Hydrogen Integration for Achieving Net-Zero Emissions with Plug-in Fuel Cell Hybrid Electric Vehicles

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Abstract. Currently, to achieve net-zero emissions, the transport sector is going through a decarbonization process, with Battery Electric Vehicles (BEVs) leading the race. However, these vehicles present a limited range and high charging time as barriers to replacing 100% of the transport sector. Also, BEVs cannot achieve net-zero emissions given that the electric rechargeable stations are powered by the local grid electricity. Thus, even though electric vehicles do not produce greenhouse gas (GHG) emissions directly; there are indirect emissions linked to the electricity used, relying on the balance between renewable and non-renewable energy sources in the local network. In this study, green Hydrogen is assessed as a possible solution to reach net-zero emissions with Fuel Cell Plug-in Hybrid Electric Vehicles (FC-PHEVs) that count with a greater range. A specific model of a cradle-to-grave life cycle is developed, allowing the assessment of its environmental impacts. Consequently, 3 scenarios are implemented to be assessed and compared using the model. The analysis shows that a considerable part of GHG emissions of Hydrogen implementation is found in its transportation, although research is being carried out on alternative solutions to mitigate this drawback.

1 Introduction

Climate change is considered one of the most critical challenges for this century. At the United Nations Climate Change Conference in 2015, an agreement was established to keep global warming below 2 °C [1]. To reach this goal, the world should decarbonize in different sectors, including energy production and transportation. Concerning the energy sector, the implementation of renewable sources plants continuously increases, aiming to reduce fossil fuel dependence [2]. Likewise, Green Hydrogen plays a key role in the energy transition due to its potential applications like electricity generation where no GHG emissions are produced [3]. On the other side, concerning the transportation sector, specifically road transportation, the scientific community, governments, and private companies have put their efforts into

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developing and supporting alternative fuel vehicles (like electricity, biodiesel, etc.) to reduce GHG emissions [4].

Battery Electric Vehicles (BEVs) are leading the race to decarbonize the transportation sector with the increase in their implementation over the world in the last years. However, BEVs have market disadvantages due to their relatively low autonomy range and high battery refilling time [5]. For this reason, Hydrogen has been assessed as an alternative to decarbonize the transportation sector being used as fuel for vehicles using Fuel Cells. These electrochemical devices are used to generate electricity from the chemical reaction of Hydrogen with air and only emitting water vapor as a byproduct. The vehicles that use them are called Fuel Cell Electric Vehicles (FCEVs) [6]. However, considering the current limitations in the production of Hydrogen to supply the fuel demand, it was introduced the idea of hybrid configurations for vehicles based on Hydrogen, giving as a result, the Plug-in Fuel Cell Hybrid Electric Vehicles (FC-PHEVs) [5]. In this way, Hydrogen can deliver that extended range needed for BEVs and decrease the refill time. Nevertheless, despite all the advantages of using Hydrogen as a fuel in transportation, the main barriers to its use are the currently limited Hydrogen production and the lack of refueling infrastructure [5].

2 State of the art

For the implementation of Hydrogen to achieve the goal of decarbonization, first, it is necessary to consider the Hydrogen production pathways and evaluate which one is the cleanest option. Currently, the most common way to produce Hydrogen is Steam Methane Reforming, a thermochemical process where natural gas reacts with steam at high temperatures. However, a significant amount of greenhouse gases is emitted from this process, although it could be captured up to 90% using carbon capture and storage systems, meaning that this is a low-carbon emissions production pathway. This Hydrogen has been denominated as Blue Hydrogen [3]. Another method for Hydrogen production is based on electrolysis, which is considered the cleanest Hydrogen production pathway. This process requires deionized water as feedstock and electricity. The GHG emissions linked to Hydrogen production could be avoided entirely if the electricity used is generated from renewable sources, obtaining a zero emissions Hydrogen known as Green Hydrogen [7].

Regarding renewable energy and its use to produce Hydrogen, in Europe, there are renewable energy plants (REPs) already working on generating electricity for the local grid and producing Hydrogen, as is the case of Iberdrola in Spain, which has developed a 20 MW Electrolysis plant powered by a 100 MW solar energy park with a production nominal of 3000 ton per year [8]. Also, there are cases like the Energy Park Haringvliet Zuid in the Netherlands, where a Hydrogen production unit is planned. This last case presents an interesting project of hybridizing two common renewable sources, solar and wind, clarifying the advantages that a Hybrid Power Plant (HPP) offers. The HPPs can prolong the electricity generation timing, in comparison with a standalone solar plant or a wind farm, and, at the same time, control the widespread intermittency production issue, complementing one another because there is more solar energy production during the day and in the summertime, and more wind energy production at night and in wintertime [9].

