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ORIGINAL ARTICLE

A total cost of ownership comparison of log truck decarbonization in pulp mills

Comparação do custo total de propriedade da descarbonização do transporte florestal em fábricas de celulose

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ABSTRACT

The Global carbon dioxide (CO_2) emissions from energy combustion and industrial processes have steadily increased along the time to more than 80% in the last 30 years. Many efforts are being made to set policies and international targets to reduce the Greenhouse Gas Emissions (GHG). Transport globally accounts for 30% of final energy consumption, and still is only 4.1% based on renewable sources. Thus, decarbonization is an important challenge, especially in long-distance heavy duty vehicles, as non-fossil fuel technologies are not mature enough for large scale implementation. There is a broad list of alternative fuel technologies being developed, from ethanol, biodiesel, HVO, biomethane, natural gas (compressed or liquified), electric hydrogen fuel cells, hybrids, and fully electric vehicles. The pulp and paper sector has the wood fibers coming from planted forests as the primary and renewable power source, being energy self-sufficient and generating a surplus, which is usually sold to the market. Therefore, this study analyzed the potential application of promising low emission heavy duty trucks for log transportation in a Brazilian pulp industry, integrated to the pulp mill energy generation. Owing to uncertainty of several variables, a sensitivity analysis was performed to check costs and benefits using the Monte Carlo simulation. Results were: Electric truck option with lower TCO per kilometer, 1.52 USD/km; gas options LNG, 1.59 USD/km and CNG 1.73 USD/km; Diesel with 1.87 USD/km and highest cost for Fuel Cell, with 2.02 USD/Km. The main inputs impacting the results were fuel costs and distance. The LNG solution was the only one having positive ROI. Although Electric HDT did not yield a positive ROI, it looks like the simplest solution to connect with the energy from the pulp mill and is expected to have the highest market share. Therefore, it has the potential to be the first position in renewable trucks option in pulp mills operations in the medium to long term.

Keywords: *Log hauling; Pulp mill; Carbon emissions; Renewable energy; Monte Carlo simulation.*

RESUMO

As emissões globais de dióxido de carbono (CO_2) provenientes da combustão de energia e dos processos industriais aumentaram constantemente ao longo do tempo, mais de 80% nos últimos 30 anos. Muitos esforços estão sendo feitos para definir políticas e metas internacionais para reduzir as emissões de gases de efeito estufa (GEE). O transporte responde globalmente por 30% do consumo final de energia, e ainda tem apenas 4,1% baseado em fontes renováveis. Assim, a descarbonização é um desafio importante, especialmente em veículos pesados de longa distância, uma vez que as tecnologias de combustíveis não fósseis não estão suficientemente maduras para implementação em larga escala. Há uma ampla lista de tecnologias de combustíveis alternativos em desenvolvimento, desde etanol, biodiesel, HVO, biometano, gás natural (comprimido ou liquefeito), células elétricas de combustível de hidrogênio, híbridos e veículos totalmente elétricos. O setor de celulose e papel tem como fonte de energia primária e renovável as fibras de madeira provenientes de florestas plantadas, sendo autossuficiente em energia e gerando excedentes normalmente vendidos ao mercado. Portanto, este estudo analisou a aplicação potencial de promissores caminhões pesados de baixa emissão para transporte de toras em uma indústria brasileira de celulose, integrados à geração de energia da fábrica de celulose. Devido à incerteza de diversas variáveis, foi realizada uma análise de sensibilidade para verificar custos e benefícios utilizando simulação de Monte Carlo. Os resultados mostraram que: opção de caminhão elétrico com menor TCO por quilômetro foi de 1,52 USD/km; opções de gás GNL, 1,59 USD/km; GNV 1,73 USD/km; Diesel com 1,87 USD/km; e maior custo para Fuel Cell, com 2,02 USD/km. Os principais insumos que impactaram os resultados foram custos de combustível e distância. A solução de GNL foi a única com ROI positivo. Embora o HDT elétrico ainda não tenha um ROI positivo, parece a solução mais simples para conectar-se à energia da fábrica de celulose e espera-se que tenha a maior participação de mercado. Portanto, tem potencial para ocupar a primeira posição em opção de caminhões renováveis nas operações de fábricas de celulose no médio e longo prazo.

