



Study for Replacing the Diesel-Powered Bus Fleet with Green Hydrogen in Londrina

Estudo para Substituição da Frota de Ônibus Movido à Diesel para Hidrogênio Verde em Londrina

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ABSTRACT

To reduce greenhouse gas emissions, this work aims to study the possibility of replacing the diesel-powered bus fleet with green hydrogen in a public transport concessionaire in Londrina over the next few years, estimating its technical and economic feasibility. This case study applied the Total Cost of Ownership (TCO) tool and its financial parameters. Taking the year 2023 as a basis, based on Net Present Values (NPV), our model showed that the fleet replacement strategy, considering the life cycle of the buses, is not financially viable, since the payback occurs 19 years after the purchase of the first H₂V vehicles, compared to 6 years in the other case. Regarding emissions, the target of reducing by 50% would be achieved in 2033 and fully mitigated in 2043, which would mean no more than 400,000 tons of CO₂ being emitted into the atmosphere over the next 20 years. For the TCO of vehicles, only in 2040 would hydrogen-powered buses become cheaper, per kilometer driven, compared to buses powered by fossil fuels. This study considered a scenario of economic stability, using economic data from 2023 for future projections.

keywords green hydrogen, total cost of ownership, greenhouse gases, carbon credit

RESUMO

Com o intuito de reduzir emissões de gases do efeito estufa, este trabalho visa estudar a possibilidade de substituir a frota de ônibus movido a diesel por hidrogênio verde em uma empresa concessionária do transporte público de Londrina ao longo dos próximos anos, estimando a sua viabilidade técnica e econômica. Este estudo de caso aplicou a ferramenta *Total Cost of Ownership (TCO)* e seus parâmetros financeiros. Tomando como base o ano de 2023, com base nos Valores Presentes Líquidos (VPL), nosso modelo mostrou que a estratégia de substituição da frota, considerando o ciclo de vida dos ônibus, não é viável financeiramente, já que o *payback* ocorre 19 anos após a compra dos primeiros veículos H₂V, contra 6 anos no outro caso. Em relação às emissões, a meta de reduzir 50% seria atingida em 2033 e totalmente mitigada em 2043, o que deixaria de emitir na atmosfera, durante os 20 anos, aproximadamente 400 mil toneladas de CO₂. Para o TCO dos veículos, somente em 2040 os ônibus movidos a hidrogênio se tornariam mais baratos, por quilômetro rodado, comparados aos ônibus movidos a combustíveis fósseis. Neste estudo foi considerado um cenário de estabilidade econômica, considerando para as projeções futuras os dados econômicos de 2023.

palavras-chave hidrogênio verde, custo total de propriedade, gases de efeito estufa, crédito de carbono

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Introduction

The greenhouse effect is an essential natural phenomenon that keeps the Earth warm (with gases like CO₂ and CH₄ absorbing solar heat), but the increased concentration of these gases due to human activities (such as burning fossil fuels and deforestation) intensifies the effect, leading to global warming. This excess heat causes average temperatures to rise, resulting in consequences like melting ice caps and extreme weather events. To combat this, in November 2021, Brazil and over 190 countries attended COP 26 in Glasgow, committing to reduce their greenhouse gas (GHG) emissions by 50% by 2030 to limit warming to 1.5°C, highlighting the use of Hydrogen (H₂) as one of the mitigation strategies.

Hydrogen, the least dense and most abundant chemical element in the universe, when linked to another hydrogen atom forms the H₂ molecule, better known as hydrogen gas, which has a great capacity for generating energy and according to Neoenergia (2023), signatories (of the Paris Agreement and UN SDGs) project that green hydrogen will replace oil and natural gas and become the main energy resource by 2050. Hydrogen chains also form fossil fuels (Silva, A. R. L., 2023). To obtain sustainable hydrogen fuel (Green Hydrogen), it is necessary to use appropriate technologies that, today, still present adversities concerning their high cost of production, infrastructure, storage, distribution, and safety.

According to data from the Greenhouse Gas Emissions and Removals Estimation System (Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa [SEEG], 2021), Brazil emitted 2.42 billion tons of carbon dioxide into the atmosphere (CO₂), with the Transport responsible for 18% of these emissions.

In this context, the company chosen for this study has 87 heavy vehicles that provide public transportation in Londrina. Considering a CO₂-to-diesel ratio of 2.6 kg per liter burned (Carvalho, 2011), these buses, powered by fossil fuels, emit approximately 17.2 tons of CO₂ per day into the atmosphere. It is noteworthy that biodiesel can reduce greenhouse gas emissions by up to 80% when compared to fossil diesel. Studies in this context have been conducted (Borsato et al., 2010; Cordeiro et al., 2020; Turra de Ávila et al., 2023).

Considering that the burning of the hydrogen molecule is three times more efficient when compared to gasoline (International Energy Agency [IEA], 2019), this study aims to analyze the Total Cost of Ownership in replacing diesel-powered buses with hydrogen-powered buses for a company that holds the concession for public transportation in Londrina. The financial viability of this replacement in this company over the years is also studied. This study, in addition to contributing to an analysis of the reduction of greenhouse gases, can be a model for other cities to adopt the same strategy and contribute to the environment and the goal of reducing greenhouse gas (GHG) emissions.

