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Life cycle assessment of solid oxide fuel cell vehicles in a natural gas producing country; comparison with proton electrolyte fuel cell, battery and gasoline vehicles

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Life cycle assessment of solid oxide fuel cell vehicles in a natural gas producing country; comparison with proton electrolyte fuel cell, battery and gasoline vehicles

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ABSTRACT

In this paper, the technical and economic feasibility of Solid Oxide Fuel Cell-Battery Hybrid Vehicles is studied based on Iran conditions and compared against Polymer Electrolyte Fuel Cell (PEFC) Vehicles, Battery Electric Vehicles (BEV) and Gasoline Vehicles. Existence of enormous resources of natural gas and its extensive distribution and transmission lines in Iran are a great opportunity to develop SOFC-Battery hybrid vehicles fueled by natural gas. In this paper, energy consumption and greenhouse gas emissions and life cycle cost were analyzed. We ranked different vehicles in 2021 and forecast their ranking for 2030, which is crucial for policymaking and technology support. The results show the well to wheel energy consumption of SOFC-Battery hybrid vehicle per km in 2021 is nearly same as PEFC FCEVs and 1060 kJ and 560 kJ less than gasoline and battery electric vehicle respectively. The well to wheel emission of SOFC FCEVs in 2021 is a little less than PEFC FCEV and 50% and 28% lower, respectively than gasoline vehicle and BEV. It is expected that the life cycle cost per km on a charge of SOFC hybrid vehicles with equal driving range will be the best choice in 2030 with 23.9 cents per km.

Introduction and literature review

Overview and importance

Fuel cell is an attractive alternative technology to the conventional method for power generation in transportation and residential applications. Fuel cells offer possibility of zero emission at the point of use, high power density, and low noise pollution. In recent years, the employment of fuel cells have been increasing significantly, with 800 MW of fuel cell stacks shipped in 2020 bringing the total accumulated capacity over 4 GW [1]. According to Global EV Outlook report [2], by the end of 2020, there are approximately 540 hydrogen refueling station (HRS) installed and about 34,800 fuel cell electric vehicles (FCEVs) on the roads; a 38% increase compared to 2019. Approximately three-quarters of the FCEVs in operation today are light-duty vehicles, which are commonly Toyota Mirai, Hyundai i35 and Nexo, and Honda clarity. In 2020, as shown in Fig. S1, Korea took the lead in having the highest number FCEVs, surpassing the United States and China, to reach more than 10,000 vehicles, and Japan has dedicated the largest HRS infrastructure in the world.

Internal combustion engine (gasoline and diesel) is still the dominating technology for propulsion in all transport applications despite their relatively low energy efficiency and environmental impact from emitting greenhouses gases. In an effort to combat climate change, many countries have made commitments to move towards more efficient and sustainable transportation using technologies such as hybrid vehicles, battery electric vehicles (BEV) and fuel cell electric vehicles. The pervasiveness of clean and sustainable transport methods require the creation of extensive infrastructure in cities and countries, in addition to the technology improvement and cost reduction. Although fuel cell electric vehicles have become more popular in recent years through launching several new models by world-renowned automakers, they are still more expensive than other types of vehicle technologies. Moreover, due to use of hydrogen, they need significant infrastructure for the production of hydrogen and its delivery to the point of use via refueling stations.

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Currently, polymer electrolyte fuel cells (PEFCs) are the most common technology in fuel cell vehicles due to their fast response and low operating temperature [3–4]. However, there is a growing interest in solid oxide fuel cell (SOFC) for vehicle propulsion [5–7] as SOFC can be operated with a variety of fuels, such as methane, carbon monoxide, hydrogen, methanol, ethanol, and more complex fuels with more carbons offering fuel flexibility which PEFCs cannot accommodate. Moreover, other advantages include better thermal management, heat utilization and lower infrastructure requirement. Therefore, SOFCs have the potential to apply in transport applications with long and fixed operating schedule and in countries where hydrogen infrastructure development is not underway [8].

Although SOFCs have some negative features such as high temperatures and brittle ceramic components, so that SOFCs may seem not be the suitable power source for transportation applications. But during recent years, there has been remarkable advances in the design and materials of SOFCs to overcome these issues, where SOFC would have a promising future in transportation application due to the improvement in efficiency, pollution tolerance, fuel flexibility, and lifetime which will result in lower costs [9]. Also, proton conductors or thin film electrolytes will allow lower operational temperatures [9]. Udomsilp et al. [10] reported the development of a metal-supported SOFC system with high power density which meet the industrial performance target by providing a current density of 2.8 A cm^{-2} at 0.7 V and 650 °C. Targeted current density defined by AVL List GmbH that have to be met for SOFC-based range extender systems is 2 A cm^{-2} for single-cell and 0.8 A cm^{-2} for stack [10–11].