Palavras-chave: *Transporte florestal; Fábrica de celulose; Emissões de carbono; Energia renovável; Simulação de Monte Carlo.*

1. INTRODUCTION

The Global carbon dioxide (CO_2) emissions from energy combustion and industrial processes have steadily increased through time; more than 80% in the last 30 years (International Energy Agency, 2022a). Many efforts are being made to set policies and international targets to reduce the Greenhouse Gas Emissions (GHG); starting mainly with the Paris Agreement, an international treaty on climate change stablished at the United Nations Climate Change Conference (COP21) in 2015; which set as the main goal to hold the global average temperature increase below 2°C above pre-industrial levels (United Nations Climate Change, 2015). The countries were committed to communicate their actions to reduce GHG emissions, called as Nationally Determined Contributions (NDCs), and formulate Long-Term Strategies (LT-LEDS).

After the Paris Agreement many other global meetings and treaties have been made, to set actions targeting net zero emissions. In November 2022, the Conference of the Parties of the UNFCCC in Egypt, the COP27, was held. Among several discussions around climate changes, carbon economy, global temperature targets, one of the main announced results were the one by the European Union, which increased their target of carbon emissions reduction, from 55% to 57% by 2030, and the agreement to create the new “Loss and Damage” fund for vulnerable countries (United Nations Climate Change, 2022). There are also organizations discussing and proposing strategies to achieve those targets, as the International Energy Agency (IEA), which has published its Net Zero by 2050 in 2021: “A Roadmap for the Global Energy Sector” (International Energy Agency, 2021).

The share of final energy consumption is similarly distributed among three main groups; Buildings with 33%, Industry with 33%, and Transport accounting for 30%. Decarbonization in transport is an important global challenge, especially in long-distance heavy-duty vehicles, as non-fossil fuel technologies are not mature enough for large scale implementation. Yet according to the Renewables Global Status Report transport globally still uses only 4.1% based on renewable sources; the lowest share among end-use sectors, and represents nearly a third of total final energy consumption (REN21, 2023).

However, there are several initiatives under development for vehicles with low carbon emissions. The Energy Policy Act of 1992, U.S. Public Law 102-486, has defined alternative fuels such as: biodiesel (B100), natural gas and liquid fuels domestically produced from natural gas, propane (liquefied petroleum gas), electricity, hydrogen, blends of 85% or more of methanol, denatured ethanol, and other alcohols with gasoline or other fuels, methanol, denatured ethanol and other alcohols, coal-derived, domestically produced liquid fuels, fuels (other than alcohol) derived from biological materials, and P-Series fuels (United States Department of Transportation, 1992).

The U.S. Department of Energy (DOE), through its Alternative Fuels Data Center (AFDC), names more than a dozen alternative fuels in production or under development. Among them, the main ones are: ethanol, widely used renewable fuel made of corn, sugar cane and other plant materials, which is used in vehicles blended with gasoline. Biodiesel; a renewable fuel made from vegetable oil, animal fats or cooking oil for use in diesel engines, is already largely used in some countries. Natural gas is already abundant for domestically usage. Hydrogen is used in vehicles known as full cell electric vehicles (FCEV), still in development or demo applications, uses similar principles as the electric ones, storing energy as hydrogen which is later converted to electricity by the fuel cell. Electricity is used directly in electric powered vehicles, also referred as battery electric vehicles (BEV) (U.S. Department of Energy, 2023a). There are other emerging options, such as: biobutanol, dimethyl ether, methanol, renewable hydrocarbon biofuels, and especially hydrotreated vegetable Oil (HVO), which became widely commercially available in 2020, as a “drop-in” substitute for fossil-diesel.

However, the industry sector still relies heavily on logistics to run its activities. The pulp and paper sector, object of this study, has the wood fibers coming from planted forests as the primary and renewable power source. However, despite wood fiber being a renewable and sustainable material with high carbon retention, the diesel consumption in log transportation is the highest consumption in the pulp production chain.

