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Analysis of Energy Consumption and CO₂ Emissions of the Life Cycle of Bio-hydrogen Applied to the Portuguese Road Transportation Sector

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In this work the main objective is to analyze energy consumption and CO₂ emissions of bio-hydrogen for use in the transportation sector in Portugal. A life cycle assessment will be performed in order to evaluate bio-hydrogen pathways, having biodiesel and conventional fossil diesel as reference. The pathways were production of feedstock, pre-treatment, treatment, compression, distribution and applications. For the well-to-tank analysis the SimaPro 7.1 software and excel tools are used. This study includes not only a well-to-tank analysis but also a tank-to-wheel analysis (using ADVISOR software) estimating hydrogen consumption and electricity consumption of a fuel cell hybrid and a plug-in hybrid. Several bio-hydrogen feedstocks to produce hydrogen through fermentation processes will be considered: potato peels.

To estimate the environmental impacts of hydrogen vehicles we consider all emissions associated with the system. The following environmental effects are considered: greenhouse gas emissions and energy consumption. Life Cycle assessment is an analytic tool for quantifying the environmental impacts of all processes used in converting raw materials into a final product [7, 8]. The LCA of the considered fuels was divided in two stages: well-to-tank (WTT) and tank-to-wheel (TTW). WTT considers the fuel from resources recovery to delivery to the vehicle tank. The methodology for the WTT for bio-hydrogen includes the following 5 processes: production of feedstock, fuel production (pre-treatment and treatment), compression and distribution. The pre-treatment and treatment correspond to hydrolysis and fermentation processes respectively. The feedstock to produce hydrogen through fermentation process is potato steam peels as carbon sources. The process for the production of biohydrogen differs primarily concerning the involved microorganisms, the substrate and the light dependence. In this case study the technology considered is bioreactors. The potato steam peels are introduced in the bioreactor where they are hydrolyzed to glucose. This is introducing into the thermoreactor containing thermophilic bacteria. The residual solids of the thermoreactor are introduced in photoreactor containing photoheterotrophic bacteria that convert all organic acids to H₂ and CO₂ [9].

The hydrogen gas has to be compressed to the required pressure. If no heat exchange with the environment is assumed, the compression is adiabatic [10]. Then for estimate energy emission of compression (isentropic compression) used the Equation 1.

$$(W)_{isen} = \frac{nRT_1}{k-1} \left(\left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} - 1 \right)$$

Equation 1: Compression equation

Where the k is adiabatic exponent, n is amount of moles, R is real gas constant, T_1 is the temperature in the suction, P_1 is a suction pressure and P_2 is final (delivery) pressure. In the study case was considering that compression efficiency is about 68%. Hydrogen is compressed at 45 MPa [10].

The pathway considers potatoes produced in Portugal, that average productivity (from 1986 to 2008) is 13 790 kg ha⁻¹ [11]. We considered that potato peels are 35% of potato production [12]. Hydrogen pathway is resumed in Figure 1.

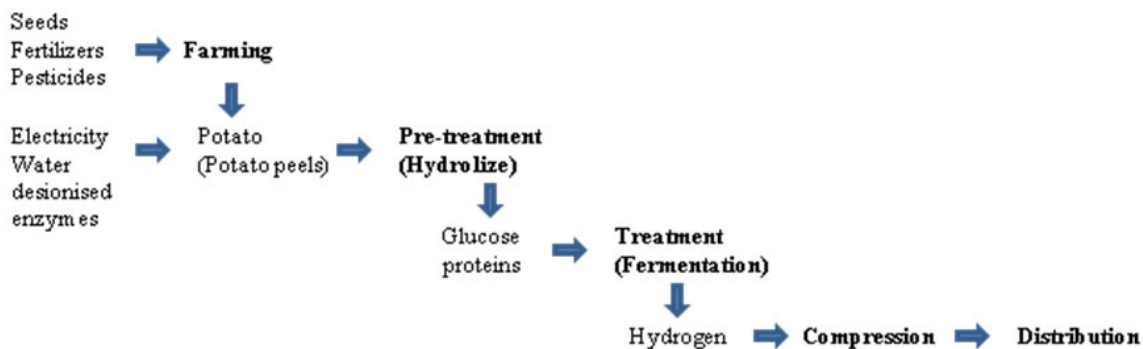


Figure 1: Bio-hydrogen fuel pathway.

This case study considers emissions from the electricity used in hydrogen pathways steps. Electricity consumed in all processes is assumed to come from power mix for Portugal.

