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ENERGETIC, ECONOMIC AND ENVIRONMENTAL EVALUATION OF INTERNAL COMBUSTION ENGINES TECHNOLOGIES USED IN BRAZILIAN ROAD CARGO TRANSPORTATION

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Not applicable.

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Eyko Medeiros Rios: Conceptualization, Methodology, Investigation, Formal analysis, Writing - Original Draft and Visualization.

Ronney Arismel Mancebo Boloy, Cristina Gomes de Souza, Valter Silva: Conceptualization, Methodology, Investigation, Formal analysis, Supervision and Project Administration.

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1.8 Consent for publication

The authors give consent for the publication of details within the text to be published in the Journal.

ABSTRACT

This study presents a comprehensive energetic (thermal efficiency, mass flow rate), economic (environmental cost of the life cycle) and environmental (ecological efficiency) analysis that was carried out to promote the possible replacement of the conventional internal combustion engine operation mode by ignition compression with the dual fuel mode, promoting the use of biofuels, namely: biodiesel, biogas and hydrogen in the proportion of 70% when applied to road cargo transportation. Three methods; energetic analysis, environmental life cycle costing assessment and ecological efficiency are used to obtaining the highest economic profitability from the alternative fuels with the minimum environmental impact for Brazilian road cargo transportation. A truck model delivery 6.160 Volkswagen is selected as the case study. The values of mass flow rate, thermal efficiency, environmental cost of the life cycle and ecological energy efficiency were estimated using their respective equations and indicators. The energetic analysis showed values of mass flow rates for biodiesel+hydrogen and biodiesel+biogas, equals to 6.45 kg / h and 26.94 kg / h respectively, and for conventional diesel of 33.88 kg / h. In the economic analysis, an environmental life cycle cost equal to 10.21 R \$ / km was obtained for biodiesel + hydrogen produced through electrolysis with photovoltaic energy, 5.10 R \$ / km for biodiesel + Hydrogen produced through electrolysis with wind energy, 2.83 R \$ / km for biodiesel + Hydrogen produced through methane steam reforming without CCUS, 3.02 R \$ / km for biodiesel + Hydrogen produced through biomass gasification, 3.98 R \$ / km for biodiesel + biogas and 2.11 R \$ / km for diesel scenarios. Finally, in environmental analysis, the energy-ecological efficiency achieved for the operating modes of diesel, biodiesel + biogas and biodiesel + hydrogen were 32.2%, 52% and 64% respectively. Considering the results found, it is pertinent to highlight that the most promising scenario is for the use of the biodiesel + hydrogen produced from biomass gasification proportions, which achieved greater efficiency, lower long-term cost and emissions close to zero greenhouse gases, however, it is still an expensive technology and worthy of attention, government plans and guidelines to become a competitive alternative in the market for biofuels and environmentally friendly technologies.

Keyword Keys: Biofuels, dual fuel mode, energy-ecological efficiency, economic estimative.

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NOMENCLATURE (alphabetic order)

BTE	Brake Thermal Efficiency
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BP	Brake Power
VE	Volumetric Efficiency
TE	Thermal Efficiency
EGT	Exhaust Gas Temperature
CA	Crank Angle
BFR	Biogas Flow Rate
FR	Fuel Replacement
GFR	Gas Fuel Rate
DFR	Diesel Fuel Rate
MFB	Mass Fraction Burnt
FFR	Fuel Flow Rate
ID	Ignition Delay
CP	Cylinder Pressure
HRR	Heat Release Rate
CD	Combustion Duration
CO	Carbon monoxide
CO ₂	Carbon Dioxide
HC	Hydrocarbon
NO _x	Nitrogen Oxide
SO	Smoke Opacity
CH ₄	Methane
UHC	Unburnt Hydrocarbon
PM	Particulate Matter
CH ₂	Methylene
H ₂	Hydrogen
LCA	Life Cycle Assessment
BG	Biogas
BD	Biodiesel
CNG	Compressed Natural Gas

LNG	Liquid Natural Gas
NG	Natural Gas
LFG	Liquified Petroleum Gas
CI	Compression Ignition
SI	Spark Ignition
ON	Octane Number
HCCI	Homogenous charge compression ignition
SCCI	Stratified Charge Compression Ignition
EGR	Exhaust Gas Recirculation

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82 ABBREVIATIONS

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84	1.4-DCB	1.4-Diclobenzo
85	ABNT	Brazilian Association of Technical Standards
86	ANP	National Agency of Oil, Natural Gas and Biofuels
87	BD	Biodiesel
88	BEN	National Energy Balance
89	BG	Biogas
90	BioG	Biomass Gasification
91	BP	Brake Power
92	BTE	Brake Thermal Efficiency
93	C ₁₈ H ₃₂ O ₂	Biodiesel
94	C ₆ H ₆	Diesel
95	CCUS	Carbon Capture Utilisation and Storage
96	CH ₄	Methane
97	CI	Compression Ignition
98	CIE	Compresion ignition engine
99	CNG	Compressed Natural Gas

100	CNT	National Transport Confederation
101	CO	Carbon monoxide
102	CO ₂	Carbon Dioxide
103	DFM	Dual Fuel Mode
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105	EGR	Exhaust Gas Recirculation
106	eLCC	Environmental life cycle costing
107	EPE	Energy research company
108	GASEQ	Chemical Equilibrium Software for Combustion
109	GHG	Greenhouse gases
110	H ₂	Hydrogen
111	HC	Hydrocarbon
112	IPCA	National consumer price index
113	LCA	Life Cycle Assessment
114	LFG	Liquified Petroleum Gas
115	LHV	Lower heating value
116	LNG	Liquid Natural Gas
117	MSR	Methane Steam Reforming
118	NG	Natural Gas
119	Nox	Nitrogen Oxide
120	ON	Octane Number
121	PM	Unburnt Hydrocarbon
122	PNPB	Program for production and use of biodiesel
123	SELIC	Special Custody Settlement System

124	SFM	Single Fuel Mode
125	TTW	Tank-to-Wheel emission in gCO ₂ eq/km
126	UNFCCC	United Nations Climate Change
127	WE	Wind Energy
128	Z	Fuel proportion

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131 GREEK CHARACTERS

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133	ε	Ecological energy efficiency
134	Π_{GW}	Global warming indicator
135	Π_{HT}	Human toxicity indicator
136	Π	Pollution indicator
137	Φ	Stoichiometric factor

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2 INTRODUCTION

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Energy source formed thousands of years ago, the fossil fuels even nowadays are still widely accepted and used. As a primary source of energy, they are unsustainable, with imminent scarcity and contribution to environmental pollution. Since the industrial revolution breakthrough, especially in developing countries, energy demand grows significantly entailing chain reactions such as health concerns, environmental negative effects and high relative costs noticeable between government – citizen relationship (NADALETTI et al., 2015). Even with the adoption of different energy development models, focused on biomass use such as ProÁlcool (1975) and national program for production and use of biodiesel called PNPB, the contribution value of fossil fuels in the Brazilian energy matrix is still noteworthy.(NADALETTI et al., 2015) . Therefore, actions to favour the use of biofuels in transport sector, generates an opportunity for research.

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In Brazil, the internal supply of energy reached 287.6Mtoe, recording a drop of 2.2% compared to the previous year, partly due to the sugarcane biomass and biodiesel offer increase and the non-renewable sources retraction supply, resulting from an atypical year of the coronavirus pandemic advent, both contributing to a renewable level of 48.4%, higher than last year's with 46.1% (EPE, 2021).