Material and methods

The work was developed to understand the green hydrogen chain and how the application of this fuel impacts the company in question. The Case Study methodology was used, whose objective is to deepen knowledge about a problem that is not sufficiently defined, aiming to stimulate understanding, suggest hypotheses and questions, or develop theory (Miguel, 2007).

Concerning data collection, the problem studied was treated in a quantitative way. All information related to the fleet, bus consumption, costs, revenue, forecasts, and available capital were obtained from contacts with the Municipal Transit and Urbanization Company of Londrina (CMTU-LD), while information on hydrogen-powered buses was obtained from the Alberto Luiz Coimbra Institute of Postgraduate Studies and Research in Engineering, of the Federal University of Rio de Janeiro (COPPE-UFRJ). Data processing, concerning the financial parameters of the economic feasibility analysis of the proposal, was performed using statistical techniques.

Carbon credit

For Souza et al. (2021), carbon credit is a measure to reduce emissions of greenhouse gases. One carbon credit corresponds to one ton of carbon not emitted into the atmosphere. Thus, carbon credits serve as “environmental currency” for countries and companies and can be sold to other countries that do not meet their reduction targets.

Brazil, because it has great potential to produce low-carbon hydrogen at a reduced price, in the coming years, H₂V-powered transportation could become more economically viable than diesel-powered transportation, in addition to bringing sustainable and economic benefits with carbon credits.

Total cost of ownership —————

For Santos (2011), the Total Cost of Ownership (TCO) can be defined as a model of the life cycle of equipment, products, or services, which considers the costs of acquisition, ownership, operation, and maintenance throughout its useful life.

This tool also allows you to measure the impact of a given investment, in addition to helping you perform financial calculations through Total Benefits of Ownership (TBO). While TCO determines the acquisition cost, TBO aims to assess the viability and return on that investment. Together, these tools allow you to calculate and perform a technical and financial analysis of a given investment.

To identify the investments, resources, and timeframe required to replace the company's diesel-powered fleet with hydrogen-powered buses, comparative calculations must be made to verify the technical and economic viability of the investment.

For Martins et al. (2019), the economic feasibility study is extremely important because it assesses whether an investment will yield a return for the investor or not. On the other hand, the technical feasibility study encompasses all project variables (risks, scenarios, and impacts), including market data, contributing positively to decision-making, since a feasibility analysis is capable of predicting whether the project will be successful or not (Instituto Brasileiro de Engenharia de Custos [IBEC], 2021).

For the economic development of the project, some fundamental financial parameters are cash flow, CAPEX, OPEX, Internal Rate of Return (IRR), Net Present Value (NPV), Return on Investment (ROI), and Payback.

Cash flow —————

According to Friedrich and Brondani (2005), cash flow can be understood as the movement of cash, that is, the inflows and outflows of financial resources in a given period of time, for example, employee salaries or the sale of a bus to third parties.

A cash flow, depending on its variations over time, can be classified as irregular cash flow (Zeidan, 2013). In this case, the inflows and outflows of money are not predictable and stable, and the cash flow is characterized by unpredictable and irregular fluctuations, which can occur for various reasons, such as seasonal sales, late payments from customers, unexpected expenses, capital investments or changes in market conditions.

CAPEX and OPEX —————

The terms CAPEX and OPEX are economic nomenclatures used to classify the types of investments made by a company (Silva, D. M., 2023).

Capital Expenditure (CAPEX) is a company's long-term investment in capital goods, such as the expenses it spends to acquire or upgrade physical assets, such as equipment, facilities, and real estate. In the case of a public transportation company, this would be the investment made in the acquisition of vehicles and infrastructure, for example.

Operational Expenditure (OPEX) are short-term operating expenses, such as day-to-day expenses, carried out constantly to keep business activities running. For the company in question, fuel is an example of OPEX.

Internal Rate of Return and Minimum Attractive Rate of Return —————

According to Barbieri et al. (2007), the Internal Rate of Return (IRR) can be interpreted as the rate that would remunerate the investment made in a project; in other words, it is an index that indicates the profitability of an investment in a given period. To calculate the IRR, the Minimum Attractive Rate of Return (MARR) is established, the minimum that the investor intends to earn from the investment. These two acronyms correlate and establish scenarios, recommending or not the investment.

Net Present Value —————

Net Present Value (NPV) is a financial tool used to analyze investments. It is a mathematical concept that can be defined as the current value of future capital, discounted at a determined interest rate over a period of time (inflation, for example).

According to Silva and Fontes (2005), the NPV given by the difference between the net present value of revenues and the net present value of costs allows us to conclude whether the project is economically viable, with the best project being the one that presents the greatest positive result. Equation (1) provides the net present value of a cash flow that occurs in N periods (Silva & Fontes, 2005)

$$\text{NPV} = \sum_{n=1}^N \frac{FC_n}{(1+i)^n}, \quad (1)$$

where FC_n is the cash flow in period n , for $1 \leq n \leq N$, N is the number of periods or duration of the project, and i is the inflation rate in the period or the MARR.

Payback

This is a financial indicator that calculates the return period of an investment; in other words, it is the period in months or years necessary to recover the initial investment in a given project (Melo, 2020).