Literature review

Several studies in literature have investigated PEFC vehicle technologies and compared them to conventional technologies technically and economically. Yang et al. [12] studied internal combustion engine, electric and PEFC FCEVs under different scenarios in China. In this study, different hydrogen production pathways and drive profiles were evaluated. They concluded that PEFC vehicles with sustainable hydrogen productions such as coke oven gas and electrolysis by abandoned hydropower are more sustainable than electric vehicles. In another study, life cycle cost of PEFC, battery electric, and internal combustion vehicles were studied by Li et al. [13]. In this study, economic impacts of different light duty transportation policies were evaluated. Environmental and traffic policies of 12 cities in China were considered in this study and concluded that PEFC vehicles and BEVs are economically competitive and it was recommended that traffic and environmental policies must be implemented in other cities of China. The main policy advantages of BEVs and PEFC vehicles come from three aspects: government subsidies, purchase and driving restrictions, and environmental taxes. Liu et al. [14] compared energy consumption and emissions of a PEFC vehicle (Toyota Mirai) and gasoline (Mazda 3) light-duty vehicles from well to wheel. Hydrogen production source was assumed to be steam methane reforming. It was concluded that well to wheel GHG emissions and energy consumption of FCEV is 15–45% and 5–33% lower than gasoline vehicles. Sinha and Brophy [15] performed the life cycle assessment for different feasible renewable hydrogen pathways for PEFC vehicles in California. The life cycle carbon dioxide emission of FCEVs with renewable hydrogen is in the range of battery electric vehicles and about 50% of internal combustion engine vehicles. Ahmadi and Kjeang [16] performed similar study for four major provinces of Canada and found that the lowest carbon footprint between different hydrogen production pathways is thermochemical hydrogen production and the lowest cost is hydrogen form natural gas reforming. Hienuki et al. [17] performed energy and environmental life cycle analysis for PEFC FCEV using hydrogen derived from fossil fuels for Japan. The advantage of supplying hydrogen from fossil fuel are stable energy supply and economic aspects. In another study, Watabe and Leaver [18] studied the economic and environmental aspects of new and old light duty PEFC FCEVs in Japan. If FCEVs until 2030 become 50%, Japan can meet its commitment under Paris Agreement. Life cycle emission of PEFC vehicle utilizing hydrogen from SMR with carbon capture (CCS) is 40% more than wind or solar based electrolysis. Candelaresi et al. [19] performed life cycle assessment of hydrogen light-duty cars in Europe. In this study, FCEVs, hydrogen-fed hybrid electric vehicles and hydrogen ICE vehicles were assessed. Also, two vehicles that utilize hydrogen mixture with natural gas and gasoline were evaluated. The source of hydrogen was wind-powered electrolysis. Vehicles using hydrogen mixture with gasoline and natural gas were found to be very good short-term solutions and pure hydrogen vehicles were found to be very good long-term decarbonization solutions. Sagaria et al. [20] studied battery and fuel cell light-duty vehicles and buses in Portugal. In their study, it was concluded that energy consumption of battery vehicles and FCEV are the lowest for light duty vehicles and trucks, compared to internal combustion engine vehicles in real world conditions.

Costs of PEFC FCEVs were analyzed in different studies. Ruffini and Wei [21] used learning rate approach to forecast future costs of FCEVs. With an 8% learning rate, PEFC FCEVs will be cost competitive in 25 years and with 18% learning rate it will reach competitive point by 2025. In another study, Baptista et al. [22] worked on the market penetration scenarios of PEFC vehicles for light-duty fleet in Portugal. It was concluded that fuel cell cost will be competitive with internal combustion engine cost with power density increase and sufficient market penetration.

Most studies on FCEVs are focused on PEFC vehicles and there are limited papers on SOFC vehicles. Velandia and Abel [23] performed a life cycle analysis for light-duty SOFC and PEFC vehicles in Brazil. In this study, it was found that SOFC vehicles help electrification and utilization of biofuels in the transport sector. By using available biofuel infrastructure, there is no need to build an entire hydrogen infrastructure. Bessekon et al. [24] modelled an SOFC-Battery powertrain vehicle. SOFCs are being widely proposed in the transport sector as range extender or auxiliary power unit due to their high electrical efficiency and compatibility with the current fuel infrastructure; CNG, LNG, and LPG can be used as fuels for SOFCs. A 12 kW SOFC module coupled with a partial oxidation fuel reformer was integrated into a modified Nissan Leaf electrical vehicle. The vehicle achieved drive ranges of 264 km for CNG, 705 km for LNG, and 823 km for LPG compared to 170 km range achieved by the BEV original vehicle [24].

Dimitrova and Maréchal [25] simulated an electric vehicle coupled with an SOFC gas turbine (GT-SOFC) system as a range extender under Matlab/Simulink. The GT-SOFC system, which was integrated with on-board fuel reforming, has high efficiency of 70%. The presented range-extender was optimized based on environmental and techno-economic criteria. The optimization is decomposed into four major parts: a master multi objective optimization, a thermo-economic simulation, a slave optimization (energy integration), and the techno-economic evaluation. The optimal environomic design demonstrated an electric vehicle with more than 600 km range, 30 g carbon dioxide per km, and 30,000 € cost.

Research objectives

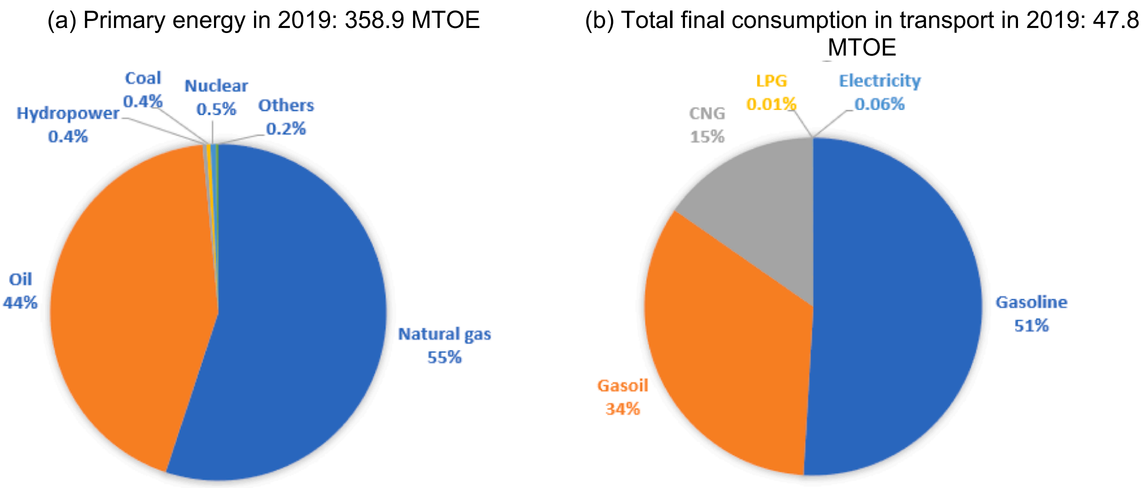
In the case of hydrogen fueled FCEV, there are different methods of hydrogen production but today steam methane reforming (SMR) of natural gas remains the main one. The major factors on the cost of delivered hydrogen to vehicles are as follows: Availability of natural gas and its price, capex of SMR, cost of hydrogen transmission to refueling stations and cost of construction of hydrogen refueling stations. With its vast natural gas resources (16% of the world's proved natural gas reserves) and gas transmission and distribution lines throughout the country (about 40 000 km), Iran has a significant part of the required hydrogen infrastructure, making it superior to other countries. But Iran still needs large investments to produce hydrogen and use it in fuel cell vehicles. It consists of installing the decentralized hydrogen production plants through SMR and the construction of refueling stations at potential user sites. In addition to PEFC FCEVs, enormous resources of natural gas and its extensive distribution and transmission lines in Iran are a great opportunity to develop SOFC FCEVs fueled by natural gas, where the need for additional infrastructure is eliminated. Given that Iran needs to shift its transport fleet to green energy for reasons such as high levels of urban pollution, it needs to decide which system to focus its infrastructure investment on. For this purpose, this study compares the various parameters of fuel cell (both PEFC and SOFC), electric and gasoline vehicles based on well to wheel energy consumption, emission and life cycle cost to identify the most suitable technology. The study aims to assist the decision-making process on the optimum type of transportation system and its requisite infrastructures based on Iran's energy and infrastructure situation. It should be noted that estimations are based on Iran with huge natural gas resources and transmission lines and for other regions with different energy and power portfolio, for example with high renewable share, conclusions could be extremely different.

