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Abstract

Hydrogen has been presented as an alternative to conventional fuels for vehicles (gasoline and diesel). In this paper a life cycle analysis of Hydrogen is presented involving several processes of H_2 production. The main objective was to adapt the GREET 1.8c_0 model (developed by Argonne National Laboratory), in order to represent the European reality and more specifically the Portuguese energy sector. Since GREET model considers renewable energy with zero emissions (it does not consider the stages of production and transportation of renewable technologies), GEMIS 4.5 model (developed by Oeko-Institut) was used in order to obtain energy consumption and pollutants emissions related with the production of photovoltaic panels and wind towers. The integration between the adapted GREET model with GEMIS model generated the MACV2H_2 model. This model was calibrated and applied to a case study in order to compare the life cycle of hydrogen with gasoline.

It was concluded that the use of wind energy is the best way to produce hydrogen, both in terms of energy consumption and pollutant emissions. The hydrogen produced by electrolysis of electricity from wind energy and applied in fuel cell vehicles (FCV) presents better results than the internal combustion engine (ICE) vehicle, with the exception of PM emissions per kilometer. The greenhouse gases (GHGs) emissions per kilometer are 85% lower in FCV than in the gasoline vehicle. The production of hydrogen by electrolysis using the Portuguese electricity mix presents the worse well-to-wheel (WTW) results. This H_2 applied in FCV presents more 43% GHGs emissions per kilometer than ICE vehicle.

Keywords

Alternative fuels, GEMIS, GREET, Hydrogen, Life Cycle Analysis, MACV2H_2, WTW

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Introduction and Research Objectives

World consumption of primary energy has increased over the years and in 2008 exceeded 11000 Mtoe [1]. In Portugal the situation is similar; however, 83% of primary energy consumption is due to imports. In 2007 the primary energy consumption in Portugal was close to 25 million toe. In the same year the production of primary energy just surpassed the 4.5 million toe [2]. The transport sector is the major contributor, with 24% of the total energy consumption.

This situation requires an alternative not only for environmental reasons, but also by economic factors. The transport sector is heavily dependent on fossil fuels, which have limited reserves, thus giving rise to speculation and constantly fluctuating prices.

The main objective was to adapt the GREET 1.8c_0 model (developed by Argonne National Laboratory), in order to represent the European reality and more specifically the Portuguese. GREET model considers renewable energy with zero emissions, i.e., it does not consider the stages of production and transportation of renewable technologies, thus the GEMIS 4.5 model (developed by Oeko-Institut) was used obtaining the energy consumption and the pollutants emissions for production of photovoltaic panels and wind towers. The interaction between the adapted GREET model with GEMIS model generated the MACV2H_2 model.

In this study the liquid and gaseous H_2 production using fossil fuels and renewable energy sources was considered, namely from the following sources:

1. Hydrogen produced by fossil fuels:
    - Steam Reforming of Natural Gas
    - Gasification of Coal
2. Hydrogen produced by renewable energy:
    - Electrolysis with electricity from wind energy
    - Electrolysis with electricity from solar photovoltaic
    - Gasification of Biomass

In addition to these processes the production of H_2 by electrolysis with electricity power generation system in Portugal was also considered. A well-to-wheel (WTW) of H_2 was performed.

Methodology

The purpose of this study was to conduct an LCA WTW of H_2 updating the GREET LCA model version 1.8c_0 (developed by Argonne National Laboratory), since this is based in American reality [3]. The LCA presented here is based on energy use and emissions of greenhouse gases (GHGs).

GREET model does not take into account the emissions and fuel consumption in the production of wind towers and solar photovoltaic panels, i.e., the electricity produced by these technologies in GREET model have zero emissions. Thus, for H_2 production by use of electrolysis with electricity from wind power and photovoltaic panels GEMIS model version

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4.5 [4] was used to get the energy consumption and pollutant emissions associated with towers and solar photovoltaic panels production. By introducing these values in the resulting model MACV2H_2, it is possible to obtain emissions and energy consumption in power generation either by wind or solar photovoltaic. Note that H_2 production by use of electrolysis with electricity from wind power is an addition to the GREET model, since it does not incorporate this. The combination of model data GEMIS with the updating of GREET model for the national reality originates MACV2H_2 model, which is an acronym for Model for Life Cycle Analysis for Hydrogen. The MACV2H_2 model is representative of Portuguese reality; in the cases that data were not found specifically for Portugal, the European reality was considered. Figure 1 characterizes the structure of MACV2H_2.