In this way, several studies have developed possible scenarios and requirements for Hydrogen implementation in the transport sector. The most common scenario is that Hydrogen is produced in a central production plant (off-site), which means it may be transported to the refueling stations [10]. This scenario needs to consider the Hydrogen transportation pathway and the storage technology which depend on the Hydrogen's physical state. For gaseous Hydrogen (GH2) transportation, it is necessary to compress it into tube trailers at 25-50 MPa in a distribution gas terminal suited next to the electrolysis plant preferably; these vessels must be mounted on trailers and transported by trucks. In the refueling station, the GH2 must be further compressed at 70 – 90 MPa and stored in high-pressure buffer storage before dispensing [11]. Another GH2 transportation pathway is through pipeline systems, which need compressor stations and storage facilities; that makes this alternative a highly cost-effective option for high-scale hydrogen production plants [12]. One of the main barriers to the use of pipelines as a transport medium for Hydrogen is the phenomenon known as Hydrogen Embrittlement [12,13], which affects metallic materials commonly used for long-distance gas transportation, reducing their mechanical properties and degrading their load-bearing capacity when Hydrogen is present [13].

On the other hand, Liquid Hydrogen (LH2) needs to be cooled down at cryogenic temperatures, stored in cryogenic tanks at 0.4 MPa, and transported by trucks. In the refueling station, LH2 must be evaporated and stored in its gaseous state at 70 – 90 MPa. LH2 has an advantage in refueling energy usage but is inefficient in energy consumption due to the liquefaction and evaporation process. GH2 has the advantage of the current infrastructure, but in comparison with LH2, it can only be transported in low amounts [10]. Finally, vehicles based on Hydrogen, FCEVs, and FC-PHEVs have already been developed by several automotive companies. The difference between FCEVs and FC-PHEVs is the powertrain configuration. On one side, FCEVs can only be refueled by Hydrogen, which means it has a higher storage level of Hydrogen than FC-PHEVs. However, besides the Hydrogen refueling, FC-PHEVs can also be plugged-in to be charged [5]. Finally, these vehicles can be refueled in less than 5 minutes, representing a significant advantage against the BEVs (hours of charging time) [6].

3 Model of green Hydrogen implementation in the transport sector with Plug-in Fuel Cell Hybrid Electric Vehicles

This study is focused on developing a model to assess the environmental impacts of a cradle-to-grave scenario using green Hydrogen as a fuel to power Plug-in Fuel Cell Hybrid Electric Vehicles (FC-PHEVs). A life cycle assessment is suited as the best option for this type of assessment [14]. The model proposed covers the production, distribution, end of use, and end of life of green Hydrogen as an alternative to reach net-zero emissions in the transport sector. The cradle-to-grave model starts with electricity generation from renewable sources corresponding to feedstock and energy inputs in the system boundaries [15]. Depending on the circumstances, solar power plants and wind farms are considered two of the best options for obtaining the clean energy needed. These are the most common renewable energy plants due to their continuously decreasing energy technology prices.

Nevertheless, considering the advantages of Hybrid Power Plants (HPPs) presented in Section 2, and the excellent complementation between solar and wind energy across the time of the day and seasons of the year, a Wind-Solar HPP is assumed for this study, having the wind and sunlight as the feedstock to generate the electricity. Consequently, the clean electricity generated is used to supply the model's local grid demands and other processes, as shown in figure 1. The next stage is Hydrogen production, in this case via electrolysis powered by the HPP from the first stage. In this way green Hydrogen is obtained; therefore, there are zero direct emissions during its production process. The electrolysis plant to supply enough Hydrogen for the scenario requires deionized water, high-voltage electricity, and a high-scale electrolyzer. Moreover, the electrolysis plant is assumed to be located near the HPP. In addition, the Hydrogen produced in the electrolysis plant can also be used to store energy for the cases of peak electricity demands in the local grid, as is shown in figure 1. In this way, Hydrogen could help to supply that demand using Fuel Cells to produce electricity [3], although this is not part of this assessment. Before the transportation of Hydrogen to the refueling stations, Hydrogen (in its gaseous state for this study) needs to be compressed into tube-trailer vessels in the compression station next to the Electrolysis plant. These vessels are mounted on trailers and then transported by diesel trucks to the refueling stations [11,16]. The next stage introduces the idea of Refueling and Charging Hybrid Stations (RCHS), where Hydrogen would be transported, further compressed, and stored in a high-pressure storage system before being dispensed to vehicles [16]. These stations offer the service of refueling Hydrogen to vehicles and the service of charging vehicles. The operations of the RCHSs are based on a compressor to refuel Hydrogen and points of charging to supply electricity to the vehicles. The energy used in these stations for the compressor and the charging points is also taken directly from the HPP, as shown in figure 1. Finally, the vehicle used in this model is an FC-PHEV that is supposed to be charged and refueled in the RCHS. This vehicle has a smaller battery than BEVs but uses Hydrogen Fuel Cell technology to generate electricity by recombining the Hydrogen with oxygen from the air for the electric engine to obtain an extended range. The only result of this reaction is water vapor that goes through an exhaust pipe and is emitted into the atmosphere [5].