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According to BEN 2021, the transport sector was one of the most impacted by the COVID-19 pandemic, with its consumption having decreased by 5.5 million ton. Practically all fuels used suffered a decrease compared to 2019. Unlike light vehicles, which suffered with restrictive measures due to social distance, cargo transport was less affected by the pandemic since this mode it is essential for the supply of most brazilian cities. As a result, the brazilian transport sector presented an energy matrix composed of 25% of renewable sources in 2020, maintaining the same level as the previous year and representing around 31.2% of total energy consumption, just behind the industrial sector, which owns of 32.1% (EPE, 2021).

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Conventionally slow to change, the energy sector has experienced unprecedented dynamism in recent years, in large part due to the advent of renewables, even with limited

employability at global scale. With the emergence of COVID-19 pandemic, renewables revealed significant resilience. In addition, the role in decarbonizing economies and the potential to create jobs by supporting economic recovery got them out of the supporting role to take the lead role (IRENA, 2021).

The 2030 Agenda consider sustainable transport techniques, as well as other associated energy methods and policies, would create a powerful economic foundation for all countries (SOLAYMANI; SHARAFI, 2021). In this regard, governments have a vital role to play in improving energy transition and limiting the global temperature increase to 1.5°C. Policy priorities such as climate change, energy security, energy access and air pollution can place energy transition at high level of implementation (IRENA, 2021).

Biofuels have been successfully applied worldwide, in electricity production, transport or agricultural mechanization , being appointed for developing and industrialized countries (SIDIBÉ et al., 2010) .It can be generated in gas, solid and liquid form. (RODINOVA et al, 2017). Among the existing options, for specific applications like long distance driving or heavy-duty transport, biogas, biodiesel and hydrogen have great features. (WONG et al., 2015)

Due to low cetane number, gaseous fuels can be applied through Dual Fuel technology, where the engine system operates on both liquid and gaseous fuels simultaneously. In diesel engines, the air temperature is more than 553 K close to the moment of diesel injection (ALOUCHEK et al., 2017). However, in dual fuel mode, there is a need to use liquid fuel to attain the temperature at the end of the compression stroke in a Compression Ignition engine. The self-ignition temperature of gaseous fuel is lower and the temperature raise up to about 1087 K is mandatory (ALOUCHEK et al., 2017). Once, a liquid fuel with high Cetane number is fired in the air- gas fuel mixture at the end of compression stroke, initiates the ignition process of the gaseous fuel and the liquid fuel, known as the pilot fuel, acts as a source of ignition. The gaseous fuel is called the primary fuel on which the engine largely runs. Furthermore, it has been observed that the dual fuel engine requires a shortened combustion duration when compared to diesel conventional mode (ALOUCHEK et al., 2017).

The other benefits resulting from dual fuel mode engines employment includes: easier fallback to pure diesel mode in case of shortage of inducted gaseous fuels; no

modification of the engine combustion chamber, substantial reductions of smoke and NO_x emissions, engine efficiency maintenance and versatility on fuel supply types like hydrogen, biodiesel, Liquefied petroleum gas, methane, natural gas, producer gas, syngas and biogas,.(BORA; SAHA, 2016; SARKAR; SAHA, 2020)

In other hand, given the distinct attributes of two different fuels having dissimilar phases, the Dual Fuel Mode engine performance deteriorates considerably as compared with the engine's operation in pure diesel mode. The important methods suggested (Karim 1980) are control and quality of pilot fuels, modulating the inducted gaseous fuel in terms of Φ_{global} , and intake charge preheating.(SARKAR; SAHA, 2020)

Many researchers from different perspectives are still investigating Dual Fuel compression ignition engine effects. DEHERI et al. (2020) centers on the application of biogas and hydrogen as alternative fuel in CI engine, noticing optimized performance and low emission characteristics. KHAYUM; ANBARASU; MURUGAN (2020) conducted in the DFM engine experiments to assess the performance, emission and combustion parameters, operating to run on three different mass flow rates of biogas, three different injection timings, and three different nozzle opening pressures. KHATRI; KHATRI (2020) through experimental results exposed the improvement of dual fuel mode performance with hydrogen-biogas-diesel fuel and emissions reduction. VERMA et al. (2020) investigates the usage of EGR and establish that it could improve the utilization of hydrogen in dual fuel engine, especially at the high loads. ROSHA et al. (2022) investigated hydrogen-enriched biogas and diesel in a DFM mode at variable compression ratios, noticing that in higher compression ratio improves the engine performance to a great extent, along with emissions reduction.

When it comes to the best of the authors' knowledge from scientific publication, literature efforts are directed to bioenergy research trends and prospects, themes like life cycle assessment, biomass conversion technologies, patent analysis and global energy use takes place. Due to the lacking scenario, there is a potential growth of studies regarding experimental studies of dual fuel mode fueled with liquid-gaseous application on CIE, such as energy efficiency, energy-ecological efficiency and economic estimative applied specifically to heavy load segment.

Reducing the heavy-duty trucks operation is a great incentive for investment in alternative technologies. The LCA metrics provides potential cost savings when

considering different technologies. The cost of converting a truck engine to a dual-fuel system is expected to be minor when compared to the cost of the vehicle itself and the fuel consumed along the time, there is only the need to modify the fuel injection system and add tanks to store gaseous fuel in the truck. The annual maintenance fees are assumed to be the same for diesel conventional engine and dual fuel engine. Is even pertinent to anticipate fewer maintenance costs for the converted trucks, due to preliminary internal studies showing diesel particulate filter being less activated frequently under dual-fuel system. Since the conversion technique of a conventional vehicle to a dual fuel one is minimal, it does not require any additional maintenance actions over the lifetime period. While dual-fuel heavy duty trucks are currently under development by several major truck manufacturers, further research and development efforts are needed for these vehicles to become commercially available, consequently a solution that can be implemented as soon.(EL HANNACH et al., 2019)

Energy efficiency simply means using less energy to perform the same task, therefore, eliminating energy waste. It brings a range of benefits like reducing greenhouse gas emissions, reducing demand for energy imports, and lowering costs on a household and economy-wide level. Renewable energy technologies also assist to accomplish these purposes, introducing cheapest and often immediate ways to reduce the use of fossil fuels. In case of transport sector, more energy efficient vehicles require less fuel to cover a given distance. This generates fewer emissions and makes them significantly less expensive to operate, especially on the truck transportation segment.(RIMKUS; STRAVINSKAS; MATIJOŠIUS, 2020)