This industry has passed through many improvements in the last decades, with its chemical cycle almost closed, turning as energy self-sufficient, and even selling the surplus energy to the market. Planted forests supply the raw material not just for the pulp, as fiber, but also for energy through biomass (residues, branches, and bark) and lignin as the primary source, which is burnt in the recovery boiler as black liquor. Food and Agriculture Organization (2004) notes that ‘black liquor’, a by-product of the wood pulp industry, is classified as a liquid wood fuel, alongside solid residues, and highlights its efficiency in heat and power generation. All the improvements and parameters that impact this well-developed industrial process, with more than 75% of solid contents burning, are well explored in several studies in the literature (Bajpai, 2017). With new energy source trucks being developed, following the demand to reduce gas emissions all over the globe, combined with the energy generation capacity of pulp mills, it may turn out to be a great opportunity as a new technology breakthrough for the sector. Therefore, this study aims to explore the feasibility and potential benefits of leveraging pulp mill-generated energy as a sustainable alternative to fossil fuels in freight transportation, assessing the cost-effectiveness of this integration by comparing capital and operational expenditures with conventional energy and fuel systems. Ultimately, the goal is to determine whether this approach can offer a viable, scalable pathway for decarbonizing the forestry value chain while enhancing energy efficiency and industrial competitiveness.

2. MATERIALS AND METHODS

2.1. Object of study

This study considers the feasibility analysis of replacing heavy-duty diesel trucks with alternative options with renewable-based energy, in a fictious pulp mill in the State of Mato Grosso do Sul, Brazil. The pulp mill has a 2.5 million tons production per year, with surplus energy generation of 180 MWh on average and a distance average radius from mill to the field of 80 km. Considered is the most common tractor and trailer combination used in Brazilian pulp mills: the three-wagon truck, known in Portuguese as “tritrem”. The composition consists of a 6x4 tractor truck with at around 440 hp, with total gross weight of 74 tons and a total payload of 52 tons (Figure 1).

In this sense we consider two innovation breakthroughs which will be studied in an integrated way. The new trucks technology, identifying the feasibility of main options, both the existing and most promising ones; and the pulp mill integrated with the wood supply logistics as the fuel supplier. The pulp mill can generate different types of fuel, using several pathways; however, due to the complexity in the mill side, this study will concentrate the analysis only on the scenario of a mill supplying energy for electric vehicles.

Four alternative solutions were considered as replacement for diesel. The options studied were: Battery electric vehicles (BEV), Full cell electric vehicles (FCEV), Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG).

Figure 1. The most common tractor and trailer combination used in Brazilian pulp mills.

2.2. Methodology

To verify the technologies' feasibility a multivariate analysis was run, comparing the Total Cost of Ownership (TCO) of new trucks' alternatives in relation to the diesel option. Additionally, in the case of electric vehicles, the energy balance from the mill, volume available and cost comparison between truck utilization and income from selling it to the network was considered. For both cases we also estimated the impact of CO_2 emissions.

As the historical data of renewable energy HDVs are still not available, we used the best references, from manufacturer technical catalogues and scientific studies to determine the value of main parameters, as refilling infrastructure, investment costs, estimate energy efficiency, and others; and used the sensitivity analysis to minimize the uncertainty.

For the TCO sensitivity analysis, a Monte Carlo simulation was performed using the @Risk 8.5.2 Industrial Edition, Student license, software from Lumivero/Palisade. The simulation was run using the variation of several inputs, variables that cause greater uncertainty, especially as related to technology maturity and early-stage adoption, in order to determine the probability of the output results and provide the ranking of the variable with the greatest interference. A total of 5 million scenarios were performed, from a combination of 100 simulations and 50,000 iterations in each simulation. Table 1 presents the main input and output variables used in the Monte Carlo simulation, categorized by financial (e.g., USD), operational (e.g., km, tons, kWh), and performance metrics (e.g., fuel efficiency, speed, emissions), along with their respective units.

A market screening was performed, checking all the manufacturers options available in the market or under development, review of the literature to map initial trials' data, and perform an expert survey, in order to map what the stage and potential trends on implementation was.

The CO_2 emissions estimates were calculated following 3 steps. First: identifying the truck emissions factors (median score reference of 3.41Kg of CO_2 per liter). Second: multiplying the distance by truck emissions factor. Finally: conversion to metric tons by dividing by 1,000,000 (Mathers, 2015).