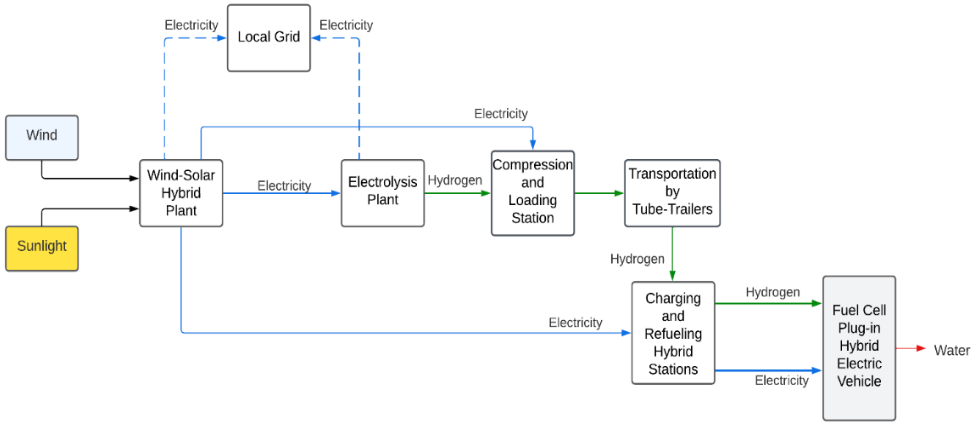

Fig 1. Model to integrate green Hydrogen to power Fuel Cell Plug-in Hybrid Vehicles

4 Case study – cradle-to-grave scenarios of using green Hydrogen to fuel Plug-in Fuel Cell Hybrid Electric Vehicles

For this study, three scenarios are created from the model shown in figure 1 changing only the renewable sources used to generate the electricity that powers the whole scenario. These scenarios assess the environmental impacts of the production and use of electricity and green Hydrogen to charge and refuel 1,000 FC-PHEVs daily. Thus, 10 “Refueling and Charging hybrid stations” with a capacity to refuel and charge 100 FCPHEVs each. For the specifications of the vehicle used for the assessment, there is a “Mid-power Plug-in Hydrogen Fuel Cell Electric” system that counts with a 10.5 kWh high-voltage lithium-ion battery and 3 Hydrogen storage tanks with a capacity of 4.4 kg at 70 MPa available on current market. Regarding electricity generation, the 60MW Energy Park Haringvliet Zuid located in the Netherlands mentioned in section 2 was chosen as a reference for the scenarios; but only due to its location and function of supplying electricity to the grid using 2 renewable sources; thus, the data for simulating the electricity generation from wind and solar energy used for the LCA is taken from the Ecoinvent database. For the stage of Hydrogen production, it is assumed a 10MW electrolysis plant with a nominal Hydrogen production of 4400 kg/d at 3 MPa of pressure; these specifications are found in commercial PEM electrolyzers. Based on the literature, 10 kg of deionized water and an electrolyzer consumption of 64.5 kWh is assumed per kg of Hydrogen produced [17]. Likewise, the Hydrogen produced would be compressed into tube-trailer vessels at 25 MPa to be transported by diesel trucks; then, 3 compressors would be needed, due to their inherent-flow capacity and the total energy consumption, assumed as 6440 kWh, based on commercial compressors. For the transportation of Hydrogen, based on literature, each truck could transport a total amount of 440 kg in 3 tube-trailer vessels [11], but in this case, to simplify the calculation, is assumed that each truck transports only 440 kg of Hydrogen. It is also assumed a round-trip route for every station with an average of 65 km distance from the Hybrid Energy Park to the Rotterdam Center, which means 20 travels of 65km per day. Finally, for the RCHSs, it is assumed that every station needs a compressor, and the calculated consumption for around 100 FC-PHEVs refueled by the compressor per day is 1104 kWh, then the total consumption for 10 compressors is 11040 kWh. The electric part has 4 charging points, and the total charging consumption for 1000 FC-PHEVs is 10500 kWh due to the battery size chosen. As mentioned, three scenarios are created and differentiated by the renewable sources used; thus, the amount of GHG emissions is expected to change in every scenario. The three scenarios developed are:

1. Wind Scenario: FC-PHEVs are refueled with Hydrogen produced using electricity from only wind energy; they are also charged with the same electricity (100% wind energy).

2. Hybrid Scenario: FC-PHEVs are refueled with Hydrogen produced using electricity from wind and solar energy and charged with the same electricity (50% wind and 50% solar energy).

3. Solar Scenario: FC-PHEVs are refueled with Hydrogen produced using electricity from only solar energy; they are also charged with the same electricity (100% solar energy).

5 Life Cycle Assement

The Life Cycle Assessment (LCA) is a method to quantify and assess environmental impacts linked to a product's life cycle from raw material extraction to the final life of the product. This method has 4 phases: Definition of goal and scope, Life cycle Inventory, Life Cycle Impact Assessment, and Interpretation [3].

5.1 Goal and Scope

This study aims to assess the feasibility of using green Hydrogen as an alternative to reach absolute net-zero emissions in the transportation sector from a GHG emissions point of view. The scenario presented in section 3, where most processes have no direct GHG emissions, tries to obtain the closest result to net-zero emissions. As in several studies of LCA about transportation, the functional unit is defined in terms of distances [17]. This study defines the functional unit as "1 km travelled by a Plug-in Fuel Cell Hybrid Electric Vehicle (FC-PHEV)". The system boundary used for this LCA is the "cradle-to-grave"; it comprises the entire life cycle of the Hydrogen (feedstock and energy inputs, hydrogen production and transportation, and end of use and end of life of Hydrogen) [15]. The scenario is developed in the Netherlands context, where is assumed that the electricity used is from the Energy Hybrid Park Haringvliet Zuid located 20 km outside Rotterdam, and the electrolysis plant is assumed close to that energy park [9]. Thus, it is also assumed that the proposed hybrid stations are in Rotterdam. This study excludes infrastructure construction, manufacturing, and decommissioning of capital goods, including the energy hybrid park, hydrogen production plant, hydrogen production devices, and refueling hybrid stations. Finally, the vehicle cycle is also excluded.

5.2 Life Cycle Inventory

Table 1 describes the specifications of each process stage used in the scenario developed with its respective sources. It is also added the data used to compare the three FC-PHEV scenarios with a BEV scenario charged with the electricity grid.

Table 1. Life Cycle Inventory.

Process stage	Specifications	Source
Solar Electricity	Electricity, high voltage {RoW}| electricity production, solar thermal parabolic trough, 50 MW	
Wind Electricity	Electricity, high voltage {NL}| electricity production, wind, >3MW turbine, onshore	
Electrolysis Plant	10 kg of deionized water and an electrolyzer consumption of 64.5 kWh per kg of Hydrogen produced. A total amount of 4400 kg of Hydrogen	[17]
Compression into tube-trailers	Commercial Hydrogen compressor at 25 MPa; 3 compressors necessary due to the flow capacity of each one; total energy consumption is 6440 kWh	[11] Adapted
Transportation by trucks	Transport, freight, lorry 3.5-7.5 metric ton, EURO3 {RER}, 4.4 tons of Hydrogen, 20 travels of 65 km	[11]
Refueling and Charging Hybrid station	*Hydrogen Compressor:* Power capacity of 110kW. Consumption for 100 FC-PHEVs refueled per day is 1104 kWh. The total consumption for 10 compressors is 11040 kWh *Electric Chargers:* The total charging consumption for 1000 FC-PHEVs is 10500 kWh	[11] From the available market FC-PHEVs
Fuel Cell Plug-in Hybrid Electric Vehicle (FC-PHEV)	10.5 kWh high-voltage lithium-ion battery and 3 hydrogen storage tanks with a capacity of 4.4 kg at 70 MPa Range of 400 km	From the available market FC-PHEVs
Battery Electric Vehicle (BEV)	BMWi with a 50kWh battery and 210 km of range	[4]
Local electricity grid	Electricity, high voltage {NL} production mix	