The energy consumption and CO₂ emissions for all processes are calculated based on SimaPro software data. The energy spent (MJ/MJfuel) in each of the processes calculated in the present study excludes the energy transferred to final fuel. CO₂ emissions (g/MJfuel) of the processes do not include the CO₂ capture during the crops “agricultural” or algae production stage. A life cycle assessment will be performed having biodiesel and conventional fossil diesel as reference. The three biodiesel studied were [13]:

- Sunflower – the only Portuguese native crop considered for massive biodiesel production. However, considering the maximum land occupancy (from 1980 to 2007), only 6% of the consumed diesel would be replaced.
- Blended rapeseed and soybean biodiesel – Portugal inevitable has to import oil seed crops for biodiesel production, which contradicts many of the sustainability issues in by lorry to Portugal and American soybean shipped to Portugal. A typical oil blend of rapeseed (60%) and soybean (40%) was considered for biodiesel production.
- Microalgae biodiesel – microalgae could become a suitable alternative due to its high biomass production and CO₂ fixation. Nonetheless, it is not a mature technology so

few accurate data is available. The technology considered were photobioreactors and average yields for algae productivities and oil content were considered.

This study will include not only a well-to-tank analysis but also tank-to-wheels, since the vehicle usage simulation will also be performed. TTW is assessing vehicle architecture, power train and fuels effects. The program ADVISOR was used to simulate the energy consumption and emissions of each vehicle in the specified driving cycle.

The vehicle specifications are [14]:

- Hybrid (FC-HEV): fuel cell vehicle with a 75 kW electric motor, Li-ion 6 Ah 267 V battery, 50 kW fuel cell and a total weight of 1388 kg;
- Plug-in hybrid (FC-PHEV): lightweight materials, plug-in series hybrid with fuel cell. Fuel cell stack 50 kW, electric motor 75 kW, battery Ni-MH 45 Ah 335 V and a total weight of 1315 kg.
- Internal Combustion Engine Vehicle (ICEV): internal combustion engine vehicle that can run with diesel and blends of diesel and biodiesel B10 with a four cylinder Diesel engine with 67 kW of power and total weight of 1210 kg.

These vehicles have a total power-to-weight ratio of 55 W/kg since this is representative of the top sales of new vehicles sold in Portugal, with whom these new technologies will compete when they start entering the market. Additionally, it guarantees that similar vehicle performances are being compared.

The used driving cycle is a real measured driving cycle, representing a mix of urban (24% of km, speed below 50 km/h), rural (57% of km, speed between 50 and 90 km/h), and highway (19% of km, speed higher than 90 km/h) driving. Figure 2 shows the journey driving cycle.

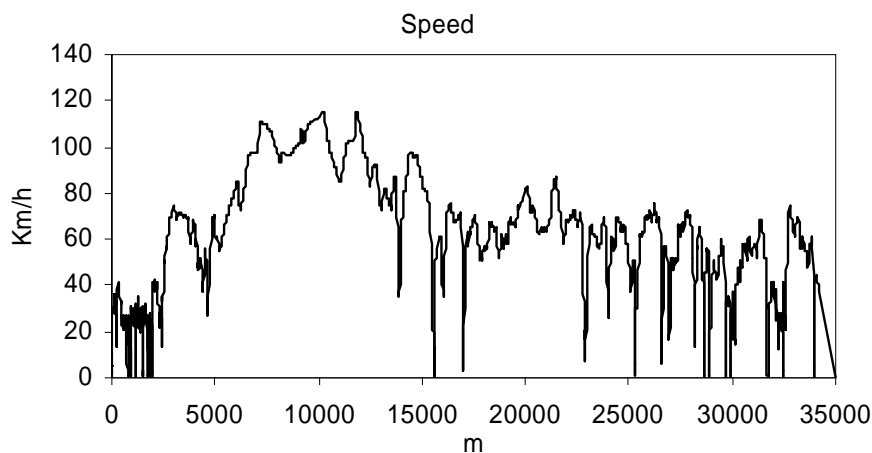


Figure 2: Drive cycle.

The WTT results for energy and global warming gases for life cycle stages farming, “pre-treatment”, “treatment”, compression and distribution of hydrogen production from potato steam peels are present in Figure 3.