Based on above literature review, our research focuses on the evaluating of the possibility to replace the compression ignition engine powered only by conventional diesel to dual fuel compression ignition engine fueled by the proportions of soybean biodiesel and sugarcane biogas or soybean biodiesel and hydrogen produced through electrolysis with photovoltaic energy, electrolysis with wind energy, methane steam reforming without CCUS and biomass gasification as the solution to achieve the highest profitability from the alternatives fuels used and, at the same time, produce the minimum environmental impact. The present study is projected to fill this gap in the literature. This extensive investigation over dual fuel operation modes allied with waste energy valorization can be a potential solution to heavy road freight transport, fortifying decision-making sustainable and environmentally friendly technologies. The contribution

of the paper is fourfold as we simultaneously obtain technology, environmental, economic and social contributions. Seen by technology contribution perspective the dual fuel technology does not involve any major engine modification only a pre-mixer is attached on the inlet manifold and the use of liquid fuel allied with gaseous fuel contributes to engine efficiency and fuel economy. Lower emissions and less harmful pollutants in the exhaust gas helps to reduce the percentage of greenhouse gases and prevents global warming, proving to be a great ally in the environmental context. Despite the additional cost when compared to the conventional diesel engine, the dual fuel system has an excellent cost-benefit ratio when applied to cargo vehicles due to the extensive useful lifetime on average of 20 years, allowing the investment to be easily diluted over the years. Lastly, Brazil has a great agricultural power and global interest is rising in green hydrogen as one of the solutions for an energy transition toward zero or net-zero emissions. which makes the dual fuel engine when powered by biofuels a potential alternative that can be socially accepted and able to promote new working fields

3 METHODOLOGY

The truck model delivery 6.160 Volkswagen was designated to estimate impacts on costs, health and environment through analysis of energy-ecological efficiency and cost estimative, aiming to replace the compression ignition engine fueled only with conventional diesel to dual-fuel compression ignition engine fueled with soybean biodiesel and sugarcane biogas or soybean biodiesel and Hydrogen produced through electrolysis with photovoltaic energy, electrolysis with wind energy, methane steam reforming without CCUS and biomass gasification. In addition, the mass flow for biodiesel/biogas and biodiesel/hydrogen for dual-fuel operation mode will be calculated. Therefore, this item divided into sections: Section 2.1 describes the operating modes of delivery 6.160 Volkswagen; Section 2.2 estimates mass flow rate of biodiesel, biogas and hydrogen for compression ignition engine; Section 2.3 shows the simulation of diesel, biodiesel, biogas and hydrogen combustion on GASEQ software; Section 2.4 demonstrates the estimation of the human toxicity and global warming indicator and calculation of the energy-ecological efficiency of the compression ignition engine; 2.5 estimates the life cycle costing to implement the dual fuel mode system.

3.1 Compression ignition engine operating modes

The truck model delivery 6.160 Volkswagen has three operate engine mode: Single compression ignition engine fueled with Diesel, Dual-fuel compression ignition engine fueled with Biodiesel-Biogas and Dual-Fuel compression ignition engine fueled with Biodiesel-Hydrogen.

3.1.1 The Single fuel compression ignition engine: operation mode

The single compression ignition engine, or in other words, the diesel engine is a machine that transforms thermal energy into mechanic energy obtained from fuel combustion inside the engine cylinder. having principles of intake, compression, combustion, and discharge. Unlike otto engines, the Diesel engine uses higher compression, igniting the fuel instead of using spark plug. Figure 1 describes the Single Fuel compression ignition engine operation mode

Figure 1: Single Fuel compression ignition engine operation mode

Source: Self-elaboration

The operation begins with the ignition of the engine. Due to the compression of the air, the temperature in the chamber rises, with combustion occurring in such a way

that it reaches the point of self-inflammation of the fuel. The diesel when introduced into the chamber by means of an injector, meets heated air suffering from combustion and consequently expelling emitting gases. The accelerator will regulate the amount of fuel supplied by the pump and, consequently, the power that the engine will generate.

3.1.2 The Dual-Fuel compression ignition engine operation mode

The Dual Fuel compression ignition engine system allows diesel engines to run with a mixture of liquid fuel and gas fuel, giving preference to the gas fuel to take advantage of the economic and environmental benefits. In this study the proportions biodiesel-biogas and biodiesel-hydrogen will be considered.

Figure 2 and 3 describes the Dual-Fuel compression ignition engine operation mode under biodiesel+biogas and biodiesel+hydrogen mixtures.

Figure 2: Dual-Fuel compression ignition engine operation mode

Source: Self-elaboration

Dual-Fuel Compression ignition engine Dinamic

Figure 3: Dual-Fuel compression ignition engine operation mode

Source: Self-elaboration

In this case, the gas is mixed with air before the intake valve during the air intake period. After the compression phase, the gas air mixture is ignited by small amounts of liquid pilot fuel, which is pressurized and fed to the cylinder by a small common rail system. Combustion is fast, and after the working phase the exhaust gas valve open and the cylinder is empty from the exhaust gases. Lastly, the inlet air valve open when the exhaust gas valve close and the process starts again.

The vehicle chosen to perform the cost analysis was Delivery 6.160, a medium truck manufactured by Volkswagen, being the best seller in its category and widely used for urban and road freight. The Volkswagen Delivery is a heavy- load disguised as a pickup truck. It has a cabin, chassis, engine and truck gearbox. But, according to the Brazilian Traffic Code, it is a medium pickup truck. It is a Volkswagen vehicle that can be driven by ordinary drivers, with B license. The B license in Brazil allows to drive vehicles with up to eight passengers and that do not exceed 3.500 kg, which is exactly the total gross weight approved by Delivery Express, in this way, the Delivery truck pays as car toll and has no traffic restrictions in cities or roads and in the eyes of the legislation it is like Hyundai HR. Brazilian labeling program estimates the Delivery Express energy consumption and efficiency as D in general classification out of a scale from A to E and B classification when compared to its own category.(INMETRO, 2020).Table 1 presents the truck specifications provided by Volkswagen:

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Table 1: Truck specifications

Delivery Express	
Truck specifications
Categorie	Medium Truck
Brand	Volkswagen
Model	Delivery 6.160
Power (Kw)	110
Autonomy (km)	440 (City) / (Road)
Income (km/l)	5.5 (City)/ 8 (Road)
Engine	Cummins ISF 2.8 Turbocompressor - 4 Cylinder
Tank Fuel (L)	80

Source: Adapted from Volkswagen,2020

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373 3.2 Energetic Analysis. Mass flow rate of biodiesel, biogas and hydrogen in dual-fuel
374 mode

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376 When the engine is powered by two fuels, it is necessary to consider the proportion
377 of each fuel injected and its LHV. The biogas and hydrogen mass flow rate of the DFM
378 can be calculated as demonstrated in Eq. (1) and Eq. (2) respectively.

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$$m_{biogas} = \frac{z \times P}{BTE_{dual-fuel} [(1-z) \times LHV_{biodiesel} + z \times LHV_{biogas}]} \quad (1)$$

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$$m_{hydrogen} = \frac{z \times P}{BTE_{dual-fuel} [(1-z) \times LHV_{biodiesel} + z \times LHV_{hydrogen}]} \quad (2)$$

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Where, $BTE_{dual-fuel}$ is the brake thermal efficiency of the DFM; P is the vehicle power, in kW; m is the biogas and hydrogen flow required, in kg/s; LHV is the low heating value of biogas and hydrogen, in kJ/kg; z represents the proportion of biodiesel replaced by biogas or hydrogen, whose value varies between 0%-100%, with $z = 0\%$ normal operation (single fuel mode) and $z > 0\%$ dual-fuel mode operation with gaseous fuel (primary fuel) and liquid fuel (pilot fuel). According to (BORA; SAHA, 2016) the $BTE_{dual-fuel}$ is 19.54%. The biodiesel mass flow rate, in kg/s, of the DFM can be obtained from Eq. (3).

$$m_{biodiesel} = \frac{\frac{P}{BTE_{dual-fuel}} - (m_{gaseous\ fuel} \times LHV_{gaseous\ fuel})}{LHV_{biodiesel}} \quad (3)$$

When the motor is powered by a single fuel, or in other words, running in the combustion ignition engine mode fed only by conventional diesel, the mass flow rate in kg/s can be obtained through Eq. (4).

$$BTE_{diesel} = \frac{BP}{m_{diesel} \times LHV_{diesel}} \quad (4)$$

3.3 Combustion simulation on GASEQ

GASEQ developed by Chris Morley and distributed free of charge, is the most interesting free combustion package find on the Internet for chemical equilibrium program. Several different types of problem can be solved, such as composition at a defined temperature and pressure; adiabatic temperature and composition at constant pressure; composition at a defined temperature and at constant volume; adiabatic temperature and composition at constant volume; adiabatic compression and expansion; equilibrium constant calculations and shock calculations.