5.3 Life Cycle Impact Assessment

In the present study, the selected impact category to be assessed is the Global Warming Potential (GWP). The IPCC 2013 100a impact assessment method was used in a LCA software. This method can calculate and evaluate the GHG emissions in kg CO2-eq emitted by the entire scenario developed; the results are in gCO2-eq emitted per km travelled by the FC-PHEVs. For better understanding, the 3 scenarios developed in the case study were simulated. Finally, the charging of BEVs using the Netherlands grid electricity was also simulated to obtain actual results; thus, it could be compared with the FC-PHEV scenarios.

6 Results and discussion

The Carbon emissions in gCO2-eq / vehicle km of the three scenarios determined are presented in figure 2. The wind scenario has the least Life Cycle Carbon Footprint scenario with 7.93 g CO2/km, where almost all emissions are from transportation. On the other side, the Solar Scenario has the maximum contribution with 30.9 g CO2/km, mainly due to the electricity consumption of the electrolysis plant. Moreover, as expected, the hybrid scenario with 19 g CO2/km is in the middle of the range between wind and solar scenarios. Life Cycle Carbon Footprint of charging BEVs with the Netherlands grid electricity (147.24 g CO2/km) is also shown and compared with the FC-PHEV scenarios. The high difference in the results between the BEV scenario and the rest of the scenarios has a twofold explanation.

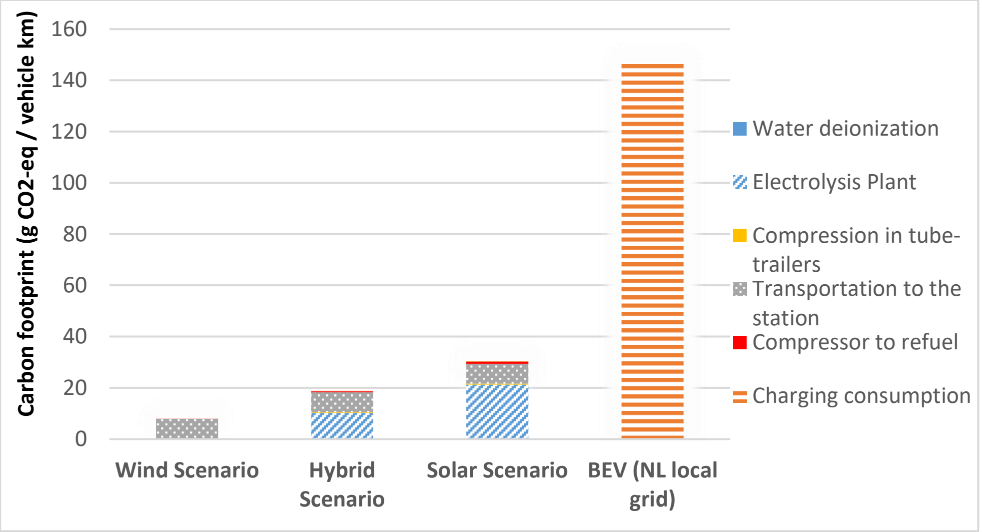

Figure 2. The carbon footprint of the 3 scenarios developed for Hydrogen integration compared with Battery Electric Vehicles charged with local grid scenario.

First, the BEVs are charged with a country grid electricity mix rather than using renewable energies like in the FC-PHEV scenarios, and as is known, the grid electricity generation of a country involves renewable and non-renewable energy sources. In this way and adding that no emissions are produced when BEVs are being driven, considerable BEV emissions are linked to the percentage of non-renewable energy in the local grid used to charge them, and this value changes in every country. However, it must be mentioned that whether BEVs were charged with electricity produced from renewable sources, their emissions would be lower than FC-PHEVs [17]. The second reason is the range of BEVs. The units of the Life Cycle Carbon Footprint for this assessment are "g CO2/km", which means that the total amount of CO2 emitted to charge the battery of the BEV has to be divided by the range of the vehicle, and based on the literature, one of the problems of using BEVs is the low range due to the battery size [4]; then, the low range of BEVs increases the magnitude of Carbon intensity per kilometer travelled. Moreover, BEVs would need to increase the battery size to obtain the same range of FC-PHEVs, which could worsen the charging time and vehicle mass [5]. In summary, having a lower range than FC-PHEVs (in this case almost half) and being charged by the selected grid electricity, BEVs produce 4.76 times the solar scenario emissions, 7.74 times the hybrid emissions, and 18.55 times the wind scenario, not considering the manufacturing of powertrains. Concerning the comparison between FC-PHEVs scenarios, Table 2 shows the specific values of carbon intensity per km travelled for each FC-PHEVs scenario detailed. Assessing these results and keeping in mind the advantages of HPPs presented in Section 2, the Hybrid scenario can be considered the best clean-efficiency option. Even though the wind scenario is a less polluting alternative (11.04 g CO2/km less than the Hybrid scenario), the HPP can increase the electricity generation hours energy compared with a solar plant or a wind farm. The advantage of this scenario is how solar and wind energy can complement one other in a HPP. There is more solar energy production during the day and summertime and more wind energy production at night and wintertime [9]. This characteristic of the HPPs ensures the production of enough energy to supply the local grid demand, hydrogen production, and the intermittency presented regularly in renewable energy plants.