The Return on Investment (ROI), was calculated using the original formula created by Donaldson Brown (Flesher & Previts, 2013). The indicator was calculated through the relation between net profit and investment spent (Investopedia, 2023).

$$\text{ROI}\ \% = \frac{\text{Net profit(Return} - \text{Investment)}}{\text{Investment}} \times 100$$

Table 1. Monte Carlo simulation model input and output variables.

Group	Item	Unit
Inputs		
General Premises	Truck depreciation	years
	Battery lifetime	years
	Filling station depreciation	years
	Filling station ratio	# trucks/station
	Carbon credit cost	$USD/ton
	Diesel emissions (entire chain)	kg CO2eq/L
	Truck power / model	KWh
	Available power for operation (per charge)	KWh
	Truck payload	ton
Mill demand & Energy Balance	Pulp mill production	Million ton/year
	Specific consumption	m3 wood/ton pulp
	Ton x m3 factor	#
	Wood demand ton	ton/year
CAPEX (investments)	Truck price	USD
	Filling station	USD
	Additional batteries	USD
OPEX (operational costs)	Fuel cost	USD/L, USD/KWh, USD/Kg
	Consumption factor on/off road	#
	Consumption on road (mix full and empty)	Km/L, Km/KWh, Km/Kg, Km/m3
	Consumption off road (mix full and empty)	Km/L, Km/KWh, Km/m3
	Consumption on road (mix full and empty)	KWh/Km, Kg/Km
	Consumption off road (mix full and empty)	KWh/Km, Kg/Km
	Maintenance cost	USD/Km
	Driver cost	USD/month
Cycle Time	Average distance	Km
	On road distance	%
	Off road distance	%
	Operating days per year	#
	Operational efficiency	%
	Operating hours per day	h
	Speed Off road empty	Km/h
	Speed Off road loaded	Km/h
	Speed On road empty	Km/h
	Speed On road loaded	Km/h
	Loading time	h
	Unloading time	h
	Refilling time	h
Outputs		
TCO Cost	Total cost per Km	$/Km
	Total cost per ton	$/ton
Benefits technology change	Saving from fuel type replacement	USD
	Emissions reduction	t CO_2
	Total benefits (fuel + emissions reduction)	USD
	ROI	%

3. RESULTS

3.1. Total cost of ownership results

The TCO result is expressed in cost per kilometer calculated for each solution. The lowest estimate cost is the BEV with 1.52 USD/km, followed by gas trucks, LNG with 1.59 USD/km and CNG with 1.73 USD/km. In the sequence comes the technology "baseline", the diesel truck estimate in 1.87 USD/km, and finally the highest cost being the FCEV, Hydrogen truck, with 2.02 USD/km.

In general, the fuel cost and investment cost, trucks and filling station had the highest contribution to the final cost per kilometer, as seen in Figure 2. The maintenance and insurance costs had a lower impact on the total cost and didn't differ much between the technologies. Manpower contributed with one of the highest costs, however it is almost the same for all solutions.

Besides the static numbers from standard calculation, each TCO is presented in a range of potential values, according to the probability distribution, by performing the Monte Carlo simulation. The summary results are listed in Figure 3, including minimum, maximum, mean and standard deviation values. The probability followed the same rank as found in the static calculation, giving the lowest minimum for BEV, CNG, LNG, Diesel, FCEV, with 1.24 USD/Km, 1.32 USD/Km, 1.33 USD/Km, 1.56 USD/Km and 1.64 USD/Km, respectively. The same works for the maximum, with the lowest maximum according to solution with lowest static, mean and minimum, meaning the curves are positioned following the same as static rank, with no higher variation for some specific technology, despite differences in standard deviation.