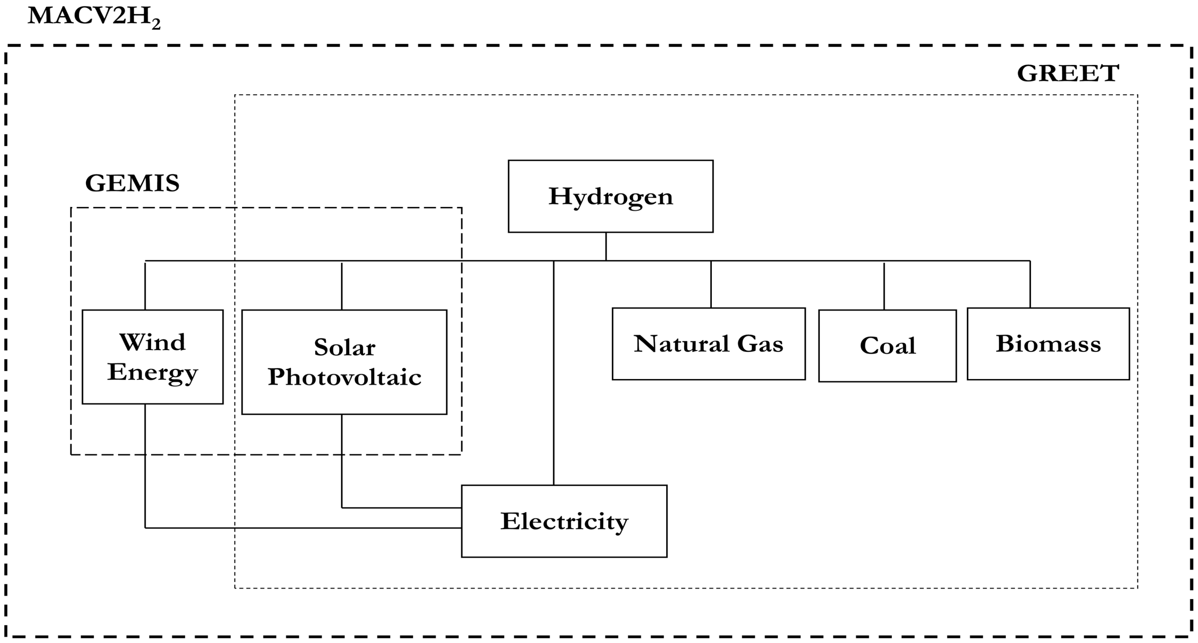

Figure 1 – Scheme of the features of the model MACV2H_2.

MACV2H_2 model is composed in twenty spreadsheets that interact between them. The user just has to enter the values in sheet "Data Entry". The results are later presented in sheet "Results" or in graphical form in the sheet "Graphics". Each one of the intermediate sheets shows the necessary assumptions for analysis.

Another software was used in the development of MACV2H_2 model, NETPAS distance [5], which allows the calculation of distances by sea. It was used to calculate distances between ports for the transport of raw materials and fuels for ship and oil tanker. More significant changes made in MACV2H_2 model development are on the database of vehicles and electricity generation system in Portugal. The relative weight of each energy source in electricity generation in Portugal is shown in Table 1.

Table 1 – Relative weight of each energy source in electricity generation in Portugal [2].

	[%]	[GWh]	[tep]
Oil	10,4	4870,0	1412,3
Natural Gas	28,1	13124,0	3806,0
Coal	26,6	12398,0	3595,4
Biomass	3,4	1588,0	460,5
Photovoltaic energy	0,1	24,0	7,0
Wind energy	8,6	4037,0	1170,7
Others	22,8	10650,0	3088,5
Total	100	46691,0	13540,4

Regarding the database of vehicles the equations presented in the *Emission Inventory Guidebook* [6] were considered. The model allows MACV2H_2 to perform an LCA with the following vehicles:

- Heavy Duty Vehicles < 7,5t
- Heavy Duty Vehicles 7,5t - 12t
- Heavy Duty Vehicles 12t - 14t
- Heavy Duty Vehicles 14t - 20t
- Heavy Duty Vehicles 20t - 26t
- Heavy Duty Vehicles 26t - 28t
- Heavy Duty Vehicles 28t - 32t
- Heavy Duty Vehicles above 32t
- Buses < 18t
- Buses > 18t
- Urban buses < 15t
- Urban buses 15t - 18t
- Urban buses > 18t
- Passenger cars with capacity < 1,4l
- Passenger cars with capacity between 1,4l - 2,0l
- Passenger cars with capacity > 2,0l
- Motorcycles with capacity < 50 cm^3

Originally a calibration of MACV2H_2 model was made to verify the accuracy of the results. Calibration was performed for three passenger cars. Table 2 shows the vehicles data used for model calibration.

Table 2 – Vehicle data used for calibration [7-10].

	BMW mono-fuel	Fiat Panda 3rd Generation	Quantum Prius
Year	2007	2006	2005
Engine	ICE 6,0l V12	FCV	HEV:ICE 1,5l
Urban Consumption [kg_{H2}/100km]	-	0,73	-
Combined consumption [kg_{H2}/100km]	-	-	1,04 – 1,55
Highway consumption [kg_{H2}/100km]	2,1	-	-

The mono-fuel hydrogen BMW was built on the BMW 760Li. It was carried out in a simulation model taking into account an analysis of highway route. The results of the MACV2H_2 model, which can be seen in Table 3, are consistent with data provided by the manufacturer, the largest variation is 2.9%.

Table 3 – Model results for BMW mono-fuel hydrogen.