It can create combustion equilibrium simulations by setting the desired parameters and performing complex calculations involving ideal gases. it's possible to automatically increment any of the problem parameters, save the results in a spreadsheet, define mixtures and use as a single species, calculate equilibrium while specifying concentrations of unreactive species, handle "super-equilibrium" radical concentrations,

enter and display species concentrations in mass as well as molar units, calculate viscosities and thermal conductivities of mixtures of gases and use multiple thermodynamic database files in a standard NASA polynomial format.

Making use of GASEQ software it was possible to evaluate the combustion reaction of Diesel (Eq 5), biodiesel (Eq 6), Hydrogen (Eq 7) and biogas with 60% CH₄ and 40% CO₂ (SARKAR; SAHA, 2018) (Eq 8). The combustion simulation was promoted in separate analysis. Diesel engines always operate with a significant excess of air (lean burn, $\alpha > 1$). Diesel engines operate with $12 \leq A/F \text{ ratio} \leq 70$; therefore, the excess of air for diesel and biodiesel fuel was considered to be 100% and excess air for biogas and hydrogen considered to be 40%. (CORONADO et al., 2009a).

Diesel is a fuel formed mainly by carbon and hydrogen. The equation ($C_{16}H_{36}$) was rewritten as $4C_4H_9$ to run on the GASEQ software and promote evaluation.

The average fatty acid distribution for soybean biodiesel compounds products as it shown in Table 2. Biodiesel already has as its initial advantage the very small or zero presence of sulfur, having no combustion emission products containing this gas. The simplified equation was adopted:

Table 2: Typical soybean oil methyl ester

Fatty acid	Weight(%)	Mol.Wt (g)	Formula
Palmitic (A)	12	270.46	C ₁₅ H ₃₁ CO ₂ CH ₃
Stearic (B)	5	298.52	C ₁₇ H ₃₅ CO ₂ CH ₃
Oleic (C)	25	296.5	C ₁₇ H ₃₃ CO ₂ CH ₃
Linoleic (D)	52	294.48	CH ₃ (CH ₂) ₄ CH=CHCH ₂ CH=CH(CH ₂) ₇ CO ₂ CH ₃
Linolenic (E)	6	292.46	CH ₃ (CH ₂ CH=CH) ₃ (CH ₂) ₇ CO ₂ CH ₃

Source: adapted from (CORONADO et al., 2009a)

In case of Biogas, the composition has a mixture of gases where methane and carbon dioxide are in greater proportions and the other gases present are considered in the forty percent of carbon dioxide. After the purification process, biogas has a very low or zero sulfur values.

Hydrogen has a wide range of flammability when compared to other fuels. As a result, it can be burned in a compression ignition engine in a wide variety of fuel-air proportions.

3.4 Energy-ecological efficiency

Proposed by (CÂRDU; BAICA, 2001) Eq (9), the method energy-ecological efficiency (ε) considers the potential of air pollution and the efficacy concerning to convert fuel into energy and estimate human toxicity and the global warming indicators for SFM Eq.(10) and Eq. (11), Eq. (12-13) for DFM.(CARNEIRO; GOMES, 2019)

$$\varepsilon = \left[c \frac{n}{n+\pi} \ln (K \pm \Pi) \right]^N \quad (9)$$

$$\Pi_{GW} = \frac{f_{co2 eq}}{LHV_{fuel}} \quad (10)$$

$$\Pi_{HT} = \frac{f_{1.4 DCBeq}}{LHV_{fuel}} \quad (11)$$

$$\Pi_{GW} = \frac{f_{co2 eq}}{Z * LHV_{Gaseous fuel} + (100 - Z) * LHV_{Liquid Fuel}} \quad (12)$$

$$\Pi_{HT} = \frac{f_{1.4 DCBeq}}{Z * LHV_{Gaseous fuel} + (100 - Z) * LHV_{Liquid Fuel}} \quad (13)$$

Where, π_{GW} considers the emissions that contribute to global warming, expressed in $kg_{eq.pollutant}/MJ_{fuel}$; and π_{HT} considers the emissions that contribute to human toxicity, expressed in $kg\ 1.4DCBeq/kg_{fuel}$, being 1.4-dichlorobenzene the substance used to calculate the level of human toxicity (CARNEIRO; GOMES, 2019). The equivalent carbon dioxide emission factor (f_{co2eq}) and the equivalent 1.4-dichlorobenzene emission factor ($f_{1.4DCBeq}$) for single fuel mode is determined through the Eq. (14) and (15).

$$f_{co2eq} = f_{CO2} + 28f_{CH4} + 265f_{N2O} \quad (14)$$

$$f_{1.4DCBeq} = 4.54f_{SO2} + 56.71f_{NOX} + 38.75f_{MP} \quad (15)$$

In case of the compression ignition engine operates in dual fuel mode, the value for $f_{DFco2eq}$ and $f_{1.4DCBeq}$ considers the proportion of liquid fuel replaced by gaseous fuel and can be determined by Eq. (16) and Eq (17) respectively:

$$f_{DFco2eq} = Z * f_{Gaseous\ Fuel\ co2eq} + (100 - Z) * f_{Liquid\ Fuel\ co2eq} \quad (16)$$

$$f_{DF1.4DCBeq} = Z * f_{Gaseous\ Fuel\ 1.4DCBeq} + (100 - Z) * f_{Liquid\ Fuel\ 1.4DCBeq} \quad (17)$$

The specie emission factor (f_{specie}) represents the emission factor of each species rising from the combustion of the air-fuel mixture, in kg_{specie}/MJ_{fuel} , determined by Eq. (18):

$$f_{specie} = \frac{(n_{specie} \times W_{specie})}{(n_{fuel} \times W_{fuel})} \quad (18)$$

The pollution indicator, Π , is composite by Π_{HT} and by Π_{GW} , and is estimated through Eq. (19), stated in $kg_{eq\ pollutant} / MJ_{fuel}$ for both operation modes, single fuel mode and dual fuel mode:

$$\Pi = 0.742\Pi_{HT} + 0.258\Pi_{GW} \quad (19)$$

Ultimately, the energy-ecological efficiency can be acquired through Eq. (20), applying c, K and n constant values considered by (CARNEIRO; GOMES, 2019)

$$\varepsilon = \left[2.01 \frac{n}{n+\Pi} \ln (1.645 \pm \Pi) \right] 1.7 \quad (20)$$

3.5 Environmental Life Cycle Cost

Combining the aforementioned equations and the parameters illustrates in Table 3, it becomes possible to calculate the liquid and gaseous fuels flows required to power a diesel engine operating in single and dual-fuel mode of a heavy-duty vehicle and later estimate the autonomy archived.