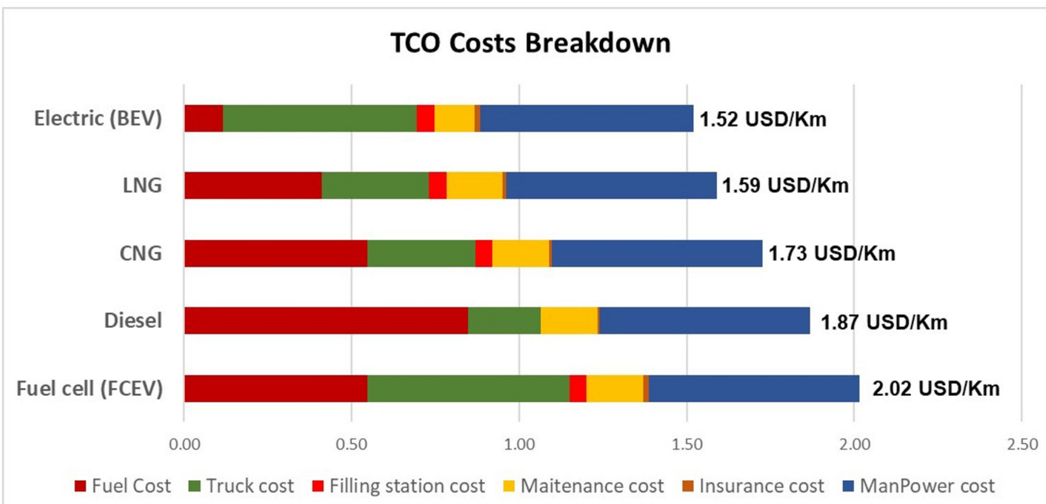

Figure 2. Total cost of ownership breakdown

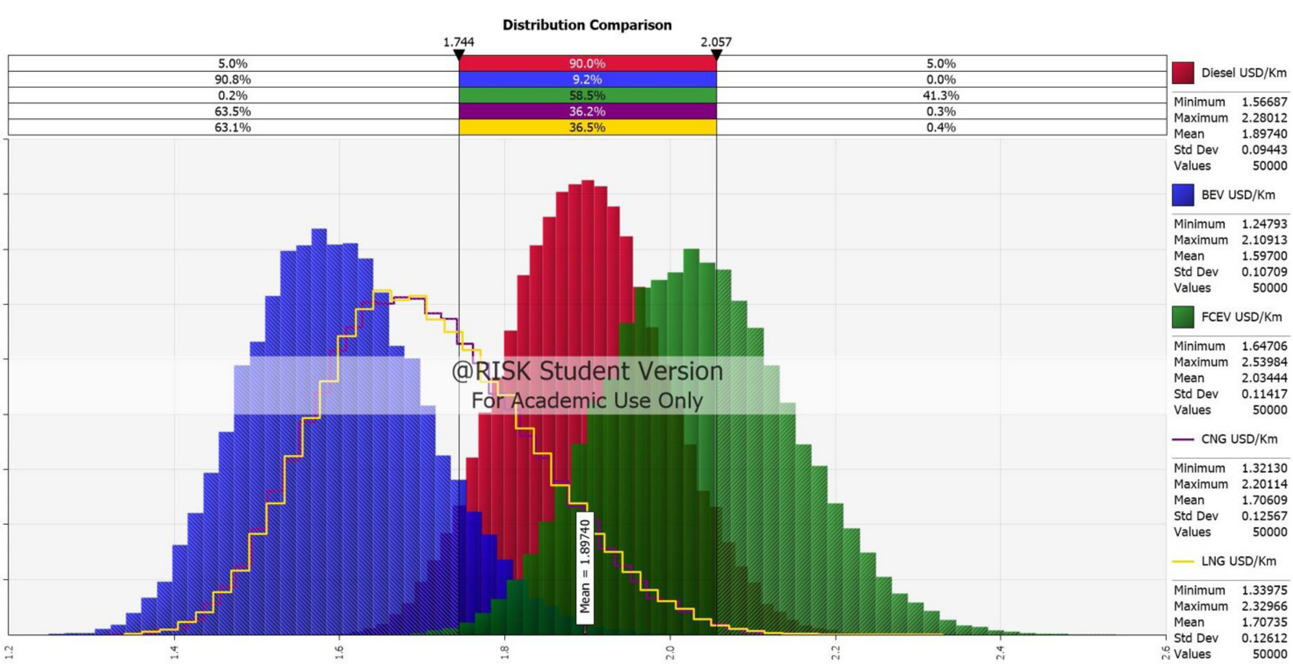

Figure 3. Total cost of ownership probability distribution from Monte Carlo simulation

3.2. Benefits of technology replacement

For the total benefit of technology transition the unitary TCO difference times total kilometers to be run with complete fleet in its lifetime of 5 years was used. The results are presented in two ways, the static calculation and the probability distribution from the Monte Carlo simulation.