	BMW 7 H_2	**Scenario 1 V=110 km/h**	**Scenario 2 V=115 km/h**	**Scenario 3 V=120 km/h**
Consumption [kg_{H2}/100km]	2,10	2,05	2,10	2,16
Δ	-	-2,4%	0,0%	2,9%

The Fiat Panda 3rd Generation is a fuel cell vehicle (FCV), which was simulated in the urban route in $MACV_2H_2$. However, for a speed of 35 km/h the results already show some discrepancy with the manufacturer (see Table 4) that can be explained by some variation on the speed considered, since the manufacturer only states that consumption data were gathered in urban conditions.

Table 4 – Model results for Fiat Panda 3rd Generation.

	Fiat Panda H_2	**Scenario 1 V=35 km/h**	**Scenario 2 V=40km/h**	**Scenario 3 V=45km/h**
Consumption [kg_{H2}/100km]	0,73	0,84	0,78	0,75
Δ	-	15,5%	7,3%	3,1%

Quantum Prius is a hybrid electric vehicle with H_2 internal combustion (data shown in Table 2) and was simulated in mixed route. The results of the model are all within the range of values provided by Toyota for the vehicle (see Table 5).

Table 5 – Model results for Quantum Prius.

	Quantum Prius	**Scenario 1 V=40 km/h**	**Scenario 2 V=70 km/h**	**Scenario 3 V=110 km/h**
Consumption [kg_{H2}/100km]	1,29	1,37	1,20	1,30
Δ		6,2%	-7,0%	0,8%

Results

In the WTW analysis the gas and liquid H_2 ($G.H_2$ and $L.H_2$) production in centralized plants and refueling stations was considered. In centralized plants the H_2 production by steam reforming of natural gas (NG), by gasification of biomass and coal, and electrolysis with electricity from solar photovoltaic and wind energy was considered. In refueling stations the H_2 production by steam reforming of NG and by electrolysis with electricity from power generation system was adopted. It was felt even beyond the ICE vehicle with gasoline, the ICE vehicle with H_2 and the FCV with H_2 an average speed of 108 km/h.

The heavy duty vehicles were considered to be EURO IV and with a mass between 28t and 32t. The vehicle is running at an average speed of 50 km/h. Oil tankers and ships carrying fuel and raw materials make the outward journey with a load factor of 80% and the return trip the load factor is 60%. Also noteworthy is that the average speed of oil tankers is 30 km/h and the ship speed is 8 km/h. In the processes of liquefaction and compression the energy source electricity from the national electricity system was considered.

Figures 2 and 3 show the WTW energy consumption for $G.H_2$. The analysed production processes of H_2, the $G.H_2$ produced by electrolysis with electricity from wind energy and applied in FCV is the one with lower energy consumption in 34% when compared with the ICE vehicle (see Figure 3). The use of electricity power generation system for H_2 production is the one that has a higher energy consumption per kilometer. Even applying this H_2 in FCV the energy consumption is 51% for $G.H_2$, higher than the ICE vehicle with gasoline.

The use of biomass for production of $G.H_2$ with gasification and application in FCV has a 9% lower energy consumption than ICE gasoline vehicle in a WTW analysis. The ICE $G.H_2$ vehicle with H_2 produced by gasification biomass has a higher energy consumption when compared with the ICE gasoline (see Figure 2).