Table 3: Parameters adopted in fuel consumption calculations

Parameter	Value	Unit	Reference
BP	110	kW	Medium Truck, Cummins ISF 2.8 Turbo compressor Motor (VWCO, 2020)
LHV Hydrogen	120.0	Mj/kg	(KORAKIANITIS; NAMASIVAYAM; CROOKES, 2011)
LHV Diesel	42.1	Mj/kg	(SARKAR; SAHA, 2020)
LHV BG	17.65	MJ/kg	(ALOUCHEK et al., 2017)
LHV BD	34.04	MJ/kg	(MOURAD; WALTER, 2011)
BTE CIE	27.76	%	(BORA; SAHA, 2016)
BTE DFM	19.54	%	(BORA; SAHA, 2016)
Z biogas	70	%	(BORA et al., 2014)
Z Hydrogen	70	%	(HOSSEINI; AHMADI, 2017)

Source: Self-elaboration

511

512 To execute the environmental life cycle cost of a heavy duty vehicle operating in
 513 single fuel mode (diesel fuel) and dual fuel mode powered by liquid-gaseous proportions
 514 (soybean biodiesel- sugarcane biogas, soybean biodiesel-hydrogen produced through
 515 electrolysis with photovoltaic energy, electrolysis with wind energy, methane steam
 516 reforming without CCUS and biomass gasification their lifetime was considered, taking
 517 into account the Capital cost C_{CAP} , Operational cost C_{OP} , reposition and technology cost
 518 C_{REP} . With the same parameters it is possible to obtain the annual cost for the heavy duty
 519 vehicle life cycle (Life Cycle Cost – C_{LC}) in R\$/km, as follows the adapted equations (21)
 520 (22) (23) (24) from (CORONADO; DE CARVALHO; SILVEIRA, 2009; LAJUNEN;
 521 LIPMAN, 2016)

522

$$523 \quad C_{CLC} = C_{CAP} + (C_{OP} + C_{REP}) X (1 + d_{rate})^{-j} \quad (21)$$

524

$$525 \quad C_{OP} = C_m + C_n + C_{CO2} \quad (22)$$

526

$$527 \quad C_{CO2} = E_{CO2} X P_{CO2} \quad (23)$$

528

$$529 \quad E_{CO2} = m_{fuel} X F_{fuel} \quad (24)$$

530

531 Where, C_{cap} = Vehicle acquisition cost in R\$/km, C_{OP} = vehicle operational cost
 532 in R\$/km, C_{rep} = reposition and technology cost in R\$/km, d_{rate} = market rate fees in %
 533 per year, j = vehicle lifetime in years, C_m = Maintenance cost in R\$/km, C_n = cost of the
 534 energy supplied by fuel in R\$, C_{CO2} = CO_2 cost in R\$/km, E_{CO2} = CO_2 emission (kg de
 535 CO_2/h), P_{CO2} = CO_2 market credit price in R\$/kg de CO_2 , m_{fuel} = Fuel mass flow in kg/h
 536 and F_{fuel} = Fuel emission factor in kg of $CO_2/$ kg of fuel

537

4 RESULTS AND DISCUSSION

538

539 In this study, the mass flow rate of biodiesel, biogas and hydrogen were calculated,
 540 and the energy efficiency of each compression ignition engine operating mode was

ascertained. The emission factors were determined to calculate the energy-ecological efficiency and the TTW emissions of the single fuel compression ignition engine powered with Diesel and Dual-Fuel compression ignition engine powered by proportions of Biodiesel-Biogas and Biodiesel-Hydrogen.

4.1 Diesel, Biodiesel, Hydrogen and Biogas mass flow in dual-fuel mode results

The biodiesel, Hydrogen and biogas mass flows in the dual fuel mode were determined, considering α value equal to 70%. The Eq. (1) was applied to calculate the Biogas mass flow adopting 19.54% BTE dual fuel by (BORA; SAHA, 2016). Then, the hydrogen mass flow was measured through Eq. (2). Lastly, the biodiesel and Diesel mass flow were measured through Eq (3) and Eq. (4). The values found for biodiesel-hydrogen and biodiesel-biogas mass flows were 6.45 kg/h and 26.94 kg/h respectively. The conventional Diesel mass flow was 33.88 kg/h as shown in the graphic 1.

Graphic 1. Mass Flow rate from different fuels

Source: Self-elaboration

Mass flow rate is a way to quantify the use of chemical energy from the fuel by the engine, being able to compare different operating points on different engines occurs by calculating the thermal yield. It can be expressed in terms of speed the fuel takes to archive the Maximo point and fulfill the engine's necessity to complete combustion phase. The combination of biodiesel and hydrogen, having the MFR of 6.45 kg/h is the

faster in terms to archive the ignition timing. In other hand, with MFR of 26.94 kg/h, the combination of biodiesel and biogas does not have the fastest timing but has the lasting combustion duration.

4.2 GASEQ simulation and indicators

With the GASEQ results assistance, it becomes accessible to evaluate the combustion reaction with the values of CO₂, N₂O, SO₂, NO_x and MP used to calculate emission factors and pollution indicators in the scenarios of compression ignition engine fed only by diesel and in dual fuel mode fed by biodiesel-biogas or biodiesel-hydrogen proportions. The stoichiometric relation with air and Biodiesel, Biogas, Hydrogen and Diesel were analyzed separately trough eq.(5) eq.(6) eq.(7) eq.(8), being used to evaluate their respective indicators of global warming and human toxicity.

The following tables 4-7 indicates the reagent species, products from each simulation and their respective emission factors, related to global warming indicators and human toxicity, calculated trough eq. (11) and eq. (12)

Table 4: Reactants and products, and specie emission factors of the biodiesel-air mixture combustion.

Reagents	No. Moles	Molecular Weight	
C ₁₈ H ₃₂ O ₂	1	280	
O ₂	50	32	
N ₂	188	28	
Products	No. Moles	Molecular Weight	F species
CO ₂	18	44	2,82857
CH ₄	0.00	16	2,8384E-27
N ₂ O	0.00	44	0
SO ₂	0.00	64	0
NO _x	0.02	30	0,32748
MP	0.00	12	0

Source: Adapted from GASEQ

Table 5. Reactants and products, and specie emission factors of the Hydrogen-air mixture

584

combustion.

Reagents	No. Moles	Molecular Weight	
H2	1	1	
O ₂	0,7	32	
N ₂	2,6411	28	
Products	No. Moles	Molecular Weight	F species
CO ₂	0	44	0
CH ₄	0	16	0
N ₂ O	0	44	7,30E-07
SO ₂	0	64	0
NO _x	0.02	30	0,4662
MP	0	12	0

585

586

Source: Adapted from GASEQ

587

588 Table 6: Reactants and products, and specie emission factors of the biogas-air mixture
589 combustion

Reagents	No. Moles	Molecular Weight	
CH ₄	0,6	16	
CO ₂	0,4	44	
O ₂	1.60	32	
N ₂	6.04	28	
Products	No. Moles	Molecular Weight	F species
CO ₂	1	44	1,61571
CH ₄	0	16	1,169E-22
N ₂ O	0	44	1,41E-01
SO ₂	0	64	0
NO _x	0.02	30	0,019929
MP	0	12	0

590

Source: Adapted from GASEQ

591

Table 7: Reactants and products, and specie emission factors of the Diesel-air mixture combustion.