Data Collection

In this case study, the collected data were separated into three groups:

- Basic data collected at BR Investing (BR Investing, 2023): Minimum Attractive Rate of Return (11.75 % – Selic 10/02/2023), Dollar (R\$ 4.93 – 09/01/2023), Euro (R\$ 5.25 – 09/22/2023), value of a carbon credit (€ 85.30 – 09/22/2023), and the amount of liters in a barrel of oil and its derivatives (159.98 liters).
- Data related to the public transport concessionaire: information about the company, fare composition, expense spreadsheet, number of passengers, scheduled mileage, and annual capital for investment.
- Data relating to the company's diesel vehicles and COPPE's hydrogen-powered vehicles: fuel consumption, fuel emissions, and vehicle depreciation forecasts over the years.

Since there is not enough market information to make predictions for both diesel-powered buses and H₂V fuel, some values were estimated. For example, the current value of green fuel is US\$5.00, and it is assumed that it will fall to US\$1.50 in 2030 and that it will fall another 50% to US\$0.75 in 2050. As for S10 diesel, the forecast made by (Ministério de Minas e Energia, 2022) for the value of a barrel of oil was adopted.

For the diesel bus, the company provided the purchase value (R\$549,830.00) and the forecast over the years. For a hydrogen-powered bus, according to Miranda et al. (2017), in 2016 it cost approximately R\$3.6 million; in 2020, the National Renewable Energy Laboratory (Eudy & Post, 2021) estimated the cost at approximately R\$2.5 million; and in 2023, the cost is approximately R\$1.5 million. The infrastructure necessary for adopting the technology, such as tanks, pumps, and compressors, would cost around US\$1.5 million, or R\$7,395,000.00, according to Clough et al. (2023).

Some other data were predicted from information obtained from the company, such as the annual depreciation of vehicles (-6.73%), the expected annual growth in ticket sales (3.5%), and the annual growth rate of mileage (3% per year).

Regarding the composition of bus fares, the data are presented in Table 1, which details the components and their respective weights in the fare composition for 2023.

Based on the weights of each component in Table 1 and estimates for the period 2023–2043, an average annual reduction of 1.05% in the fare value was obtained in Table 2, discounting inflation. For clarity, Table 2 presents only data at four-year intervals.

Results and Discussion

From the data in Tables 1 and 2, a cash flow statement can be drawn up to obtain the financial results. In this context, income from ticket sales, resale of buses at the end of their useful life, and the carbon credit marketing strategy should be considered. The outflows are related to costs, expenses, and annual investments. According to the company in question, the net margin of the fare is around 4.8%. Finally, it is worth noting that due to the investments made frequently over the years, due to the life cycle of the buses, this cash flow is classified as irregular, with large variations in its results.

Table 1 - Bus fare composition items and their respective weights in 2023, including costs and expenses.

Component	Weight (%)	Component	Weight (%)
Fuel	25.25%	Food Aid	3.55%
Lubricant	0.28%	Benefits	2.28%
Shooting	1.26%	administrative expenses	1.24%
Parts and accessories (maintenance)	5.81%	Terminal security	2.03%
ARLA expenses	0.26%	Monthly expenses for transportation vehicles	0.03%
Total capital depreciation	10.45%	Electronic ticketing services	0.44%
Total capital remuneration	5.92%	ITS Solution services	1.40%
Cost of capital: special transportation	0.00%	Vehicle Wi-Fi (buses)	0.49%
Electronic ticketing solution	0.34%	Wi-Fi integration terminals	0.34%
ITS solution: depreciation	0.35%	Taxes	5.38%
Personnel expenses	28.10%		
Revenue			
Operating remuneration	4.41%	Deductions	0.39%
Total: R\$ 5.7593 (2023)		100.00%	

Table 2 - Base data for bus fare calculations and forecasts covering the period 2023–2043.

Year	2023	2027	2031	2035	2039	2043
Passengers	765,261	878,152	1,007,698	1,156,354	1,326,940	1,522,692
Km driven	630,653.00	709,805.51	798,892.35	899,160.38	1,012,012.93	1,139,029.47
Passengers per km index (IPKe)	1.21	1.24	1.26	1.29	1.31	1.34
Quantity of H ₂ V buses	0	20	40	80	94	131
Quantity of H ₂ V buses purchased	0	0	15	3	0	7
Hydrogen bus price (R\$)	2,479,535	2,159,595	1,881,247	1,742,292	1,620,193	1,506,651
Kg of fuel (R\$)	22.49	13.87	7.14	6.21	5.41	4.71
Consumption	0.067	0.067	0.067	0.067	0.067	0.067
Quantity of diesel buses	87	67	47	25	18	0
Quantity of diesel buses purchased	0	0	15	0	0	0
Diesel bus price (R\$)	549,830	572,155	595,387	619,562	644,719	670,897
Kg of fuel (R\$)	4.35	3.07	3.38	3.69	3.99	4.32
Consumption	0.3817	0.3817	0.3817	0.3817	0.3817	0.3817
Cost per km (R\$)	1.6604	1.1149	0.9179	0.7871	0.7066	0.4749
Reduction (R\$/km)	0%	1.56%	11.96%	0.83%	1.07%	8.87%
Fare (R\$)	5.7593	4.3260	4.3850	4.4390	4.5020	4.5920
Carbon credits obtained (ton)	0	9,429	16,005	23,309	28,158	35,538
Buses to be purchased	0	0	30	3	0	7

The company's cash flow forecast until 2043, considering a fleet of diesel-powered buses only, that is, without the acquisition of hydrogen-powered buses, is presented in Table 3. For clarity, the cash flows are reported at four-year intervals. For clarity, the cash flows are reported at four-year intervals.