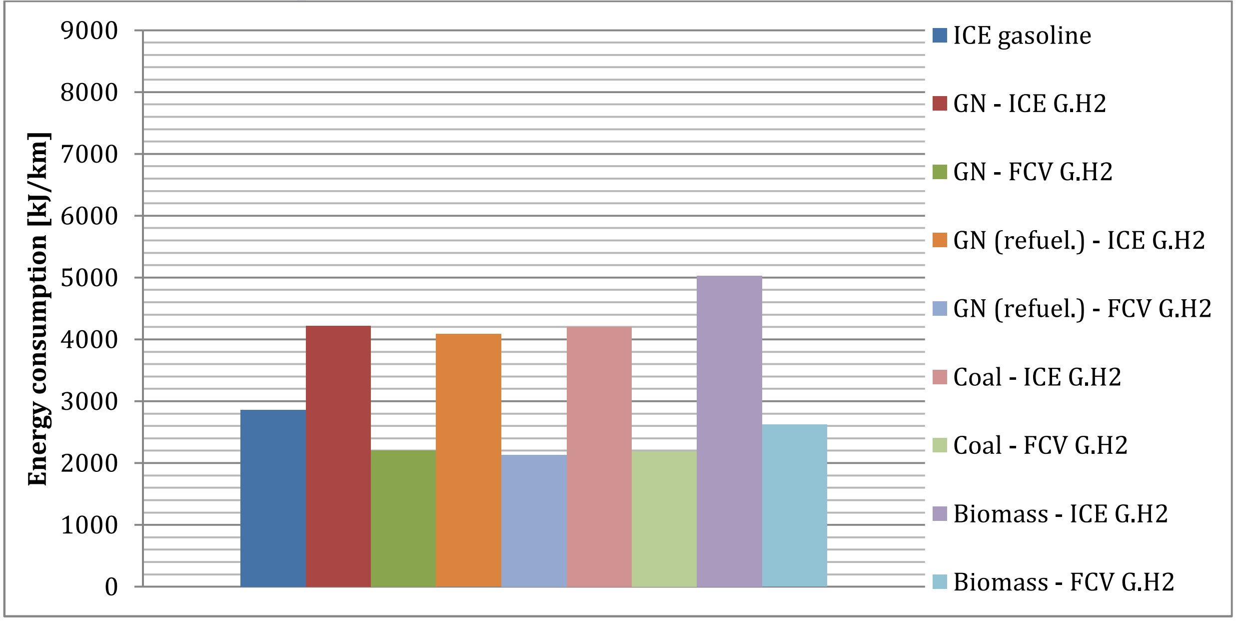

Figure 2 – Energy consumption of $G.H_2$ in WTW analysis - part 1.

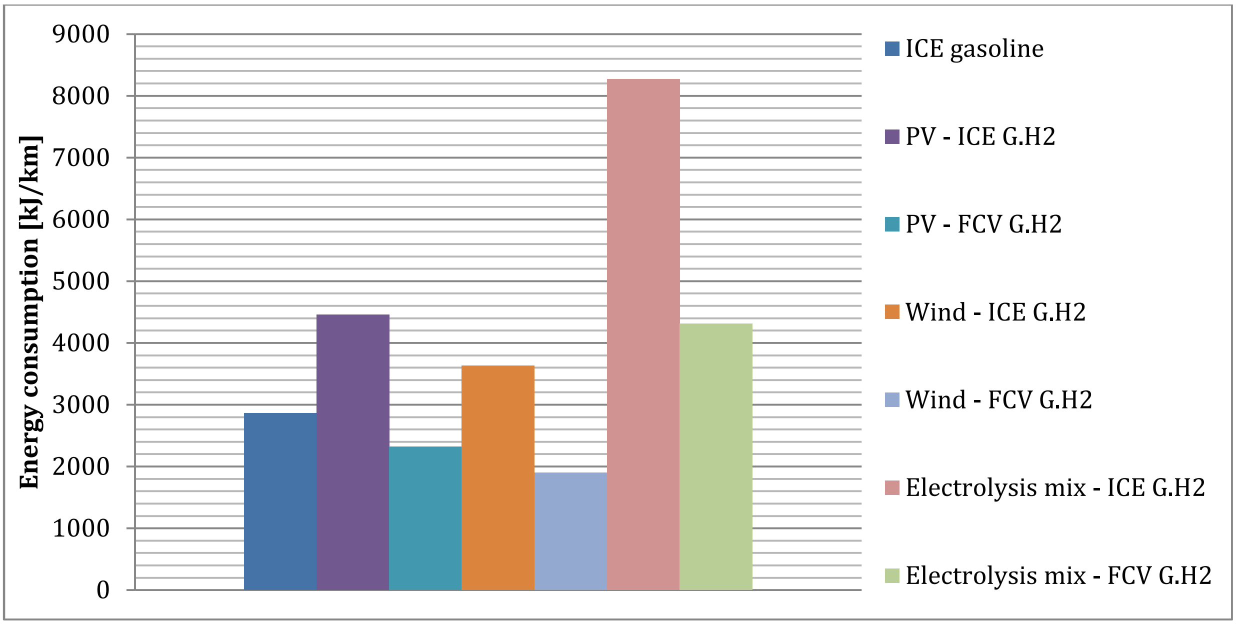

Figure 3 – Energy consumption of $G.H_2$ in WTW analysis - part 2.

In Figures 4 and 5 the WTW energy consumption for $L.H_2$ produced by the processes considered and implemented in FCV and the H_2 ICE vehicles are shown. It appears that the $G.H_2$ has a lower energy consumption than $L.H_2$. This is due to the fact that the liquefaction process requires more energy, nearly three times more than the compression process. However it must be emphasized that the $G.H_2$ produced in centralized plants is very sensitive to the distance between the place of production and refueling station. The use of electricity power generation system for $L.H_2$ production has a higher energy consumption per kilometre (88% higher than the gasoline ICE vehicle).

However, even considering the $L.H_2$ produced by electrolysis with electricity from wind energy and applied in FCV, energy consumption is 23% lower than gasoline ICE vehicle. This has the further advantage of this energy corresponds to only 29% fossil energy. The use of biomass gasification for production of $L.H_2$, this being applied in FCV, energy consumption is 6% higher than the base vehicle. However, fossil energy consumption is reduced by 33%. $L.H_2$ produced by steam reforming of NG and applied in FCV has decreased energy consumption by 8%.