Iran energy market

In this section, we review the energy and electricity market in Iran as a country with huge natural gas resources. Iran's primary energy (production and import) in 2019 is a total of 358.9 million tons of oil equivalent (MTOE), of which 55% is natural gas, 42% is oil, and the rest is from hydropower, renewable sources, nuclear and coal as shown in Fig. 1 (a) [26]. After reducing export and losses, Iran's final energy consumption is 200.8 MTOE. Therefore, it is observed that the share of natural gas in the country's energy portfolio is significant. With proved natural gas reserves of 1,200 trillion cubic feet, Iran ranks second in the world (16% of the world) after Russia [27]. Also, Iran was the world's third-largest natural gas producer after the United States and Russia in 2019 with a production of 8.4 trillion cubic feet. Iran's strategy in recent years to use natural gas as main source of final energy consumption (around 53%), has led to natural gas being transported through pipelines to all parts of the country. The length of pipelines in the country is close to 40,000 km, and this has created a good infrastructure for the use of natural gas for transportation, whether in the form of CNG or fuel cell vehicles.

Fig. 1 (b) shows the demand for energy carriers in the Iranian transportation sector. As can be seen, gasoline with 33 billion liters per year is in the first rank, followed by gasoil with 21.9 billion liters of gasoline equivalent per year, and CNG with 9.9 billion liters of gasoline equivalent per year. Electricity in hybrid/electric vehicles and LPG also have a very small share.

Fig. 1 (c) depicts nominal power plant capacity in Iran in 2019. As shown, combined cycle gas turbine power plants and open cycle gas turbine power plants are dedicated the most electricity share with 32% each, followed by steam power plants (19%) and hydro power plants (15%). In recent years, some renewable power plants (wind and solar PV) have been installed in the country, but their capacity is still a very small share (2%) of total capacity. The potential capacity of renewable power especially wind and solar, is tens of gigawatts. The Ministry of Energy of Iran provided a preliminary estimate of the potential of renewable energy and the introduction of potential sites in 31 provinces of the country separately. According to the report, the total theoretical



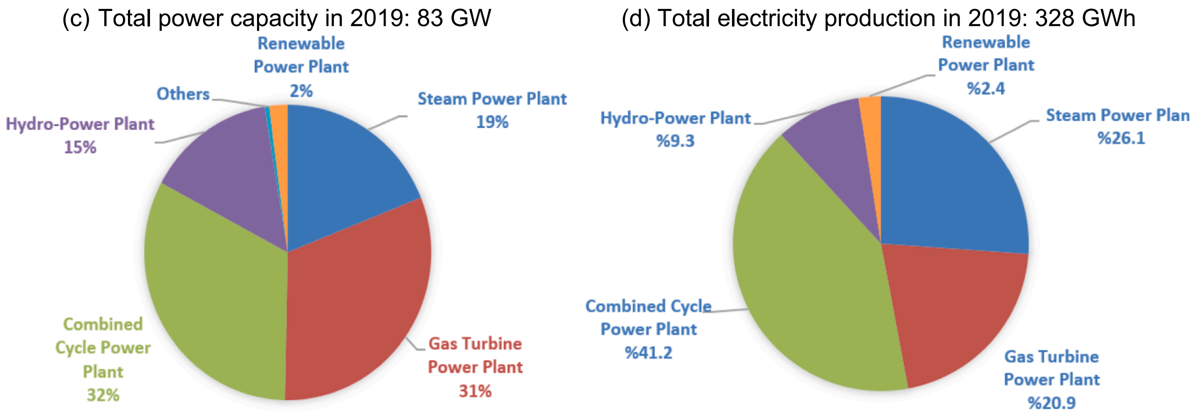


Fig. 1. Statistics of energy and electricity market in Iran; (a) Iran's total primary energy consumption, share by fuel, (b) Fuel share in transportation sector, (c) Nominal capacity of existing power plants in Iran, (d) Gross electricity production from different power plants in Iran.


Gasoline Vehicle:
Fuel: Gasoline
Fuel Economy: 32 MPGge (40 for 2030)

Battery Electric Vehicle
Fuel: Electricity from Iran Elec. Grid
Fuel Economy: 112 MPGge (135 for 2030)
Battery Capacity: 40 kWh

PEFC FCEV
PEFC fuel: Hydrogen/ Hydrogen tank capacity: 122 Lit
Fuel Economy: 67 MPGge (92 for 2030)
Battery Capacity: 1.3 kWh

SOFC FCEV
SOFC fuel: Natural Gas
Fuel Economy: 56 MPGge (81 for 2030)
SOFC capacity: 10 kW / Battery Capacity: 24 kWh

Fig. 2. Different vehicle technologies studied in this paper.

potential estimate is 120 GW, which includes 70 GW of solar capacity, 47 GW of wind capacity, 950 megawatts of biomass, 1100 megawatts of geothermal energy and 900 megawatts of small hydropower. Therefore, Iran has a huge potential in the field of renewable energy and this great potential will be efficient for the production of green hydrogen. However, the country still has a long way ahead. As said before, in forthcoming years, hydrogen production via natural gas reforming seems to be more rational in Iran.