Reagents	No. Moles	Molecular Weight	
C ₄ H ₉	4	57	
O ₂	50	32	
N ₂	188,65	28	
Products	No. Moles	Molecular Weight	F species
CO ₂	16	44	3,08772
CH ₄	0	16	3,5480E-26
N ₂ O	0	44	0
SO ₂	0	64	0
NO _x	0.02	30	0,32748
MP	0	12	0

Source: Adapted from GASEQ

Table 8 presents the values of $f_{CO_2 eq}$ and the $f_{1,4DCBeq}$ resulting from the combustion of diesel, biodiesel, biogas and hydrogen fuels in compression ignition engine operating in single fuel mode.

Table 8: Carbon dioxide and 1.4-Dichorobenzene equivalent factors of the fuels evaluated when compression ignition engine operates in single fuel mode

Fuel	F _{CO2eq}		F 1.4 DCBeq	
Diesel	3,0877	kgCO ₂ eq/kg Diesel	18,5710	kg 1.4 DCBeq/kg Diesel.
Biodiesel	2,8285	kgCO ₂ eq/kg BD	19,499	kg 1.4 DCBeq/kg BD
Hydrogen	0,00019	kgCO ₂ eq/kg H ₂	0,88192	kg 1.4 DCBeq/kg H ₂
Biogas	1,6157	kgCO ₂ eq/kg BG	1,1301	kg 1.4 DCBeq/kg BG

Source: Self-elaboration

As can be seen, the highest value of F_{CO_2} was found through Diesel fuel, due to the greater number of moles of CO₂ resulting from its combustion, with insignificant values of CH₄ and CO₂. On the other hand, Biodiesel presented the highest value of $f_{1.4DCBeq}$ due to the NO_x emissions increase in 5%. The stoichiometric ratio, temperature

and type of fuel can contribute, thus it depends on how the fuel is injected, the reaction dynamics and engine operation. According to CORONADO et al. (2009) the increment is originated by the temperature increase in the tailpipe engine, which appears due to reduction of the delay ignition, and, as outcome, to the injection point advance.

Table 9 provides values of $f_{DFCO2eq}$ and the $f_{DF1,4DCBeq}$ resulting from the compression ignition engine running in dual fuel mode according to eq (12) and eq (13).

Table 9. Carbon dioxide and 1,4-Dichorobenzene equivalent factors of the fuels evaluated when compression ignition engine operates in dual fuel mode.

Dual Fuel	FCO2eq	F1.4 ADCBeq
Biodiesel+		
Biogas	1,9795	6,6411
Biodiesel+H2	0,8487	24,3567

Source: Self-elaboration

The proportions of Biodiesel and hydrogen presents the smallest amount of Fco2 among the two dual fuel scenarios but at the same time, has the biggest value when it comes to F1.4ADCBeq emissions. This is due to hydrogen, responsible for 70% of the Dual Fuel mode. Hydrogen system has emissions close to zero CO2 but at the same time, it has a considerable proportion of NOx, which ends up influencing the F1.4ADCBeq final calculation.

Energy ecological efficiency considerers the air pollution potential and the engine conversion effectiveness to energy. Between these parameters it is possible to estimate human toxicity and the global warming indicators. Once the equivalent values are found, the π_{GW} and π_{HT} for SFM and DFM were estimated through eq (10-13). The results can be seen in the graphic 2.

Graphic 2. Human toxicity, global warming and pollution indicators found for SFM and DFM

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632

633

Source: Self-elaboration

634

635 The ecological efficiency concept depends on the environmental impact caused
636 by CO₂, SO₂, NO_x and particulate material (PM) emissions. The best scenario from the
637 ecological standpoint is that which presents a minimum amount of CO₂. Biodiesel +
638 Biogas and Biodiesel + Hydrogen present equal values of II, however, in a closer analysis
639 of the values of IIGW and IIHT it is possible to notice a significant decrease in emissions
640 from the Biodiesel + Hydrogen scenario. The share of Hydrogen causes a decrease of soot
641 and CO₂ emissions, except for nitric oxide emissions.

642 4.3 Energy-ecological efficiency in combustion ignition engine modes

643

644 Diesel engines are the source of very fine particles ranging from 0.01 to 1 mm.
645 These particles are able to penetrate deep inside the lungs and cross the walls of the blood
646 vessels causing major health issues. In contrast, gasoline engines produce 100 times less
647 particles than diesel engines. (EL HANNACH et al., 2019)

648 There are several current regulations to limit the harmful emissions from diesel
649 engines, especially heavy-duty vehicles. Ordinance IBAMA n° 85 from 1996 deal with
650 the creation and adoption of an internal self-inspection program for correct fleet
651 maintenance, regarding the black smoke emission, by a company that has its own cargo

or passenger transport fleet powered by diesel oil. EURO 6 from 2015 obligates all road vehicles manufactured in European Union countries since year 2015 to comply limited levels of particulate emissions (4.5 mg/km) and Nox.(80 mg/km). Law 8.723/93, as part of the Brazilian National Environment Policy, determines engine and motor vehicle manufacturers and fuel manufacturers to fulfill necessary steps to reduce the levels of carbon monoxide, nitrogen oxide, hydrocarbons, alcohols, aldehydes, soot, particulate matter and other polluting compounds in vehicles sold in the country, within the limits set in the law and also respecting the deadlines established.

Technologies such as diesel particulate filters (DPF), exhaust gas recirculation (EGR), and selective catalytic reduction (SCR) have been introduced to new diesel vehicles. However, the commercial truck fleet industry will still be dominated by older vehicles over the next two decades.(EL HANNACH et al., 2019)

The energy-ecological efficiency was calculated through the Eq. (20) proposed by Carneiro and Gomes (2019), considering the combustion ignition engine by respective SFM and DFM scenarios, as shown in the graphic 3.

Graphic 3. Energy-ecological efficiency for different fuels in SFM and DFM

Source: Self-elaboration

As expected, the highest efficiency goes to Biodiesel+Hydrogen scenario, with 64%. Having a poor mixture of fuel and air, the internal combustion of hydrogen does not generate emissions of CO, CO₂ and sulfur dioxide. As for Biodiesel, even with notable amount of emission gases, is still considerably less when compared to diesel fuel.

To BÖRJESSON; MATTIASSON (2008) the more efficient biofuel systems are those based on lignocelluloses and novel conversion technologies. Accordingly LEE et al. (2011) Hydrogen is expected to offer an economically and environmentally more eco-efficient means of transportation. With the help of biofuels the eco-innovation scenario becomes attractive, combines economic advantage with lower ecological-resource burdens and it is generally directed at energy input-substitutes, component recycling, among others.(LEVIDOW et al., 2016)

4.4 Environmental Life Cycle Costs

Fuel consumption is an important parameter to assess the viability to replace conventional diesel to biogas-biodiesel or biodiesel-hydrogen proportions in heavy duty trucks operation. From it is possible to estimate heavy duty autonomy by considering the total time travel (in hours). For heavy trucks the ideal average speed is between 80km/h to 88km/h. For each km/h the fuel consumption will suffer and increase of 1%. If the truck makes an average of 3.36 km/l to 88km/h it will go to 2.95km/l to 100km/h. As for effect engine, if the truck assumes the velocity at 96Km/h the vehicle will require 73% more engine power than the power required for the ideal speed. Analyzing by maintenance aspect, at 112km/h the tires wear tread will be folded and the increase on maintenance cost will be by 80%. The increase in speed for operational gain does not pay off. The costs, in addition to the higher fuel consumption that immediately observed, will also appear in the increase of maintenance and in the reduction of the useful life of the engine (Ministério da infraestrutura,2013).