In figure 3, results show that Treatment (fermentation) and Pre-Treatment (hydrolysis) are the most energy consuming processes and with higher CO₂ emissions. In these two stages of the production of hydrogen were spent 8.05 g CO₂/ MJ_{fuel} and 0.33 MJ/ MJ_{fuel}, respectively.

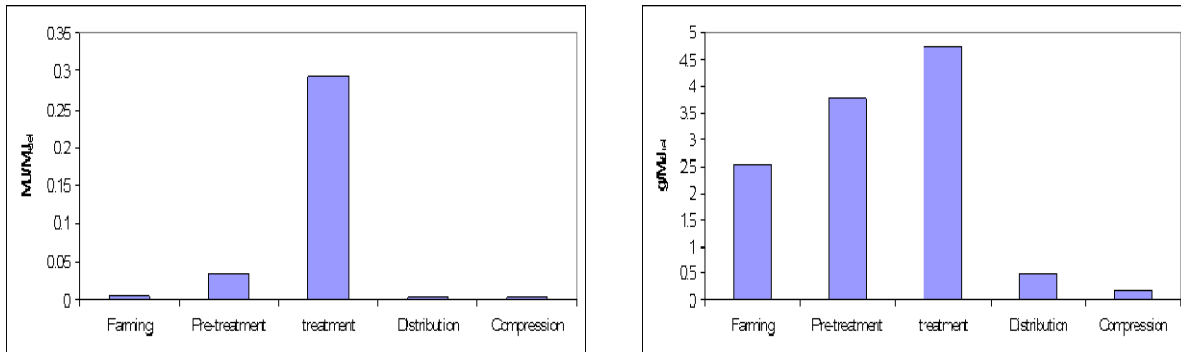


Figure 3: Energy and global warming gases for life cycle stages farming, “pre-treatment”, “treatment”, distribution and compression of hydrogen production from potato peels.

The total energy consumption of the WTT pathways doesn't include the energy content of the produced fuel. When comparing the different pathways of production of biologic hydrogen, biodiesel and diesel, different value for energy and CO₂ emissions are achieved. As it can be seen in figure 4, the diesel production pathway has the lowest values of energy consumption, and has balanced CO₂ emissions with the hydrogen pathway when produced from potato peels, but both with the lowest values.

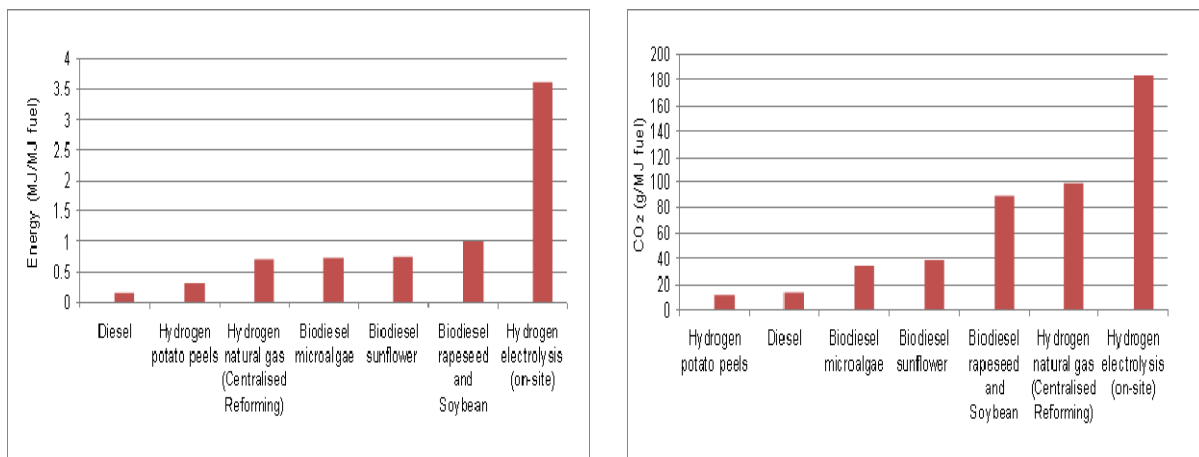


Figure 4: WTT energy consumption and CO₂ emissions of hydrogen, diesel and biodiesel fuels.

The TTW values are taken from the other study (14) as seen in table 1.

Table 1: Fuel life cycle energy and CO₂ WTT, TTW and WTW results for fuel cell hybrid and hybrid plug-in and hybrids plug-in diesel.

