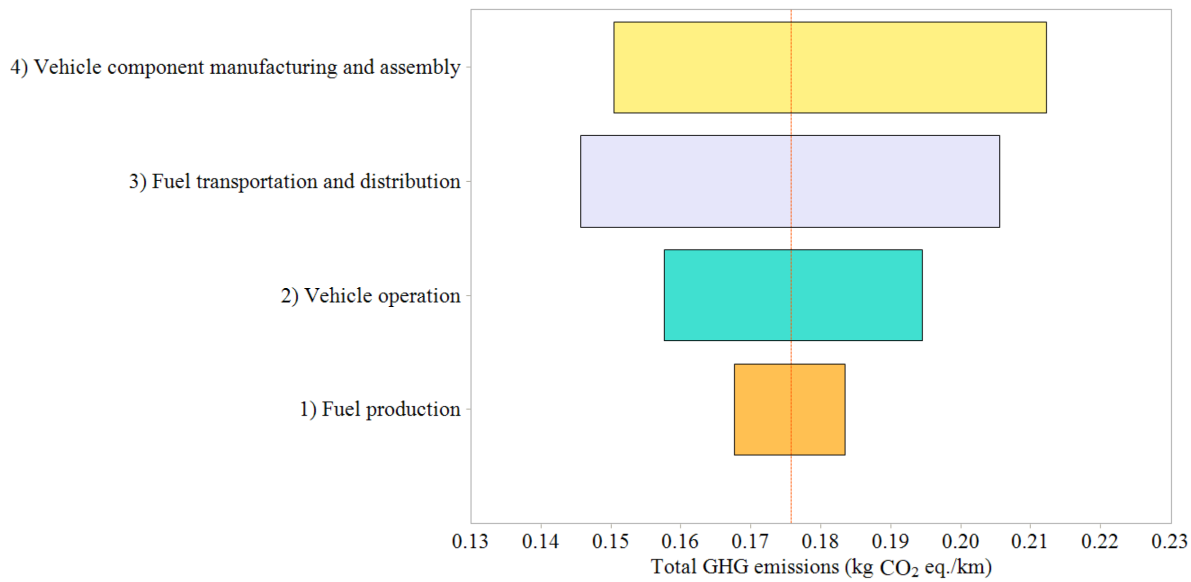

Fig. 9 Tornado plot for total GHG emissions of the FCV.

5. Conclusions

A comparative life cycle assessment study is conducted for a fuel cell vehicle considering both vehicle and fuel cycle. Five alternative hydrogen pathways including steam methane reforming, coal gasification, PV electrolysis, solar thermal electrolysis, and grid-based electrolysis are investigated in this study. The main findings of this study are as follows:

- The production of materials and component manufacturing have the highest contribution to the total GHG emissions of the FCV with a value of 0.076 kg CO_2 eq./km.
- The manufacturing of the glider, hydrogen tank, and fuel cell stack emits 0.034, 0.015, and 0.013 kg CO_2 eq./km, respectively.
- The GHG emissions during the operation phase of the FCV and ICEV are obtained as 0.01 and 0.21 kg CO_2 eq./km, respectively.
- Total GHG emissions of FCV with grid electrolysis are 0.465 kg CO_2 eq./km which is 56% higher than those of the gasoline vehicle.
- Total GHG emissions of the FCV with hydrogen from SMR are 0.30 kg CO_2 eq./km which are about 35% lower than those of the gasoline vehicle.
- FCV with grid-based electrolysis is not suitable in Iran. FCVs with renewable-based hydrogen can reduce the total GHG emissions significantly.
- The total GHG emissions of the FCV with PV electrolysis are estimated to be 0.18±0.05 kg CO_2 eq./km. The component manufacturing and assembly stage drives the total GHG emissions uncertainty the most.

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