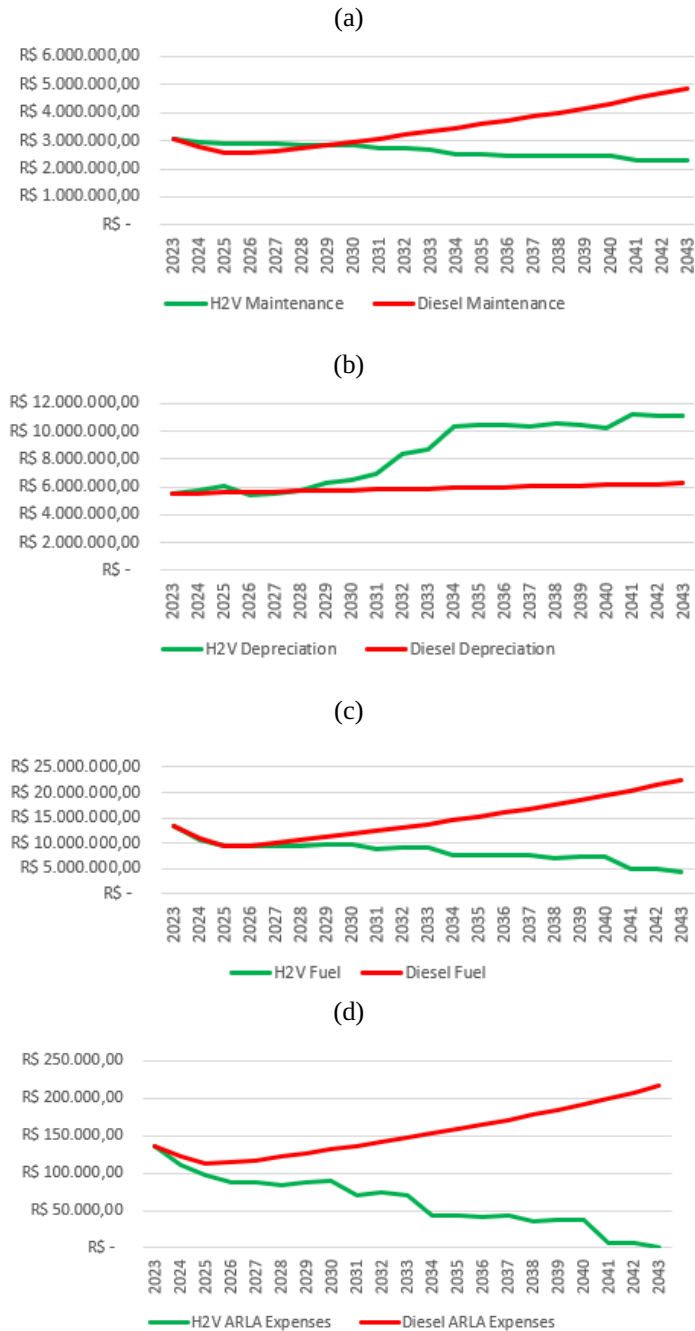
Next, we considered the proposal to replace the diesel bus fleet with hydrogen buses. To analyze and compare the two proposals, the same fare value was assumed for both. This strategy allowed us to identify in which activities there were variations in costs and expenses, and consequently in the contribution margin.

Among all costs and expenses, according to the graphs in Figure 1, four activities vary over the years if the replacement strategy of the diesel bus fleet (red curves) with a hydrogen bus fleet (green curves) is adopted. According to Sayer et al. (2022), expenses with parts and accessories for hydrogen-powered buses should decrease, while the depreciation cost of hydrogen buses, due to the high initial acquisition cost, should increase over the years.

Table 3 - Forecasts for the company's cash flow considering a diesel bus fleet (values in R\$).