Technology-Fuel	WTT (MJ/MJfuel)	WTT (gCO ₂ /MJfuel)	TTW (MJ/km)	TTW (gCO ₂ /km)	WTW (MJ/km)	WTW (gCO ₂ /km)
ICEV- Diesel	0.16	14.00	1.67	124.40	0.27	147.78
ICEV-B10-Sunflower	0.22	16.50	1.63	110.70	0.36	137.60
ICEV-B10-microalgae	0.22	16.10	1.63	110.70	0.36	136.94
ICEV-B10-Rapeseed and Soybean	0.24	21.60	1.63	110.70	0.40	145.91
FC-HEV-hydrogen Centralized Reforming	0.72	99.10	1.08	0.00	0.78	107.03
FC-HEV-hydrogen Electrolysis (on-site)	3.62	184.21	1.08	0.00	3.91	198.95
FC-HEV-hydrogen Potato Peels	0.34	11.72	1.08	0.00	0.36	12.66
FC-PHEV- hydrogen Centralized Reforming	0.72	99.10	0.34	0.00	0.24	33.69
FC-PHEV-hydrogen Electrolysis (on-site)	3.62	184.00	0.34	0.00	1.23	62.56
FC-PHEV-hydrogen Potato Peels	0.34	11.72	0.34	0.00	0.11	3.99
FC-PHEV- electricity	1.47	101.78	0.21	0.00	0.31	21.37
FC-PHEV- hydrogen Centralized Reforming+electricity	1.00	100.12	0.55	0.00	0.55	55.07
FC-PHEV-hydrogen Electrolysis (on-site) + electricity	2.80	152.76	0.55	0.00	1.54	83.93
FC-PHEV-hydrogen Potato Peels+electricity	0.77	45.95	0.55	0.00	0.42	25.36

Figure 5 shows the energy results for WTW and Figure 6 the CO₂ emissions WTW results for the fuels and technologies analyzed.

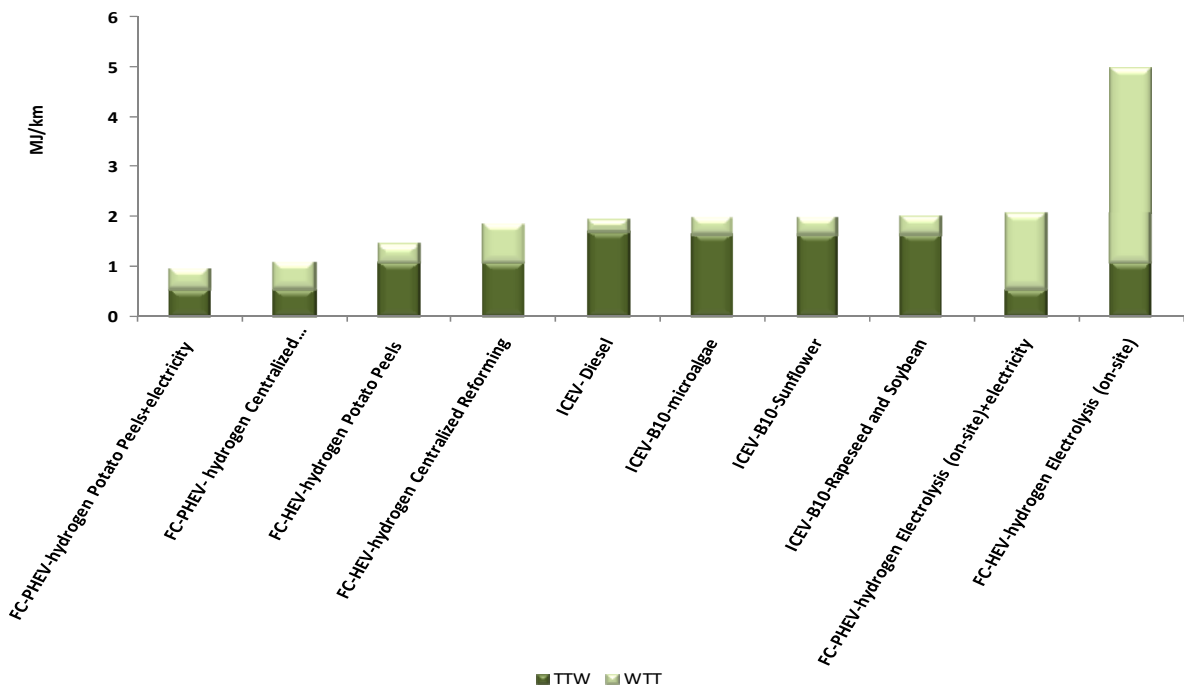


Figure 5: Energy consumption for WTW of hydrogen, diesel and biodiesel fuels and technologies analyzed.