Table 2. Global Warming Potential of the 3 scenarios developed for Hydrogen life cycle as fuel to FC-PHEVs.

	Wind Scenario ($g\ CO_2$ eq/km)	**Hybrid Scenario ($g\ CO_2$ eq/km)**	**Solar Scenario ($g\ CO_2$ eq/km)**
Water deionization	0.110	0.110	0.110
Electrolysis Plant	0.085	10.200	21.130
Compression in tube-trailers	0.002	0.210	0.460
Transportation to the station	7.730	7.730	7.730
Compressor in the station	0.003	0.360	0.750
Charging points	0.003	0.360	0.680
GWP	**7.932**	**18.970**	**30.860**

On the other side, since in neither of the three scenarios, the methodology of transporting Hydrogen in the gaseous state to the refueling stations was changed, the emissions had to be the same for each, and it can be observed in figure 1. The transportation of Hydrogen represents an important amount of GHG emissions for each scenario, in the wind scenario is 97% of the total GWP, 41% for the hybrid scenario, and 25% in the solar scenario and that could be explained because it was assumed that Hydrogen is transported in the gaseous state by diesel trucks, which generate emissions due to the engine combustion. The generated emissions are directly related to the distance and the weight of Hydrogen transported, which is why the calculations show the carbon footprint impact of most of the transportation process expressed in "tkm" units (ton-kilometers). Additionally, as explained in Section 2, the two common ways to transport Hydrogen are defined by its state [11], which determines the amount of Hydrogen that can be transported for each truck. Liquid Hydrogen can be transported in a higher volumetric capacity than Gaseous Hydrogen [10], which can change the transportation methodology, the magnitude of tkm, and consequently, the GHG emissions. Liquid Hydrogen implementation for this scenario can be assessed in another study and compared with the results of this study. Several automotive companies are working on reducing Hydrogen transportation emissions by developing Fuel Cell drivetrains for trucks and trailers [17]. In this way, fuel cell trucks can be refueled in the electrolysis plant as well as in the refueling stations creating a natural synergy between the electrolysis plant, the refueling stations, and hydrogen transportation [17]. The other alternative to reduce hydrogen transportation emissions is implementing a pipeline system due to its advantages described in Section 2. However, first, it is necessary to solve the already-mentioned phenomenon known as Hydrogen Embrittlement.

7 Conclusions

FC-PHEV scenarios developed in this study were compared with BEVs charged by the Netherlands grid electricity. The results showed that FC-PHEV scenarios have lower Carbon emissions per km travelled because they are powered by renewable energy, and BEV scenarios with a mix of renewable and non-renewable energy. Moreover, even though BEVs could be less polluting if they were charged with electricity from renewable energy sources, the emissions also depend on the range of the vehicle, and FC-PHEVs have a higher range than BEVs; thus, FC-PHEVs could be considered a real good alternative to decarbonize transportation. Concerning the comparison between the FC-PHEV scenarios, despite the Wind scenario being the less polluting alternative, the Hybrid scenario presents a clean-efficiency option even though the 11.04 g CO2-eq/km of difference between them, and that is due to the advantages of the Hybrid Energy Park, they present a significant increase in energy production because of the solar and wind energy complementation in the times of the day or the seasons of the year, keeping a low life cycle carbon footprint, not too far from the wind scenario. However, it is necessary for a deep cost-effective assessment. Finally, in the process of reaching net-zero emissions in the transportation sector with the implementation of Hydrogen as a fuel, its distribution is a key point that can be improved concerning its environmental impacts.

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