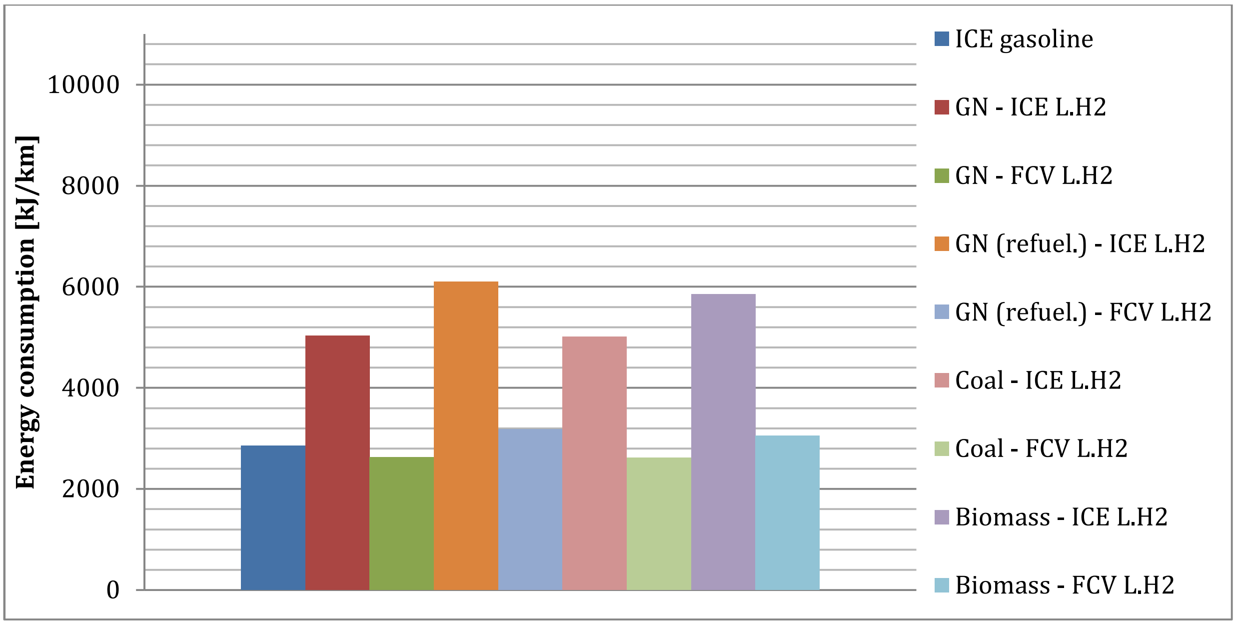

Figure 4 – Energy consumption of $L.H_2$ in WTW analysis – part 1.

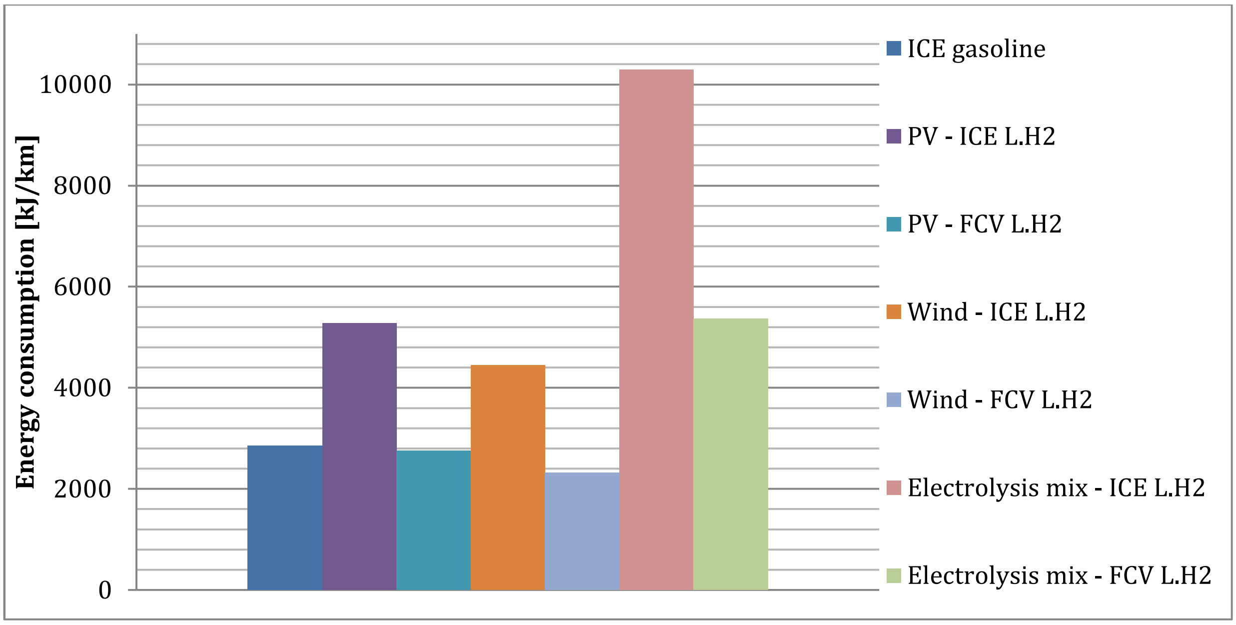

Figure 5 – Energy consumption of $L.H_2$ in WTW analysis – part 2.