Fig. 1 (d) shows total gross electricity production from different power plants in Iran, with total production of 328 GWh in 2019. The most share is related to natural gas fueled combined cycle power plant (41.2%), followed by natural gas fueled steam power plant (26.1%), open cycle gas turbine power plant (20.9%), hydropower plant (9.3%) and renewable power (2.4%). As seen, fossil fuel-based electricity accounts for more than 88% of total electricity.

Methodology

This is a techno-economic analysis of the four vehicle technologies according in Iran. Fig. 2 shows the selected cars, including a gasoline vehicle, an all-electric battery vehicle, a PEFC FCEV and a SOFC FCEV. Vehicle models selected for comparison are nearly in same class.

The following parameters were calculated to conduct the comparison between the vehicles:

Well-to-wheel energy use: The total energy use of each vehicle was calculated and compared per each kilometer of distance travelled in its lifecycle, i.e., from well to wheel (WTW). Energy consumption is divided into two parts: 1) Pump-to-Wheel (PTW), energy consumed in the car, which is calculated from fuel economy in miles per gallon equivalent of gasoline (MPGge), i.e., the distance travelled with energy equivalent of 1 gallon of gasoline (114000 Btu), and 2) Well-to-Pump (WTP), required energy consumption to produce the fuel used in the vehicle. For example, in electric vehicles, WTP includes the energy required for natural gas extraction, gas refining, transmission to power plants, electricity generation from natural gas in power plants, and the transmission and distribution of electricity up to the charging station. Section 5 details assumptions made for the calculations.

WTW greenhouse gas emissions: Obviously, gasoline vehicles have high emissions, while in battery electric vehicles or PEFC FCEVs no pollutants are emitted at the point of use. It is assumed that the electricity used in BEVs is supplied from the national grid which is generated by fossil fuel power plants associated with high pollution. In the future, Iran may reach a point to provide the required electricity from renewable energy sources due to great potential of wind/solar energy, leading to zero or negligible emissions; however, the country still has a long way ahead. To calculate the total pollution, the whole route, i.e., from well to wheel, is required to consider. The hydrogen supply in PEFC FCEVs may also be associated with emissions. For more common method (natural gas reforming), the use of natural gas is associated with the release of carbon dioxide and other emissions. The second method (water electrolysis) requires electricity, which, if supplied from the national grid or fossil power plants, the emission of pollutants would be inevitable; unless electrolysis is done by renewable electricity, which is not currently cost-effective. Section 6 details assumptions made for the calculations.

Fuel cost: In addition to fuel costs, infrastructure costs should also be applied. For example, the costs of a CNG pump, natural gas reforming, and hydrogen station in the PEFC FCEVs and the charging station cost for the all-electric vehicle should be applied. Methodology used in [28] is applied here.

Life cycle cost: Life cycle cost covers the total costs per mileage, including vehicle cost, fuel cost, and maintenance cost. The vehicle cost, known as the capital expenditures (Capex), should be discounted annually for equivalence. Mileage cost is calculated by following formula:

$$Mileagecost = \frac{EUACofvehiclecost - EUACofresidualvalue + fuelcost + maintenancecost(\$)}{Yearlymileage(km)} \tag{1}$$

where EUAC is Equivalent Uniform Annual Cost and is calculated by the following formulas:

$$EUACofvehiclecost = vehiclecost\frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

$$EUACofresidualvalue = R.V.\frac{i}{(1+i)^n - 1} \tag{3}$$

where *R.V.* is the residual value of the system for any scrapping purpose (which is considered 10% of the system cost). *i* is the interest rate, and *n* is system lifespan. The following assumptions are considered for economics study:

- The vehicles have lifespan of 10 years, which is equivalent to a mileage of 193,000 km (12,000 miles annually) [29].
- The interest rate is considered as 5% [28,29].

Tables S1 – S4 show technical and cost assumptions for analysis in four technologies.

Powertrain configuration

Fig. 3 shows a detail of powertrain system in both SOFC hybrid and PEFC vehicles. We considered power train of two technologies based on commercial models available in market. This paper is focused on SOFC battery hybrid FCEV; Therefore, the power train of this technology is compared to PEFC FCEVs. Power train of PEFC vehicles studied here is same as Toyota Mirai which is hybrid type with a small battery. In this