	2023	2027	2031	2035	2039	2043
Initial balance	-	3,533,053.37	20,007,334.63	19,034,508.71	35,929,370.23	49,670,574.07
Capital for investment	-	2,500,000.00	2,500,000.00	2,500,000.00	2,500,000.00	2,500,000.00
Inflows						
Ticket revenue	52,888,412.13	45,586,626.62	53,025,068.76	61,596,664.87	71,686,606.56	83,906,419.97
Deductions	206,264.81	177,787.84	206,797.77	240,226.99	279,577.77	327,235.04
Resale of buses to third parties	-	-	8,811,046.20	881,104.62	-	2,055,910.78
Carbon credit	-	-	-	-	-	-
Total revenue	53,094,676.93	45,764,414.47	62,042,912.73	62,717,996.49	71,966,184.33	86,289,565.79
Outflows						
Investment activity	-	-	17,861,613.07	1,858,686.62	-	4,696,279.63
Fuel	13,353,593.21	9,969,447.80	12,383,822.81	15,182,196.60	18,496,271.73	22,533,766.14
Lubricant	146,655.35	126,408.08	147,034.29	170,802.65	198,781.25	232,665.82
Roading	667,974.03	575,753.39	669,699.98	777,956.17	905,392.87	1,059,727.58
Parts and accessories	3,071,652.46	2,647,579.47	3,079,589.20	3,577,410.24	4,163,413.74	4,873,115.89
ARLA expenses	136,288.76	117,472.71	136,640.92	158,729.16	184,730.05	216,219.43
Total capital depreciation (6.73%)	5,529,409.47	5,659,547.66	5,794,969.82	5,935,890.50	6,082,532.96	6,235,129.53
Total capital remuneration	3,307,780.42	2,851,107.55	3,316,327.29	3,852,417.45	4,483,468.95	5,247,728.23
Capital cost: special transportation	-	-	-	-	-	-
Electronic ticketing depreciation	178,230.39	153,623.86	178,690.91	207,576.61	241,579.04	282,758.99
ITS Depreciation	185,204.07	159,634.75	185,682.61	215,698.53	251,031.38	293,822.59
Personnel expenses	14,881,212.52	13,475,247.65	15,674,025.17	18,207,759.05	21,190,310.58	24,802,444.76
Food allowance	1,877,829.61	1,618,576.06	1,882,681.68	2,187,020.50	2,545,268.94	2,979,139.55
Benefits	1,205,502.85	1,039,070.87	1,208,617.71	1,403,992.90	1,633,976.23	1,912,506.43
Administrative expenses	654,724.74	564,333.30	656,416.46	762,527.34	887,434.37	1,038,707.85
Terminal security	1,072,900.41	924,775.55	1,075,672.64	1,249,557.03	1,454,242.74	1,702,135.28
Operation of special vehicles	16,165.00	13,933.26	16,200.77	18,826.62	21,910.55	25,645.46
Electronic ticketing services	230,927.07	199,045.23	231,523.75	268,949.98	313,005.77	366,361.23
ITS services	742,365.85	639,874.67	744,284.03	864,598.86	1,006,225.88	1,177,748.75
Vehicle Wi-Fi	261,640.40	225,518.27	262,316.45	304,720.36	354,635.58	415,087.32
Integration terminal Wi-Fi	181,150.49	156,140.82	181,618.56	210,977.52	245,537.04	287,391.67
Taxes	2,842,978.86	2,450,476.59	2,850,324.74	3,311,084.77	3,853,462.39	4,510,329.74
Total outflows	50,544,185.98	43,567,567.53	68,537,758.86	60,727,381.48	68,513,212.04	84,888,711.87
Final balance	2,550,490.96	8,229,900.31	16,012,488.49	23,525,123.71	41,882,342.51	53,571,428.79
Contribution margin (tariff)	4.80%	4.80%	4.80%	4.80%	4.80%	4.80%

Figure 1 - Graphs of activities that would undergo cost variations with the adoption of the strategy of replacing the diesel bus fleet with hydrogen buses: (a) Maintenance, (b) Depreciation, (c) Fuel, and (d) ARLA.



Regarding the behavior of expenses with fuel and ARLA (an additive to diesel), it is noted that such costs decrease in the case of the proposed replacement of the fleet with hydrogen buses. Such situations can be observed in the graphs shown in Figure 1.

Table 4 presents the company’s cash flow forecast until 2043, considering the replacement of the diesel-powered bus fleet with hydrogen-powered buses. For clarity, the cash flows are reported at four-year intervals.

From the cash flows obtained in Tables 3 and 4, financial calculations can be performed, and the projection of the strategies can be analyzed. Based on these data, the parameters are evaluated for each scenario: the diesel fleet scenario and the hydrogen fleet scenario.

Table 4 - Forecasts for the company’s cash flow considering the replacement of the diesel-powered bus fleet with hydrogen-powered buses (values in R\$).