The static results summary is presented in Figure 4 and the summary of sensitivity analysis in Figure 5. In the static results the higher benefit comes from BEV, accounting for a total of 44.5 million USD in 5 years of operation, with 39.17 million USD being from fuel cost saving and 5.33 million USD from carbon credits. The gas trucks, LNG and CNG present savings of 31.4 and 16.0 million, respectively, from fuel cost saving alone. Both technologies didn't fully consider the carbon benefit. Finally, the FCEV presented a negative result of -11.3 million USD, due to higher fuel cost. The carbon credit was considered as the technology which didn't have any CO_2 emissions; however, it did not benefit enough to compensate for the higher cost in energy.

The same rank is presented in the results from multivariable simulation, with higher benefits from electric trucks, ranging from 1.29 million to 100.76 million USD, followed by gas trucks, later FCEV.

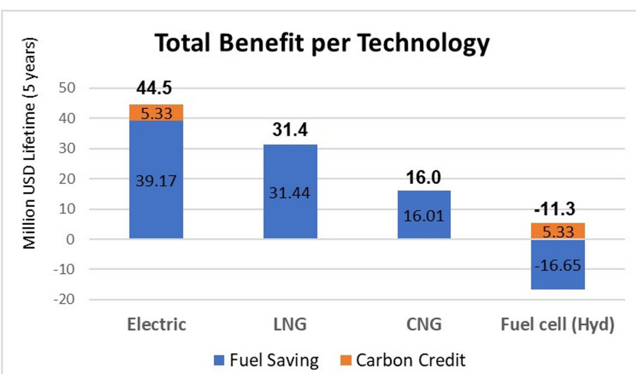

Figure 4. Total benefit per technology, according to a static simulation

Except BEV, all other technologies' minimum was negative; however, the only negative mean was from FCEV.

In Table 2 the rank of input that causes higher impact to the total benefit are summarized, with a classification from each group of inputs. In general, there was a predominance of operational costs items over investments, such as fuel cost. The Cycle time items related also appears in first positions, as distance and operational efficiency. The investment cost appears in the third position for BEV and FCEV scenarios, and fourth for CNG and LNG, but refilling stations are not in the top five items. The inputs, minimum wage (BRL), annual insurance %, refilling time (electric truck) didn't appear in the first sixteen positions of any technology scenario.

3.3. Sensitivity analysis of energy price

Considering the BEV as the highest saving technology scenario compared to the diesel trucks, with fuel costs as the main responsible for the results, an additional sensitivity analysis was performed to check the benefit in several combinations of different diesel and energy prices.

In Table 3 the results are grouped by energy pricing ranging from 100 BRL/MWh to 700 BRL/MWh, and diesel pricing ranging from 4.5 BRL/L to 7 BRL/L. Out of the 78 different combinations tested, 66 presented positive benefit; that is 84.6%.

In Figure 6, the breakeven point of diesel price scenarios of 4.5, 5 and 5.5 BRL/L is highlighted, considering the ones that present scenarios with negative results. For the 4.5 BRL/L curve, there is a positive benefit when energy prices are lower than 430 BRL/MWh. For the 5 BRL/L curve, there is a positive benefit when energy prices are lower than 520 BRL/MWh. For the 5.5 BRL/L curve, there are positive benefits when energy prices are lower than 610 BRL/MWh. The other scenarios of diesel price have positive benefits independent of the energy price. The energy price has a significant sensitivity in the results, as seen in the example comparison demonstrated in Figure 6. For instance, using diesel cost curve 4.5 BRL/L, if the energy decreases from 300 to 200 BRL/MWh, which means a 33% reduction, the saving increases from 12.07 to 21.49 million USD, representing a 78% increment.