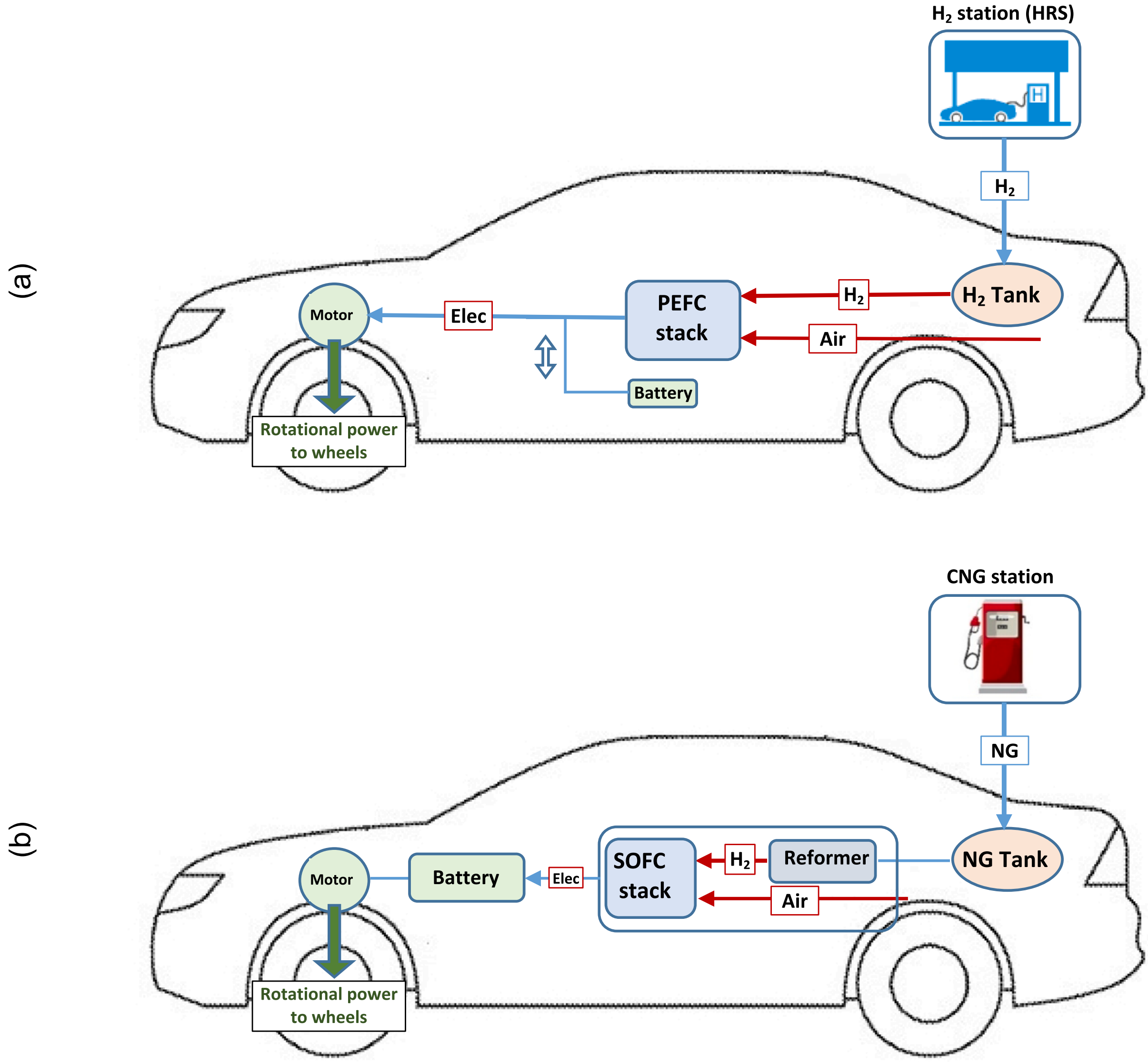


Fig. 3. Powertrain of PEFC and SOFC fuel cell electric vehicles. (a) PEFC hybrid FCEV, (b) SOFC hybrid FCEV.

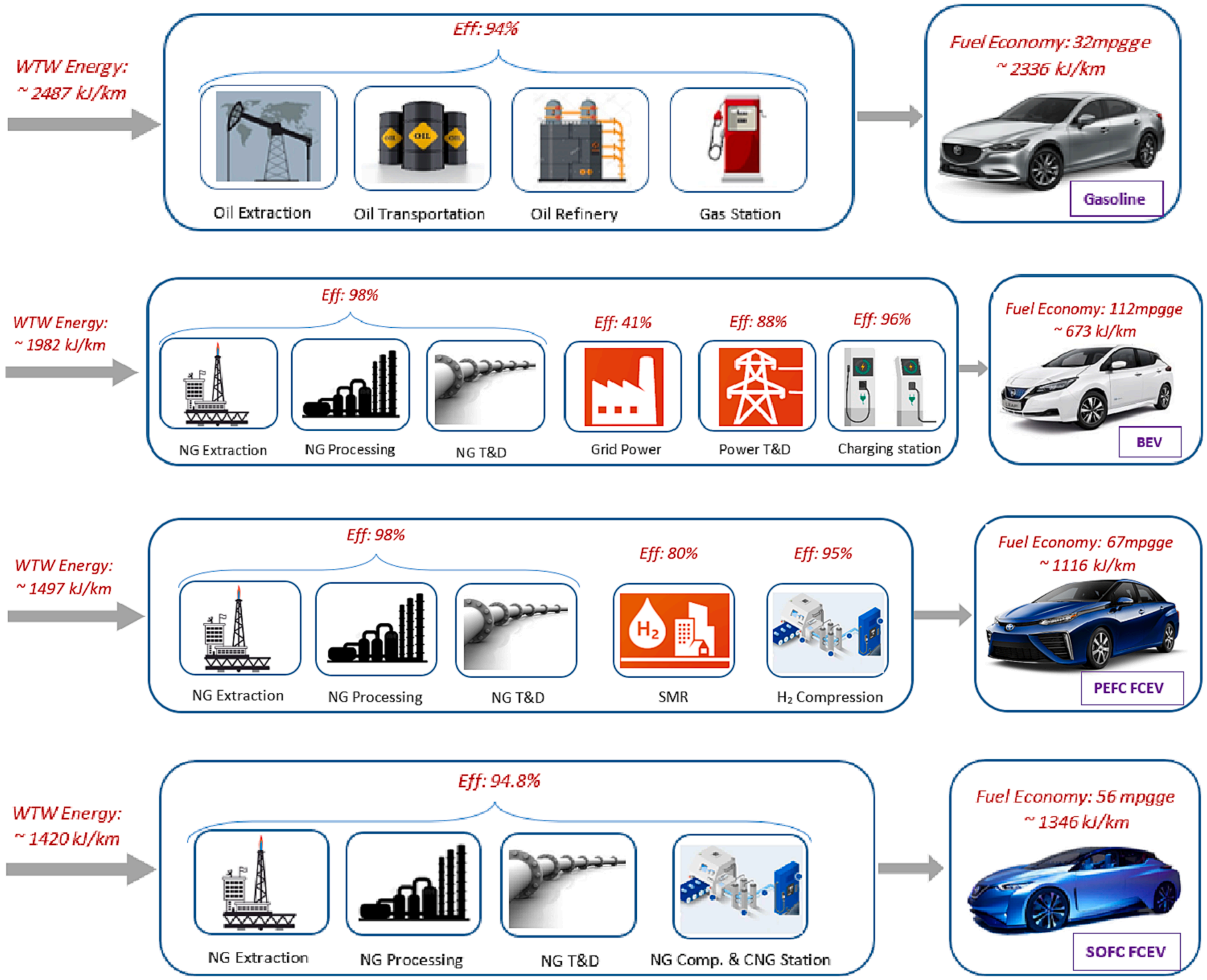


Fig. 4. Energy system for evaluating the well to wheel energy consumption for different vehicle technologies [2,28–35].

vehicle, hydrogen storage tank is filled from hydrogen refilling station (HRS), and is fed into PEFC stack, where required electricity of electric motor is generated. A lithium-ion battery is considered which is charged via fuel cell or vehicle deacceleration. Power train of SOFC battery hybrid vehicle studied here is similar to Nissan SOFC powered vehicle. In this technology, natural gas fuel tank is filled via CNG station and is injected into SOFC stack in order to generate electricity of batteries. Batteries power the electric motor of vehicle.