According to (CNT,2019), the Brazilian national transport confederation, in annual report of survey truckers' profile, truck drivers work on average of more than 8 thousand km/month.

Having a holistic evaluation of the economic and environmental impacts of a technology, for the calculation purpose, a more simplified analysis of the heavy-duty life

cycle was adopted, considering the TTW emissions. This internationally recognized assessment tool helps to inform decision makers, allowing them to identify the impacts of new products.

The calculation of the environmental life cycle cost for heavy-duty considers the capital cost, operational cost and replacing technology cost. The truck lifetime adopted is 20 years (EL HANNACH et al., 2019). Interest rate determined through SELIC rate estimated as 2.75 per year on date of May first, 2021 (Banco Central, 2021).

The replacing technology cost was disregarded for this study, since it only considers replacement of components necessary for electric vehicle operation or use of fuel cells due to the need of substitution time at time. (LAJUNEN; LIPMAN, 2016a)

The fixed values considered for calculations related to the environmental cost of the truck life cycle operating in dual fuel mode and powered by soybean biodiesel-sugarcane biogas and soybean biodiesel-hydrogen produced through electrolysis with photovoltaic energy, electrolysis with wind energy, methane steam reforming without CCUS and biomass gasification, as well reference values of diesel are presented in Table 10 with parameters, values, units and source in line with literature and official data.

Table 10: Heavy Duty specifications

Parameters	Unit	Value	Reference
CO2 cost	Euro/ton	47.82	Investing.com (2021)
Medium Cost Biodiesel	R\$/l	3.53	Ministério de minas e energia
Medium Cost Diesel	R\$/l	4.37	ANP(2021)
Medium Cost Hydrogen Electrolysis with Photovoltaic energy	US\$/kg	14.77	EPE (2021)
Medium Cost Hydrogen Electrolysis with wind energy	US\$/kg	5.96	EPE (2021)
Medium Cost Hydrogen Methane steam reform without CCUS	US\$/kg	2.05	EPE (2021)
Medium Cost Hydrogen biomass gasification	US\$/kg	2.38	EPE (2021)
Biogas Cost (RJ TAX)	R\$/MWh	663	Aneel (2020)
Biogas Factor emission	kgCo2/kg BG	1.61571	stechiometric balance
Biodiesel factor emission	kgCo2/kg BD	2.828	stechiometric balance
Hydrogen Factor emission	kgCo2/kg H2	0	stechiometric balance

Diesel Factor Emission	kgCo2/kg D	3.087	stechiometric balance (LAJUNEN; LIPMAN, 2016a)
GNV adaptation cost	%	10	
SELIC	%	2.75	bcg.gov.br
Truck Capital Cost	R\$	138.263 ,00	tabela fipe brasil.com (LAJUNEN; LIPMAN, 2016)
Maintenance Cost	Euro/km	0.16	

Source: Self-elaboration

For Capital cost to power the engine with biodiesel-biogas and biodiesel-hydrogen proportions, was considered the truck adapted through natural gas kit, since the technology similarity and for the engine powered only with diesel fuel, the truck market price was stipulated. In extend, the capital costs presented were adjusted by the correction factor previously considered.

The diesel, biodiesel, biogas and hydrogen emission factor were established through equation (24). CO₂ emissions for diesel, biogas and biodiesel in kgCO₂/h according to the respective flow rates in kg/h in SFM and DFM, result in a CO₂ cost of R\$/h established by eq. (23) as shown in Table 11.

Table 11: Emission and CO₂ emission cost for SFM and DFM scenarios

Scenario	MFR		Emission		Emission Cost	
SFM (Diesel)	33.88	kg/h	104.59	kg CO ₂ /h	32.61	R\$/h
BG Dual	62.86	kg/h	177.8	kg CO ₂ /h	54.44	R\$/h
BD Dual	26.94	kg/h				
H2 Dual	15.06	kg/h	18.28	kg CO ₂ /h	5.70	R\$/h
BD Dual	6.45	kg/h				

Source: Self-elaboration

Table 12 presents the values for energy cost, maintenance cost, Co2 cost and capital cost in R\$/km for a truck operating in single and dual fuel mode fueled with diesel, biodiesel-biogas and biodiesel-hydrogen proportions, with 20 years as lifetime and 80 km/h as average speed on the road. This study adopted a period of 12-hour workday according to the law 13.103/2015.

Table 12: Heavy duty energy cost, maintenance cost, Co2 cost and capital cost in R\$/Km

Parameters	Value	Unit	Reference
Cco2 Diesel	32.61	R\$/km	Equation (23)
Cco2 BD+BG	56.31	R\$/km	Equation (23)
Cco2 BD+H2	5.69	R\$/km	Equation (23)
Cn Diesel	2.16	R\$/km	ANP(2021)
Cn BD	1.69	R\$/km	Ministério de minas e energia
Cn H2 PV	14.74	R\$/km	EPE (2021)
Cn H2 WE	5.95	R\$/km	EPE (2021)
Cn H2 VR w/ CCUS	2.04	R\$/km	EPE (2021)
Cn H2 Bio G.	2.37	R\$/km	EPE (2021)
Cn BG	3.39	R\$/km	Aneel (2020)
Ccap SFM	138.263,00	R\$/km	tabelafipebrasil.com
Ccap SFM +GNV	152.089,30	R\$/km	tabelafipebrasil.com (LAJUNEN; LIPMAN, 2016)
Cm	1.01	R\$/km	(LAJUNEN; LIPMAN, 2016)

Source: Self-elaboration

Thus, with (j) values ranging from 1 to 20 years (heavy duty lifetime) it is possible to estimate the Environmental Life Cycle Costing.

Graphic 4 presents the environmental life cycle costs for different fuel in SFM and DFM scenarios.

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Graphic 4: C_{ELC} for different fuels in SFM and DFM

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Source: Self-Elaboration

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In the context of the global concern with the decarbonization of energy production and consumption systems, its transformation with hydrogen as the main energy vector has led to the search for diversity of hydrogen produced according to production origin, in this way, the calculation of Hydrogen produced through electrolysis with photovoltaic energy, electrolysis with wind energy, methane steam reforming without CCUS and biomass gasification became necessary.

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In turn, the differentiation of hydrogen by carbon content associated with its production has distinct consequences in terms of contributions to the mitigation of greenhouse gases emissions and prevention of global climate change. Therefore, it is necessary to distinguish this production origin through the use of classifications with reference to color distinction.(EPE, 2021b)

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Brown or black hydrogen is produced from coal without carbon capture, utilization and sequestration. Gray hydrogen is generated from natural gas without carbon capture, utilization and sequestration. Blue hydrogen refers to production from natural gas, but with without carbon capture, utilization and sequestration and it is occasionally used to name hydrogen generated from other fossil fuels with carbon capture, utilization and sequestration. Finally, Green hydrogen has been defined as the one produced from variable renewable sources (EPE, 2021b).