The energy consumption of the H_2 produced by electrolysis with electricity from wind energy and applied in FCV is less than the ICE vehicle with gasoline. This has another advantage, since only 18% of the consumption shown corresponds to the case of fossil fuels in G.H2 and 29% for L.H2. Since the gasoline ICE vehicle with the consumption of fossil energy is roughly the same as the total energy consumption.

GHGs emissions are shown in Figures 6 and 7 for $G.H_2$. The $G.H_2$ produced by electrolysis with electricity from wind energy and applied in FCV allows a reduction of GHGs by 85% compared to gasoline ICE vehicle. The use of natural gas to produce $G.H_2$ in order to apply in FCV shows 38% lower GHGs emissions. The electrolysis with electricity power generation system for H_2 production and subsequent use in vehicles shows no advantage over the gasoline ICE. Even the $G.H_2$ produced by electrolysis with electricity of power generation system applied in FCV represent more 43% GHGs emissions than the base vehicle. The FCV with

$G.H_2$ produced by biomass gasification shows an increase in the emission of GHGs by 15% over the base vehicle.

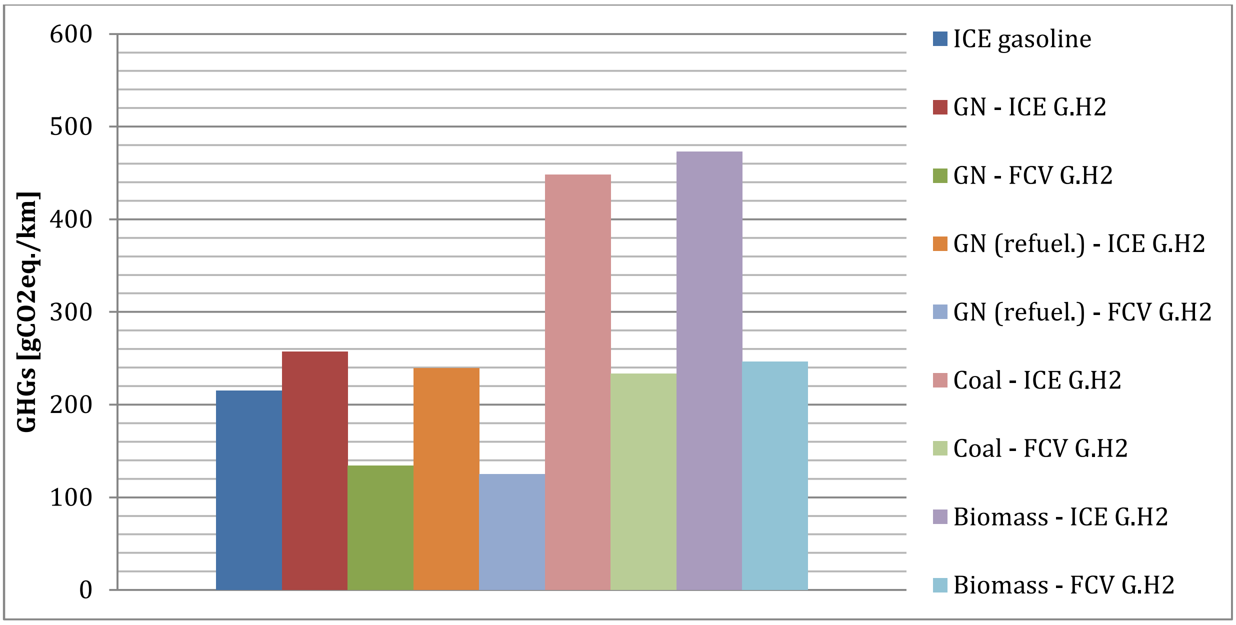

Figure 6 – GHGs emissions of $G.H_2$ in WTW analysis – part 1.