Well to wheel energy consumption

Fig. 4 illustrates the energy consumed in the whole route from the well to the wheel divided into two parts WTP and PTW. In the following, each car model will be discussed separately. Assumption and data were taken from [28–36].

Gasoline vehicle: The average energy consumption of gasoline vehicles on the market is about 32 MPGge [29–30], equivalent to the consumption of 2336 kJ of gasoline per kilometer. The extraction, transfer, refining of oil, conversion into gasoline, and delivery to the gas station require a total energy consumption of 0.065 kJ per kJ gasoline. Therefore, the average energy consumption of a gasoline vehicle is 2487 kJ per kilometer.

Battery electric vehicle: The average energy consumption (fuel economy) of electric vehicles on the market today is about 112 MPGge [30,32], which is equivalent to 0.3 kWh of electricity consumption per mile. To supply the electricity, according to the following assumptions, BEV needs to consume 1982 kJ of energy to travel each kilometer.

- Extraction, refining, and transmission of natural gas. In total, there is about 0.02 kJ of energy consumption per kilojoule of energy.
- The average efficiency of Iran's electricity generation grid is 41% [36].
- The average transmission and distribution loss are 12% in Iran [36].
- The average loss of AC to DC power conversion is about 4%.

PEFC fuel cell electric vehicle: The fuel economy of the PEFC FCEV was determined to be approximately 67 MPGge [30,32] based on the models available in the market, which is equivalent to the consumption of 1116 kJ of hydrogen per kilometer.

- Extraction, refining, and transmission of natural gas. In total, there is about 0.02 kJ of energy consumption per kJ of energy [34].
- Reforming process (Small Modular Reactor, SMR), which has an efficiency of 80% [28].
- Hydrogen compression to a pressure of about 700 bar, which will result in 5% of energy consumption [28].

In view of the above, the PEFC FCEVs requires a WTW energy of 1497 kJ to travel each kilometer.

SOFC FCEV: The assumption in the SOFC FCEVs is that due to the existence of natural gas pipelines in all parts of the country, compressed natural gas should be used in the SOFC fuel cell installed inside the vehicle. However, it is not possible to supply all the power required by the car from the fuel cell due to its size, weight, and volume, and the battery provides part of the power, so it is called a fuel cell and battery hybrid car or the fuel cell can be considered as a range extender. This study assumes a SOFC fuel cell with a capacity of 10 kW and a battery with a capacity of 24 kWh. Accordingly, in addition to the CAPEX, the WTW cost of the vehicle includes the costs of natural gas and CNG station.

- The SOFC in these electric vehicles has an efficiency of 50–60%, which provides the required electricity to the vehicles [35].
- Assuming a car similar to an all-electric vehicle with fuel economy of 112 MPGE and SOFC efficiency of 50%, 1346 kJ of dense natural gas is required to travel each km.
- The amount of energy used in gas extraction, processing, transmission, and compaction to produce one MJ of CNG equals 0.052 MJ.
- Accordingly, for each km, the WTW energy consumption is equal to 1420 kJ.

Comparison of WTW energy consumptions. Comparing the 2021 WTW energy consumption of the four vehicles shown in Fig. 4 on a per 100 km basis, the SOFC FCEV has the lowest energy consumption followed by PEFC FCEVs, and battery-powered all-electric vehicle. The gasoline car has the highest energy consumption. If one million gasoline vehicles are substituted with sustainable technologies, assuming an annual mileage of 19,300 km, the SOFC hybrid car has the highest energy savings - about 20,600 TJ/y.

Well to wheel emissions

This section discusses the WTW emissions of different options. BEVs (considered here) consumes about 0.187 kWh of electricity per km, which is equal to 0.22 kWh by assuming transmission and distribution and AC to DC losses. According to the national grid, carbon dioxide emission in the national grid is about 660.6 g/kWh [36]. Therefore, in BEV, CO_2 emission is equal to 146 g/km. In PEFC FCEV, CO_2 emission factor of natural gas was considered equal to 80 g/kBTU of fuel [32]. With total energy consumption calculated in section 5, CO_2 emission would be 111 g/km. Gasoline vehicles with 32 MPGge, and fuel emission factor of 95 g/kBTU [32], CO_2 emission will be 210 g/km. In SOFC FCEV with fuel economy of 56 MPGge and natural gas emission factor of 80 g/kBTU, CO_2 emission is estimated about 105 g/km. Fig. 5 compares the WTW emissions of 4 vehicles and shows that the emission from a SOFC FCEVs per 100 km is 6%, 28% and 50% lower than PEFC FCEV, all-electric, and gasoline cars, respectively. Therefore, in terms of emissions, the SOFC and PEFC FCEVs are the best options, followed by the all-electric vehicle. If one million gasoline vehicles are substituted with other technologies, assuming an annual mileage of 19,300 km, the annual reduction of emissions will be equal to 2.04 Mt and 1.2 Mt, respectively, for SOFC FCEV, and all-electric vehicles.

Economic life cycle assessment

In the following, the cost of driving per km for the four vehicles will be addressed. As mentioned before, all costs should be considered to determine the mileage cost, including infrastructure cost, fuel prices, capex, operation and maintenance cost. The mileage cost of the four vehicles is discussed in the following, separately.

Fig. 6 shows the cost of fuel consumption for four types of cars at present and 2030, considering all infrastructure costs. As shown, the annual cost of fuel consumption for PEFC is currently very high, largely due to the high cost of hydrogen infrastructure. In the short term, it is not possible to build large scale hydrogen production plants and charging stations. The capacity of the charging station and the hydrogen refueling station is considered 200 kg per day. Utilization factor of HRS is also assumed to be 0.4, meaning maximum use of these stations is not possible in the short term. It, in turn, leads to high cost of hydrogen and fuel cost of PEFC vehicles.