	2023	2027	2031	2035	2039	2043
Opening balance	-	-30,901,128.27	1,913,516.12	15,412,341.99	96,400,461.88	208,664,974.78
Capital per investment	-	2,500,000.00	2,500,000.00	2,500,000.00	2,500,000.00	2,500,000.00
Inflows						
Billing with ticket	52,888,412.13	45,586,626.62	53,025,068.76	61,596,664.87	71,686,606.56	83,906,419.97
Deductions	206,264.81	177,787.84	206,797.77	240,226.99	279,577.77	327,235.04
Resale of buses to third parties	-	-	8,811,046.20	3,973,464.06	-	9,271,416.14
Carbon credit	-	4,222,690.53	7,167,368.09	10,438,265.09	12,610,037.01	15,914,679.20
Total revenue	53,094,676.93	49,987,105.00	69,210,280.82	76,248,621.02	84,576,221.33	109,419,750.34
Outflows						
Investment activity	-	-	37,149,514.54	5,226,876.61	-	10,546,562.62
Fuel	13,354,324.06	9,496,674.78	8,799,513.80	8,492,517.86	8,580,852.96	6,490,826.71
Lubricant	146,655.35	126,408.08	147,034.29	170,802.65	198,781.25	232,665.82
Shooting	667,974.03	575,753.39	669,699.98	777,956.17	905,392.87	1,059,727.58
Parts and accessories	3,071,652.46	2,888,589.04	2,705,525.61	2,504,155.84	2,440,083.64	2,275,326.56
ARLA expenses	-	87,630.56	71,142.40	43,950.30	36,779.91	-
Total capital depreciation (6.73%)	5,526,839.07	5,499,510.35	6,944,880.39	10,398,273.06	10,397,732.09	11,106,723.76
Total capital remuneration	3,307,780.42	2,851,107.55	3,316,327.29	3,852,417.45	4,483,468.95	5,247,728.23
Cost of capital: special transportation	-	-	-	-	-	-
Electronic ticketing solution: depreciation	178,230.39	153,623.86	178,690.91	207,576.61	241,579.04	282,758.99
ITS solution: depreciation	185,204.07	159,634.75	185,682.61	215,698.53	251,031.38	293,822.59
Personnel expenses	14,881,212.52	13,475,247.65	15,674,025.17	18,207,759.05	21,190,310.58	24,802,444.76
Food assistance	1,877,829.61	1,618,576.06	1,882,681.68	2,187,020.50	2,545,268.94	2,979,139.55
Benefits	1,205,502.85	1,039,070.87	1,208,617.71	1,403,992.90	1,633,976.23	1,912,506.43
Administrative expenses	654,724.74	564,333.30	656,416.46	762,527.34	887,434.37	1,038,707.85
Terminal security	1,072,900.41	924,775.55	1,075,672.64	1,249,557.03	1,454,242.74	1,702,135.28
Operation of vehicles for special transport	16,165.00	13,933.26	16,200.77	18,826.62	21,910.55	25,645.46
Electronic ticketing solution: services	230,927.07	199,045.23	231,523.75	268,949.98	313,005.77	366,361.23
ITS solution: services	742,365.85	639,874.67	744,284.03	864,598.86	1,006,225.88	1,177,748.75
Vehicle Wi-Fi solution (buses)	261,640.40	225,518.27	262,316.45	304,720.36	354,635.58	415,087.32
Wi-Fi solution for integration terminals	181,150.49	156,140.82	181,618.56	210,977.52	245,537.04	287,391.67
Taxes	2,842,978.86	2,450,476.59	2,850,324.74	3,311,084.77	3,853,462.39	4,510,329.74
Total outflows	50,406,057.66	43,145,924.62	84,951,699.79	60,680,242.03	61,041,712.17	76,753,640.91
Final balance	2,688,619.27	-21,559,947.90	-11,327,902.85	33,480,720.98	122,434,971.04	243,831,084.21
Contribution margin (tariff)	5.06%	5.72%	10.20%	10.32%	15.18%	21.40%

Financial parameters for the diesel fleet scenario —

Considering a diesel fleet scenario, Table 5 presents the projected cash flow, present value, and accumulated present value over the analyzed period.

Table 5 - Forecast for the company's financial parameters when maintaining a diesel-only fleet (values in R\$).

Period	Cash Flow	Present Value	Accumulated PV
0	-18,325,833.90	-18,325,833.90	-18,325,833.90
1	-3,826,449.51	-3,424,115.89	-21,749,949.79
2	-429,936.00	-3,410.74	-21,753,360.53
3	3,533,053.37	2,531,672.96	-19,221,687.58
4	8,229,900.31	5,277,210.86	-13,944,476.72
5	10,171,465.54	5,836,411.07	-8,108,065.64
6	15,042,259.55	7,723,744.29	-384,321.35
7	20,007,334.63	9,192,984.19	8,808,662.84
8	16,012,488.49	6,593,829.51	15,392,492.35
9	21,164,529.70	7,787,151.16	23,179,683.51
10	24,227,712.44	7,976,954.09	31,156,637.60
11	19,034,500.71	5,608,139.68	36,764,777.28
12	23,525,123.71	6,202,425.18	42,967,202.46
13	27,776,780.58	6,553,359.53	49,520,561.99
14	35,550,907.48	7,083,352.03	56,603,914.02
15	35,929,370.23	6,787,918.63	63,391,832.66
16	41,882,342.51	7,080,606.43	70,472,439.09
17	47,971,803.77	7,257,348.99	77,729,788.08
18	43,287,445.88	5,860,118.38	83,589,906.46
19	49,670,574.87	6,017,222.66	89,607,129.12
20	53,571,428.79	5,807,411.41	95,414,540.52

Table 6 summarizes the main financial indicators. The project presents a positive NPV of R\$ 95.4 million and an IRR of 33.26%, exceeding the adopted MARR, indicating economic feasibility.

Table 6 - Financial indicators for the diesel-only scenario (values in R\$).

Parameter	Value
Initial investment	18,325,833.90
MARR (Selic 02/10/2023)	11.75%
Total investment	105,581,110.32
Sum of PV (Periods 1–10)	13,740,374.42
Net Present Value (NPV)	95,414,540.52
Internal Rate of Return (IRR)	33.26%
Profitability index	6.2066
Payback (years)	6.04

Financial parameters for the hydrogen fleet scenario —

Table 7 presents the projected cash flow, present value, and accumulated present value for the hydrogen adoption scenario over the analyzed period.

Table 8 summarizes the main financial indicators for the hydrogen adoption scenario. The results indicate a positive Net Present Value (NPV) of R\$ 9,638,047.47 and an Internal Rate of Return (IRR) of 12.17%, slightly exceeding the adopted MARR, which suggests the economic feasibility of the project, although with a long payback period of approximately 19.64 years.