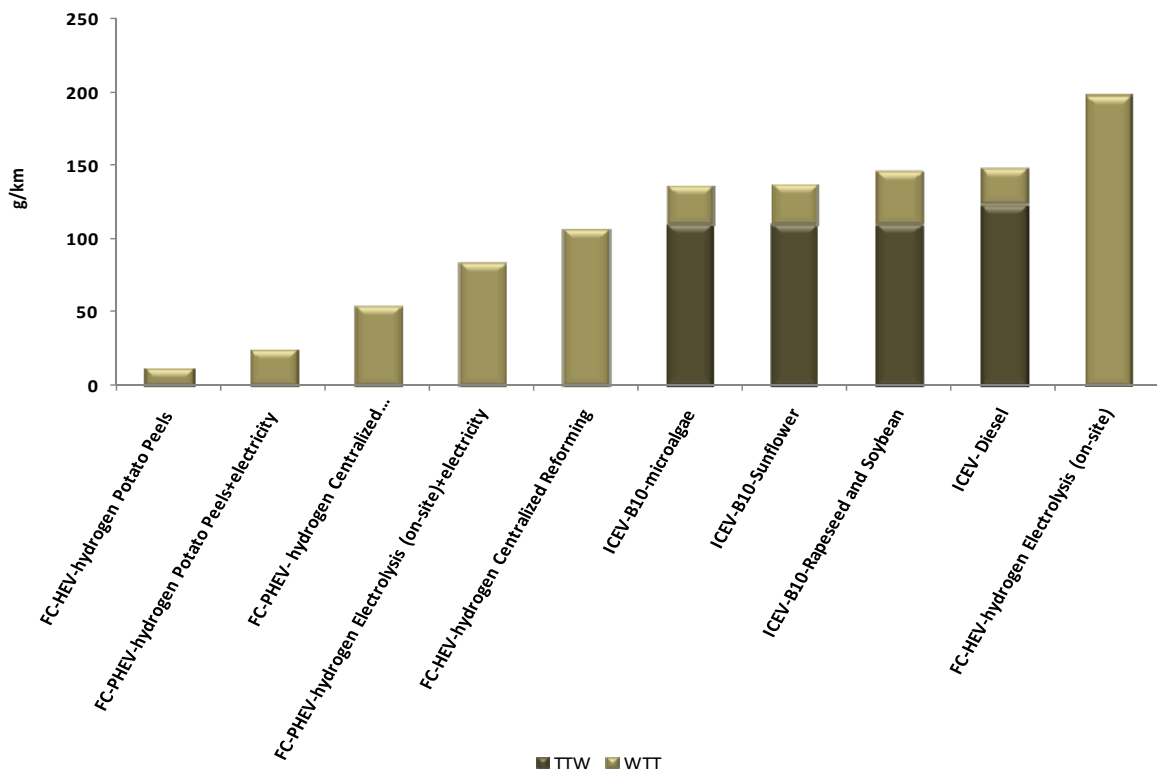


Figure 6: WTW CO₂ emissions for WTW of hydrogen, diesel and biodiesel fuels and technologies analyzed.

An extensive fuel life cycle was assessed for conventional diesel and fuel cell vehicle technologies. The main focus was on hydrogen production pathways, namely, through hydrolyses and fermentation of potato peels.

Main findings for WTT part of fuel life cycle: the required energy resulting from sunflower, rapeseed/soybean, microalgae and diesel are respectively 0.77, 0.99, 0.75 and 0.16 MJ/MJ_{fuel}. The required CO₂ emissions resulting are respectively 39, 90, 35 and 14 g/ MJ_{fuel}. For hydrogen the respective values are 0.33 MJ/MJ_{fuel} and 8.05 g/ MJ_{fuel}. No credits for CO₂ capture from crops/algae/oil were considered. The total energy consumption of the WTT pathways doesn't include the energy content of the produced fuel.

Main findings for the entire WTW fuel life cycle: with the exception of the electrolysis pathway, fuel cell vehicles presented the lowest values regarding energy consumption and CO₂ emissions. Besides potato peels pathway has balanced values for the energy consumption with centralized reforming, but both with the lowest values, for the CO₂ emissions the potato peels have the lowest values (1-1.5 MJ/km and 13-25 g/km).

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