The lowest cost of fuel consumption also goes to the SOFC hybrid car, because this technology does not require significant infrastructure given the conditions in Iran. The natural gas transmission/distribution pipelines exist in the country and it is required to build natural gas or CNG stations. For your attention, these types of stations already exist in the country for refueling CNG vehicles. After SOFC hybrid vehicles, the lowest cost of fuel consumption is related to the all-electric car (BEVs). The most important infrastructure of this technology is the construction of electricity charging stations, which can be seen in this option. It should be noted again that the electricity of this technology is supplied from Iran's electricity grid and the cost of electricity was calculated based on.

Fig. 6 shows also annual cost of consumed fuel in 2030. SOFC hybrid vehicle will still have the lowest annual fuel consumption, followed by the BEV. It can be seen that if the hydrogen infrastructure is provided, there will be a significant reduction in the fuel cost of the PEFC FCEV in 2030. For this purpose, the capacity of the hydrogen refueling station is

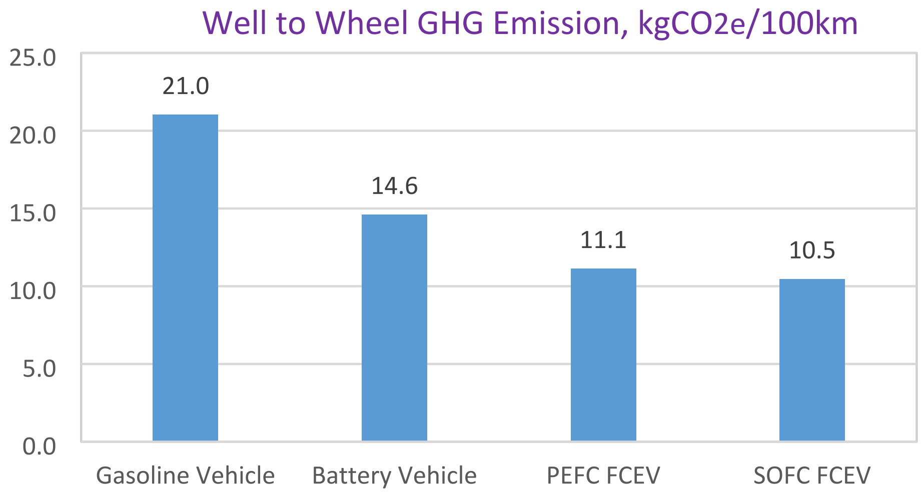


Fig. 5. Well to wheel greenhouses emission for different vehicle technologies.

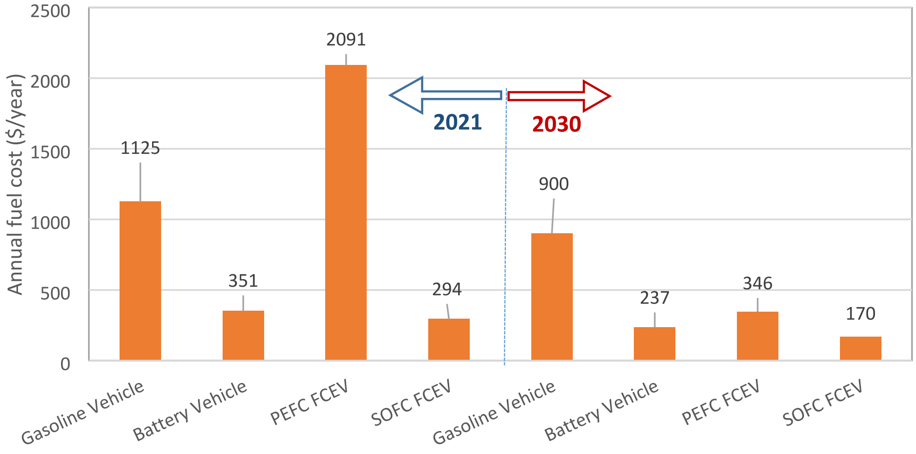


Fig. 6. Annual cost of consumed fuel for each model for present and 2030.

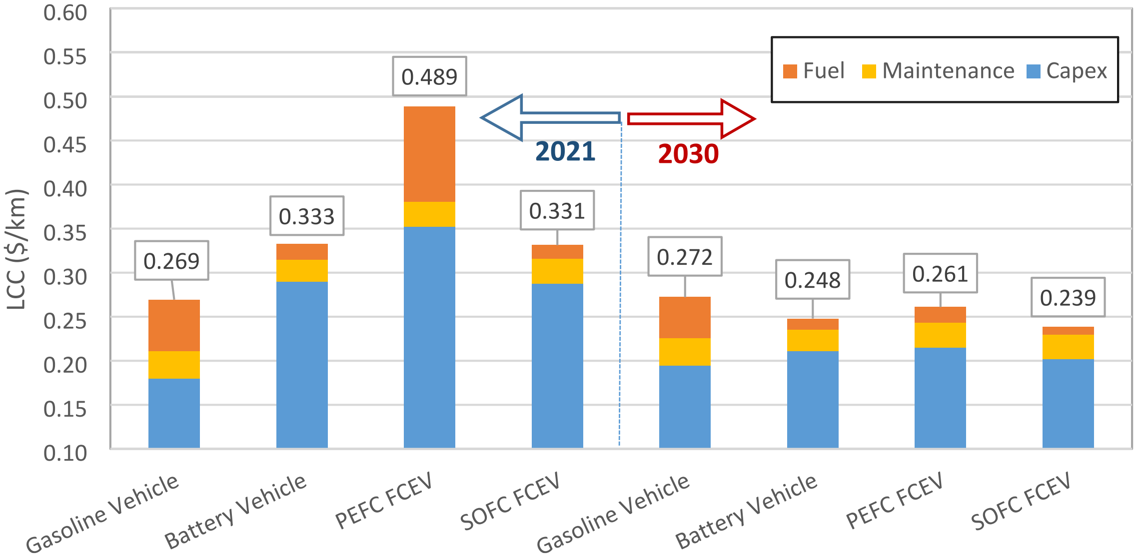


Fig. 7. The life cycle cost for different vehicles for 2021 and 2030.