Table 7 - Forecast for the company’s financial parameters under the hydrogen adoption scenario (values in R\$)

Period	Cash Flow	Present Value	Accumulated PV
0	-55,228,381.10	-55,228,381.10	-55,228,381.10
1	-37,949,577.24	-33,959,353.24	-89,187,734.34
2	-35,046,950.79	-28,064,362.10	-117,252,096.44
3	30,901,128.27	-22,142,759.41	-139,394,855.86
4	-21,559,947.89	-13,824,759.33	-153,219,615.20
5	-21,210,693.41	-12,170,746.24	-165,390,361.44
6	-10,061,296.23	-5,166,170.62	-170,556,532.06
7	1,913,516.12	879,223.73	-169,677,308.33
8	-11,327,902.84	-4,657,675.85	-174,334,984.19
9	3,287,291.98	1,209,512.87	-173,125,471.31
10	12,290,480.62	4,046,630.48	-169,078,840.83
11	15,412,341.98	4,540,940.24	-164,537,900.59
12	33,480,720.98	8,827,229.54	-155,710,671.05
13	52,817,712.09	12,461,251.79	-143,249,419.26
14	75,232,728.89	15,883,323.08	-127,366,096.18
15	96,400,461.88	18,212,356.28	-109,153,739.89
16	122,434,971.04	20,698,790.74	-88,454,949.16
17	150,144,557.74	22,714,414.90	-65,740,534.25
18	174,829,380.73	23,667,852.10	-42,072,682.15
19	208,664,974.78	25,278,217.88	-16,794,464.27
20	243,831,084.21	26,432,511.74	9,638,047.47

Table 8 - Financial indicators for the hydrogen adoption scenario (values in R\$).

Parameter	Value
Initial investment	55,228,381.10
MARR (Selic 02/10/2023)	11.75%
Total investment	270,063,910.49
Sum of PV (Periods 1–20)	64,866,428.57
Net Present Value (NPV)	9,638,047.47
Internal Rate of Return (IRR)	12.17%
Profitability index	1.174512584
Payback (years)	19.64

Greenhouse gas emissions and carbon credit analysis

Regarding the strategy of reducing greenhouse gas emissions and obtaining carbon credits, according to Carvalho (2011), each liter of Diesel burned emits 2.6 kg of CO₂, while each carbon credit corresponds to one ton of CO₂ not emitted into the atmosphere. Figure 2 presents these results for both proposals, for the period from 2023 to 2043.

By adopting the fleet replacement strategy, it can be concluded that in this 20-year period, the company would accumulate a total of 401,274 carbon credits, contributing to the environment and generating revenue of approximately R\$180 million, considering a carbon credit at €85.30 and euro at R\$ 5.25.

Figure 3 shows the Total Cost of Ownership (TCO) of vehicles over the next few decades. According to Santos (2011), TCO is a concept that considers the costs of acquiring, operating, and maintaining the property throughout its useful life. To calculate the TCO of vehicles, the values of the buses in the fleets were estimated and compared every 10 years.

Figure 2 - For both proposals are analyzed: (a) CO₂ emissions in tons, (b) carbon credits accumulated, (c) and number of bus types

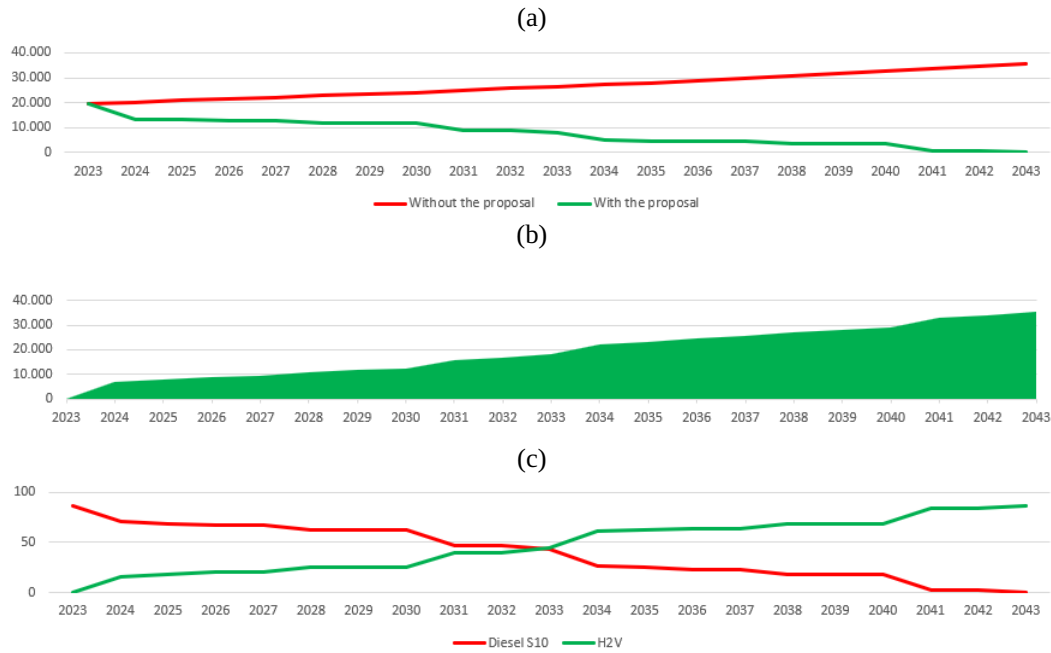
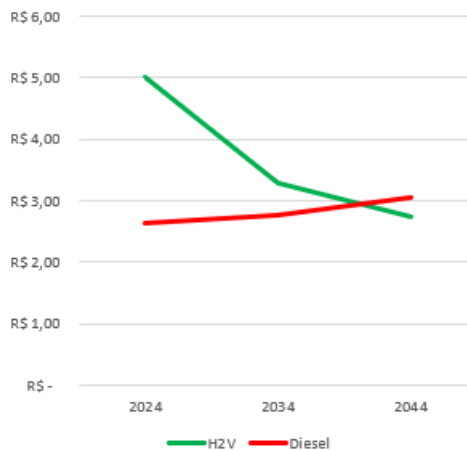


Figure 3 - Total Cost of Ownership of vehicles over the next decades.