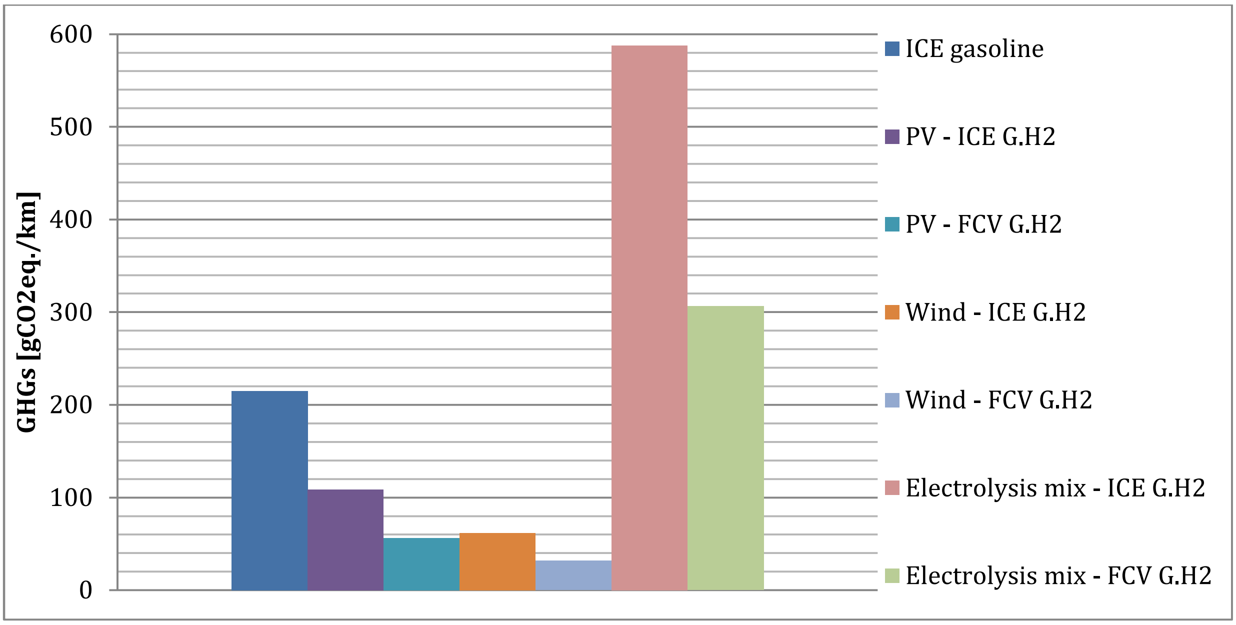

Figure 7 – GHGs emissions of $G.H_2$ in WTW analysis – part 2.

GHGs emissions are shown in Figures 8 and 9 for $L.H_2$. The $L.H_2$ applied in vehicles has more GHGs emissions than $G.H_2$, an expected fact since the energy consumption is also higher. The $L.H_2$ produced by electrolysis with electricity from wind energy and applied in FCV has a 72% reduction in GHGs emissions of the baseline scenario. $L.H_2$ produced by electrolysis with electricity from photovoltaic solar energy has benefits in terms of GHGs emissions. This shows a 60% reduction in GHGs emissions for the gasoline ICE vehicle. Even considering the production of $L.H_2$ by means of the steam reforming of natural gas, which is applied in FCV, there is a 26% reduction in GHGs emissions.

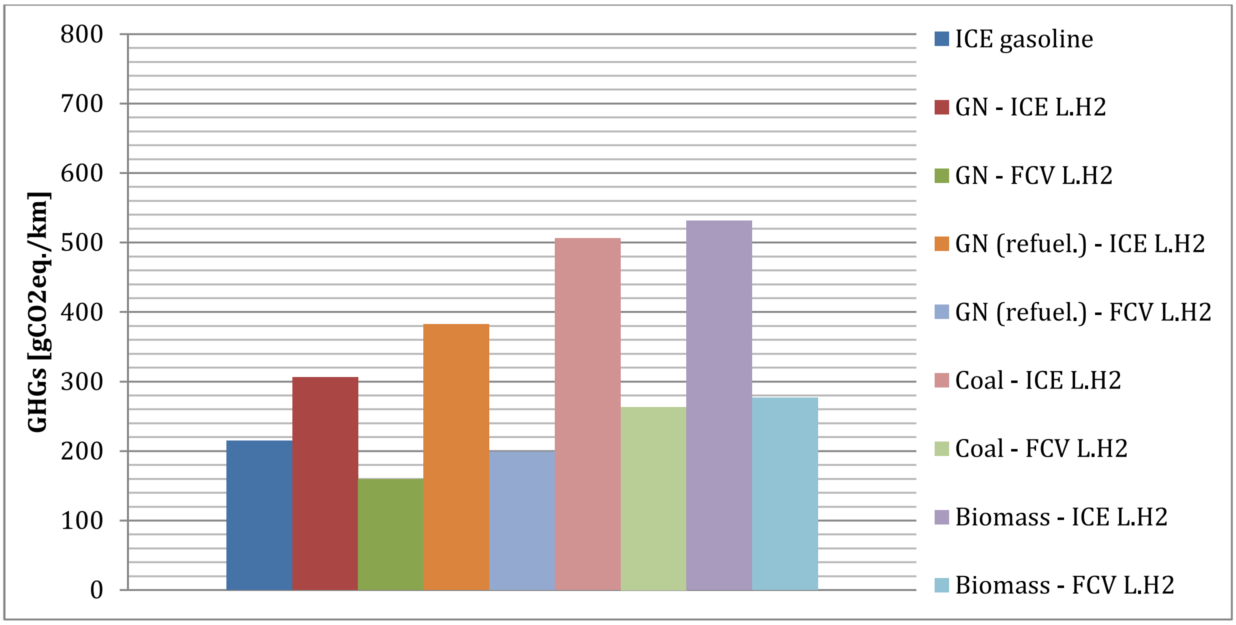

Figure 8 – GHGs emissions of L.H_2 in WTW analysis – part 1.