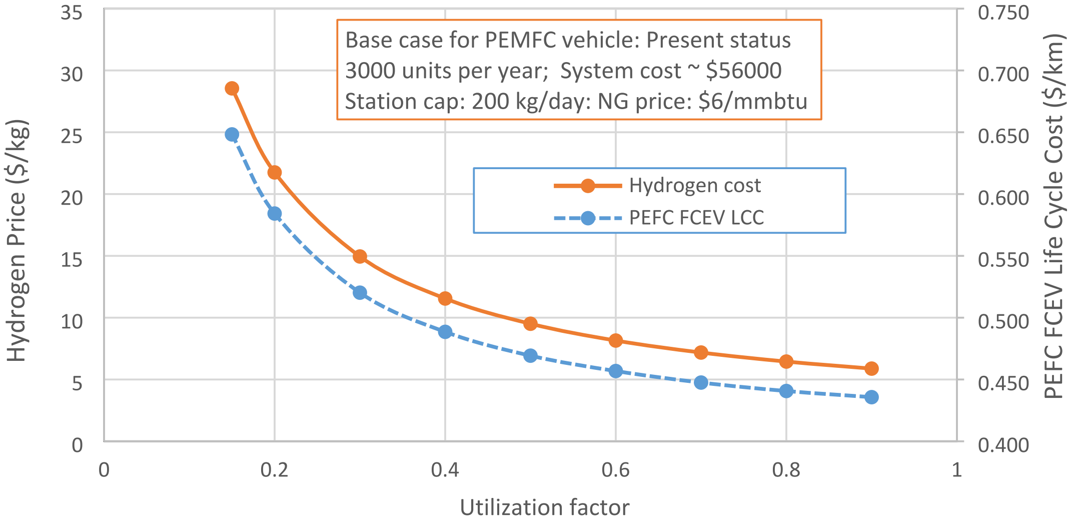


Fig. 8. The effect of utilization factor of hydrogen station on hydrogen cost and life cycle cost of PEFC vehicles.

1000 kg per day instead of 200 kg per day, which leads to the lower reforming (SMR) and hydrogen station cost per unit of hydrogen production. In addition, the utilization factor of the HRS, the ratio of actual use to nominal capacity, was assumed to be equal to 0.8 instead of 0.4.

Fig. 7 shows the total cost per mileage for four types of vehicles in 2021 and 2030, considering all costs of Capex, repair and maintenance, and fuel. As it is known, despite the high fuel consumption cost, the life cycle cost of a gasoline vehicle is lower than other technologies in 2021, which is mainly due to the low cost of the car. The highest mileage cost also belongs to PEFC FCEVs, followed by BEV and SOFC hybrid vehicle. In 2030, SOFC hybrid vehicles show the best mileage cost in Iran, followed by BEVs, PEFC FCEVs and gasoline vehicles.

As shown in Fig. 7, the PEFC FCEVs shows significant changes between present and 2030. It will be achieved just when predicted plans and policies run correctly. For instance, it needs to annual production rate of PEFC FCEV would increase from 3000 units to 100.000 units; utilization factor would increase from 0.4 to 0.8, and HRS capacity would increase from 200 kg/day to 1000 kg/day. Fig. 8 shows the cost of hydrogen production and the life cycle cost of the PEFC FCEV in terms of the utilization factor of the station. As observed, at a utilization factor of about 15%, the cost of hydrogen is very high, up to US$ 28 per kilogram, but at a utilization factor of about 90%, the cost of hydrogen is reduced significantly, approaching about US$ 5.9 per kilogram. The life cycle cost of the PEFC FCEV has also decreased from about US$ 0.65 per km to about US$ 0.44 per km.

Conclusions

This study compared four types of vehicles (gasoline, all-electric, PEFC FCEV, and SOFC FCEV) in Iran. The comparison was performed from 4 perspectives of WTW energy consumption, WTW emissions, fuel costs and mileage life cycle cost. The main findings are as follows:

- The WTW energy consumption of a SOFC FCEV per km is 43%, 28% and 5% lower than gasoline, BEV and PEFC FCEV, respectively.
- The WTW emission of a SOFC FCEV per km is 50%, 28% and 6% lower, respectively than a gasoline vehicle, a BEV and a PEFC FCEV.
- The lowest cost of fuel consumption goes to the SOFC FCEVs followed by BEVs, gasoline and PEFC FCEVs in 2021. In 2030, SOFC FCEVs will still have the lowest annual fuel consumption, followed by the BEVs, PEFC FCEVs and gasoline vehicles.
- In summary, the gasoline vehicles in 2021 has the lowest life cycle cost, followed by SOFC FCEV, BEV and PEFC FCEV. But in 2030, SOFC FCEV can be optimum vehicle technology, followed by BEV, PEFC FCEV and gasoline vehicle.

It should be noted again that estimations are based on Iran with great natural gas resources and infrastructure and for other regions with different energy and power portfolio, for example with high renewable share, conclusions would be completely different. However, the implementation of this technology will be a shortcut for the development of Hydrogen fuel cell vehicle technology until required infrastructure is provided for production, storage, transfer and hydrogen stations.

As mentioned, fuel cell vehicle technology (PEFC or SOFC) is not still matured and in a 10-year period, technology and cost should be improved. For instance, the challenges of SOFC vehicles like slow-startup and operation in high temperature can be resolved.

This paper was written in March 2022, coinciding with the industrial growth caused by the post-COVID19 situation and, more importantly, the Russia-Ukraine war which has shaken the energy market and pushed up the price of crude oil and natural gas. At times, the price of Brent crude oil has risen to more than $100 per barrel and the price of natural gas has risen to about $200 per MWh. It is obvious that such crises confirm the need to use more efficient methods for transportation applications.

CRediT authorship contribution statement

Hadi Heidary: Conceptualization, Investigation, Methodology, Software, Resources, Writing - original draft. **Ahmad El-Kharouf:** Supervision, Methodology, Writing - review & editing. **Robert Steinberger-Wilckens:** Supervision. **Shahriar Bozorgmehri:** Supervision. **Mohsen Salimi:** Methodology, Writing - review & editing. **Mohammad Golmohammad:** Conceptualization, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix 1. Energy unit conversion

1 kWh = 3600 kJ
1 BTU = 1.055055 kJ
MPGge (Mile per Gallon Gasoline Equivalent)
1 Gallon Gasoline Equivalent (GGE) = 114000 BTU = 33.41 kWh

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2023.103396.

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