In summary, according to Silva and Fontes (2005), A project is economically viable when the result of its Net Present Value is greater than zero, and more effective when it presents a better result when compared to another project. In the proposals analyzed, it can be observed that both projects obtained a positive result for the Net Present Value, R\$9,638,047.47 for the project to reduce emissions and R\$95,414,540.52 for the other project that maintains the fleet of diesel buses. According to the theory, an investment that obtains an Internal Rate of Return higher than the Minimum Attractive Rate of Return (11.75%) is recommended. In the proposal without the acquisition of hydrogen-powered buses, the IRR was 33.26%, with a Payback achieved at the beginning of the 6th year, while the proposal to replace the fleet, which reduces greenhouse gases, obtained 12.17% for the Internal Rate of Return and a Payback achieved in the middle of the 19th year from the initial investment. Tables 5 and 7 present these results.

Regarding greenhouse gas emissions, considering the proposal to maintain the fleet of diesel-powered buses, replacing them every 10 years with new diesel buses, it is estimated that the greenhouse gas emissions of this bus fleet in 2023 were around 19,676 tons of CO₂ per year into the atmosphere. Considering the expected increase in fleet mileage provided by the company, these emissions would increase by 2.91% per year, reaching 35,538 tons per year in 2043. As for the proposal to replace the fleet with hydrogen-powered buses, these greenhouse gas emissions would be reduced by an average of 16.75% per year, until there would be no more emissions of these gases in 2043. In addition to the benefit of contributing to the reduction of

greenhouse gases and consequently reducing the planet's temperature, for each ton that the company stopped emitting, it would receive a carbon credit, which could be traded with other countries or companies that did not meet their reduction targets. Taking into account the values adopted for carbon credits in 2023, the company would accumulate 401,274 carbon credits, which corresponds to R\$179,700,472.19. Figure 2 presents these results.

For the Total Cost of Ownership, which considers maintenance, operation (running), and acquisition costs throughout the useful life of the vehicles, in 2024, the TCO of the diesel-powered bus was R\$2.64 per kilometer driven, while for the hydrogen-powered bus it was R\$5.01. Projections for the year 2043 result in a kilometer driven for the hydrogen-powered bus developed by COPPE being R\$2.74, while the kilometer driven for the diesel-powered bus would be R\$3.05. The simulations predict the inflection point to occur in 2040, as observed in Figure 3.

Conclusions

The main objective of this research was to understand the advantages and disadvantages of using green hydrogen as a fuel and to carry out technical and economic feasibility analysis of replacing a fleet of diesel-powered buses with a fleet of buses powered by low-carbon hydrogen in a public transportation concessionaire in Londrina. This proposal aims to contribute to the goal of reducing CO₂ emissions and the planet's temperature in the coming years, in addition to allowing a possible replication for other public transportation companies in other cities.

Based on the results obtained, it can be concluded that although OPEX (operating costs) tend to decrease over the years, net margins increase if we compare one vehicle with another, and that the financial parameters are positive; the strategy of investing in hydrogen-powered buses is not financially viable, as the return on investment would only occur 19 years after the first acquisition. On the other hand, respecting the countries' goal of reducing greenhouse gas emissions by 50% by 2030, it follows that the company considered in this research, by adopting the strategy of replacing its fleet, would achieve this objective in 2033 and mitigate emissions in 2043, data that should be considered when making decisions about the future composition of its bus fleet.

On the other hand, all of these results depend on future projections for the variables considered in this study. For example, during the period considered, from 2023 to 2043, fluctuations in the future price of diesel and hydrogen, variations in the maintenance costs of both vehicles, and substantial cash inflows due to the receipt of carbon credits may occur. Such fluctuations can be accounted for through a sensitivity analysis study. However, such a sensitivity analysis would also be complex, as it would require modeling value ranges for the relevant variables. Another possible sensitivity analysis would be to create two scenarios, one optimistic and one pessimistic, based on the extreme values of the fluctuations for the relevant variables. Modeling for these studies is currently under consideration and will be discussed in future work.

Finally, even though Brazil has the capacity to produce hydrogen gas at an extremely low price in the coming decades, the main obstacle to the technology is CAPEX, that is, the high investment required to acquire the buses and their short life cycle.

During the research, the main limitation found was the lack of data on the by low-carbon hydrogen market and specifically on buses powered by this technology.

Author Contributions

A. M. Mariotto participated in investigation, methodology, data curation, formal analysis, investigation, visualization, validation, and writing—original draft. **J. Henrique Junior** participated in formal analysis, validation, conceptualization, and supervision. **E. R. Takano Natti** participated in supervision, and writing—review & editing.

Conflicts of Interest

The authors declare no conflict of interest.

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