Photovoltaic energy and wind energy are the fastest growing renewable energies in the Brazilian energy matrix, representing a growth of 92.2% and 15.5% respectively, in 2019 when compared to the year 2018.(EPE, 2020).Biomass gasification justified by the potential of biomass residues for production in Brazil, especially advance in the offer of biomass from sugarcane representing an increase of 5.9% of energy consumption in 2019 when compared to 2018 and in particular, it points to a strategy that takes advantage of Brazil's competitive advantages (EPE, 2021b). Methane steam reforming without CCUS, belonging to the gray hydrogen category, is the most used route production in industrial terms since it is two to three times less expensive to deliver than green hydrogen. (IRENA, 2020)

Under analysis against the four types of hydrogen as to its origin of production, the methane steam reforming without CCUS presents the smallest C_{eLC} worth, followed by biomass gasification, electrolysis with wind energy and electrolysis with photovoltaic energy respectively. In fact, the lowest hydrogen production costs are currently observed in the steam reforming of methane, which is consistent with a technological route based on fossil energy sources. The electrolysis of water using renewable wind and solar sources is the most expensive technological route among those already available on the market. Biomass gasification is not yet a mature technology, but it is estimated that by 2042 this route will allow competitive hydrogen production costs.(EPE, 2021b)

The scenario that would be easier to develop new markets because it is currently dominant and more competitive is the Methane steam reforming without CCUS. However, this route will face risks in the future related to possible restrictions in a scenario of deep decarbonization and an accelerated drop in the costs of water electrolysis based on variable renewables such as wind and solar. On the other hand, the scenarios of electrolysis with photovoltaic energy, electrolysis with wind energy, methane steam and biomass gasification are still less competitive, however, they present great opportunities in the future in a state of accelerating cost reduction of investment in electrolysis and generation electric with variable renewables and biomass gasification.

Diesel Scenario has the lowest value of C_{eLC} since there is no need to suffer engines' adaptation costs, is powered by a fuel that has national policy and therefore contains value consistent with the market. Biodiesel+ Biogas has the value due to necessity of engines adaptations, highest emission cost and market fuel price close to diesel value.

The development of renewable fuels is on the agenda of several countries, being a safe alternative to guarantee economic development and energy security. In the case of Brazil, it has policies such as ProAlcool, RenovaBio and National Biodiesel Production and Use Program (PNB) but still lacks when it comes to national public policy for Biogas and Hydrogen. Currently there is a processing bill 2193/20 which creates a federal Policy on Biogas and Biomethane and intends to increase investments in infrastructure for the production, distribution, and commercialization of biogas, biomethane and biofertilizer. (Brasil,2020). As for Hydrogen, there is no specific norm from the National Electric Energy Agency (ANEEL) or the National Petroleum, Natural Gas and Biofuels Agency (ANP) that regulates production, storage and transportation of hydrogen for energy uses, demonstrating the need for diversification and encouragement of the Brazilian energy matrix.

Currently, 99% of the hydrogen used as fuel is produced from non-renewable sources. and less than 0.1% is produced through water electrolysis, according (IEA,2021). Brazil, as one of the biggest producers of biofuels and holder of a renewable energy matrix, can become one of the major players in this market. As a promise for the future, green hydrogen is a fuel with high potential for use in power generation and consequently to use in transport sectors, as it is obtained from renewable sources, in a process in which there is no carbon emission.

The reduction in GHG emissions obtained when partially displacing diesel with hydrogen is much higher than the reductions obtained using CNG or LNG as fuel for heavy duty trucks and according to (EL HANNACH et al., 2019) although the LCC results were favorable for the dual-fuel configuration, the actual impact of introducing hydrogen on the emission of certain components, such as NO_x. The reduction of emissions and operating costs, combined with the minimal conversion process of existing trucks from diesel to dual-fuel mode, constitute a major advantage of this technology in comparison to the other available alternatives.

It remains the case of DFM vehicles powered by biofuels are the most competitive choice in relation to conventional diesel engine, along with CNG where natural gas is relatively inexpensive, but their dependence on fossil fuels and their pollutant emissions profile weakens their competitiveness in the future.(LAJUNEN; LIPMAN, 2016).

The first concept to be kept in mind is that, despite the great promise, the principal barriers to the greater use of biofuels in industry are high costs, investors' confidence, competitiveness, and a lack of policy focus. In this context, for a more accurate decision-making among the studied scenarios, it is necessary to consider the economic field, as well as the environmental, political, and social ones. Considering the characteristic Brazilian condition and the nature of application of the dual fuel system to road cargo vehicles, is safe to claim the scenario using the proportions of biodiesel and hydrogen produced through biomass gasification as the most promising and efficient. Despite being in third place in the C_{eLC} perspective and lack in government policies, since the search for the energy transition is still gradual and depends on technological innovations, in a long term perspective it combines great environmental and social capacities, once Brazil has a great agricultural power and global interest is rising in green hydrogen as one of the solutions for an energy transition toward zero or net-zero emissions, being increasingly socially accepted.

5 FINAL CONSIDERATIONS

In summary, the values found for biodiesel-hydrogen and biodiesel-biogas mass flows were 6.45kg/h respectively and 26.94kg/h. The conventional Diesel mass flow were 33.88 kg/h as shown in the graphic 5. Through implement of energy ecological method, the highest value of F_{CO_2} was found for Diesel fuel, due to the greater number of moles of CO_2 resulting from its combustion, with insignificant values of CH_4 and CO_2 . On the other hand, Biodiesel presented the highest value of $f_{1.4DCB\ eq}$ due to the NO_x emissions increase in 5%. Under operating mode scenario analysis, the proportions of Biodiesel and hydrogen presents the smallest amount of F_{CO_2} among the two dual fuel scenarios but at the same time, has the biggest value when it comes to $F_{1.4ADCBeq}$ emissions. This is due to hydrogen, responsible for 70% of the Dual Fuel mode. Hydrogen system has emissions close to zero CO_2 but at the same time, it has a considerable proportion of NO_x , which ends up influencing the $F_{1.4ADCBeq}$ final calculation. The best setup from the ecological standpoint is for Biodiesel + Biogas and Biodiesel + Hydrogen with equal values of II, however, in a closer analysis of IIGW and IIHT values it is possible to notice a significant decrease in emissions from the Biodiesel + Hydrogen

proportions and as expected,, the highest efficiency goes to Biodiesel+Hydrogen operation mode, with 64%.

Aligning all discoveries and considering the characteristic Brazilian condition and the nature of application of the dual fuel system to road cargo vehicles, is safe to claim the scenario using the proportions of biodiesel and hydrogen produced through biomass gasification as the most promising and efficient. Despite being in third place in the C_{eLC} perspective and lack in government policies, since the search for the energy transition is still gradual and depends on technological innovations, in a long-term perspective it combines great environmental with greater energy-ecological efficiency and social capacities, once Brazil has a great agricultural power and global interest is rising in green hydrogen as one of the solutions for an energy transition toward zero or net-zero emissions, being increasingly socially accepted.

The findings we presented will assist as a baseline for future developments in compression ignition engine fueled with liquid-gas fuel proportions field. Being a relatively young and emerging research area, there is still a big absence of economic and energy-ecological efficiency estimative studies in this context, therefore, the data contained in this study will open space for new research opportunities, assist practical application of these concepts, aggregate valuable information and promote better understand of science. Recapping this analysis in the future would offer perception into how this field, and possibly scientific research in general, evolves over time.

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