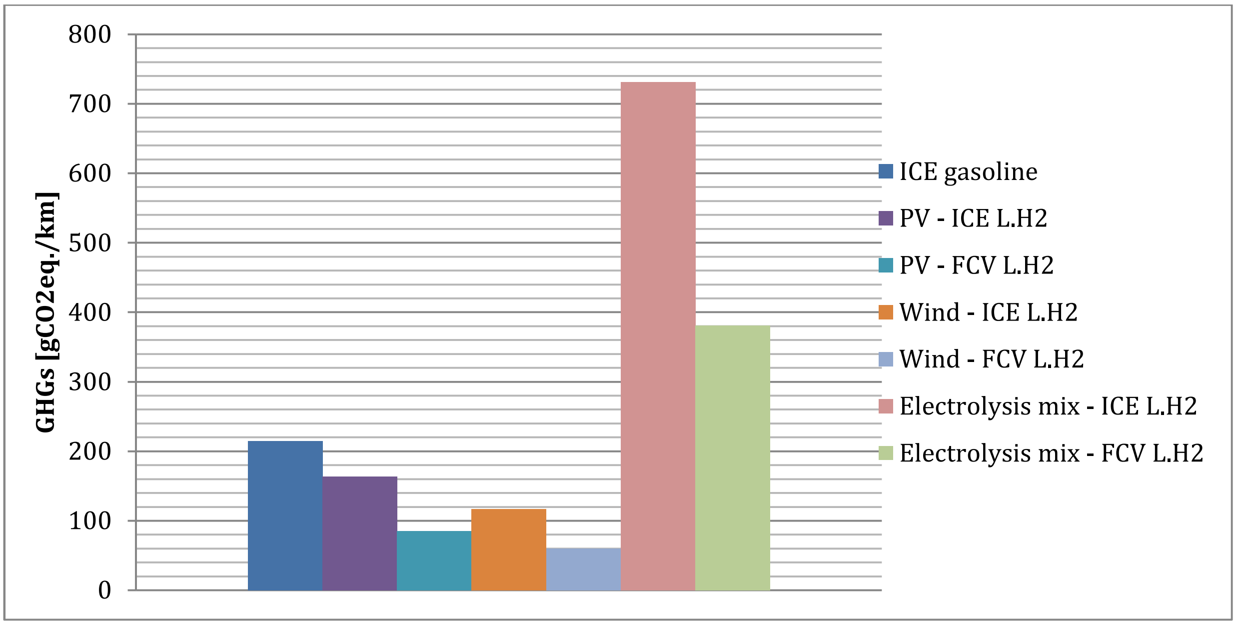

Figure 9 – GHGs emissions of L.H_2 in WTW analysis – part 2.

Conclusions

In the production of hydrogen is very important to take into account the production process. Another important factor to consider is the hydrogen storage. The compression process presents an energy consumption that is three times lower than the liquefaction. However G.H_2 transport is heavily influenced by the distance traveled, due to its low density.

In the WTW life cycle analysis carried out it is shown that H_2 has advantages in terms of energy consumption and GHGs emissions. However this is not a fact that can be generalized, since in the production of G.H_2 centralized plants, transportation fuel can make a difference depending on the distance to the refueling station.

It was concluded that the FCV has lower power consumption than the H_2 ICE vehicles. However there is also the current cost difference between the two. The $G.H_2$ produced by electrolysis with electricity from wind energy and applied in FCV has benefits both in energy consumption or GHGs emissions in relation to gasoline ICE vehicle. The energy consumption showed a decline of 34% and GHGs emissions reduced by 85%. Yet it is also noteworthy that the reduction of fossil fuel consumption is 88%.

In relation to the H_2 produced by electrolysis with electricity from solar photovoltaics and applied in FCV: although the energy source is renewable, GHGs emissions are double from those that result from the H_2 produced by electrolysis with electricity from wind power and applied to the same vehicle. However, in the case of the $G.H_2$, GHGs emissions are 74% lower than gasoline ICE vehicle.

H_2 production by steam reforming of natural gas has advantages both in energy consumption or GHGs emissions in relation to H_2 production by coal gasification. The $G.H_2$ produced by steam reforming of natural gas and applied in FCV has a 23% reduction in energy consumption and 38% in GHGs emissions.

An improvement in the efficiency of production process and liquefaction process of hydrogen, makes that the vehicle application present environmental benefits over gasoline. The production and storage of hydrogen are critical processes in energy and environmental terms. In an WTP analysis [11], it appears that the hydrogen has no advantage over gasoline. However the application in vehicles, depending on the source and production process, the hydrogen can present improvements in energy and environment compared to gasoline. GHGs emissions of the H_2 vehicle correspond almost totally to the production, transportation and storage phases of hydrogen. The operation phase of a gasoline vehicle represents 86% of total WTW GHGs emissions from gasoline.

Nomenclature

FCV: Fuel Cell Vehicle
GEMIS: Global Emission Model for Integrated Systems
$G.H_2$: Gas Hydrogen
GHGs: Greenhouse Gases
GREET: Greenhouse Gases, Regulated Emissions, and Energy use in Transportation
H_2: Hydrogen
ICE: Internal Combustion Engine
LCA: Life Cycle Analysis
$L.H_2$: Liquid Hydrogen
$MACV2H_2$: Life cycle analysis model for hydrogen
PTW: Pump-To-Wheels
WTP: Well-To-Pump
WTW: Well-To-Wheels

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