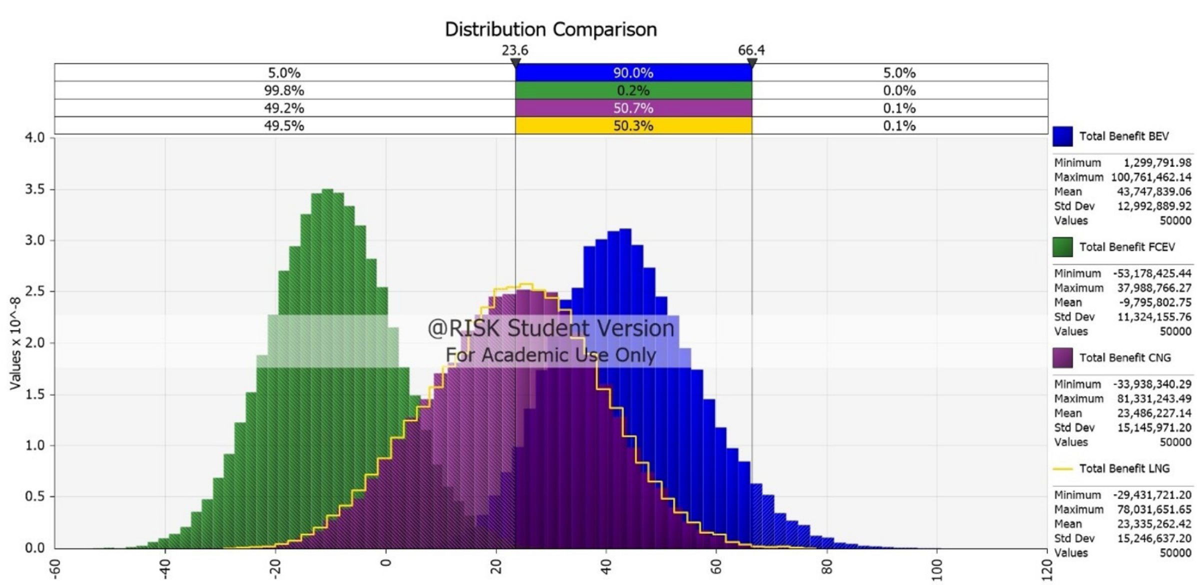

Figure 5. Total benefit probability distribution by the Monte Carlo simulation

Table 2. Monte Carlo simulation model input and output variables.

Rank	Electric	Fuel cell (Hyd)	CNG	LNG
1st	Fuel Cost - Diesel (BRL)	Fuel Cost - Diesel (BRL)	Fuel Cost - CNG (BRL)	Fuel Cost - LNG (BRL)
2nd	Distance (Km)	Fuel cost - FCV (BRL)	Fuel Cost - Diesel (BRL)	Fuel Cost - Diesel (BRL)
3rd	Electric truck cost (USD)	Fuel cell truck cost (USD)	Distance (Km)	Distance (Km)
4th	Fuel cost - Elect (BRL)	Operational efficiency (%)	CNG truck cost (USD)	LNG truck cost (USD)
5th	Consumption factor on/off road (%)	Distance (Km)	Diesel truck cost (USD)	Diesel truck cost (USD)
6th	Operational efficiency (%)	Diesel truck cost (USD)	Consumption factor on/off road (%)	Consumption factor on/off road (%)
7th	Diesel truck cost (USD)	Consumption factor on/off road (%)	Maintenance cost CNG (USD/Km)	Maintenance cost Diesel (USD/Km)
8th	Carbon credit cost (BRL/ton)	Loading time (h)	Maintenance cost Diesel (USD/Km)	Maintenance cost LNG (USD/Km)
9th	On road loaded (Km/h)	Carbon credit cost (BRL/ton)	Filling station cost	Filling station cost
10th	Loading time (h)	On road loaded (Km/h)	Operational efficiency (%)	Operational efficiency (%)
11th	Maintenance cost Diesel (USD/Km)	Maintenance cost FCEV (USD/Km)	On road loaded (Km/h)	Off road loaded (Km/h)
12th	Filling station cost	Maintenance cost Diesel (USD/Km)	Loading time (h)	Loading time (h)
13th	On road empty (Km/h)	On road empty (Km/h)	Truck payload (ton)	On road loaded (Km/h)
14th	Unloading time (h)	Unloading time (h)	Unloading time (h)	On road empty (Km/h)
15th	Off road loaded (Km/h)	Filling station cost	Refilling time - Dies(h)	Truck payload (ton)
16th	Maintenance cost BEV (USD/Km)	Off road loaded (Km/h)	On road empty (Km/h)	Off road empty (Km/h)

Input Related Group

- General Premisses
- Investments - CAPEX
- Operational Costs - OPEX
- Cycle time

Table 3. Total Benefit of Electric trucks in different energy and diesel prices.

	4.5 BRL/L	5 BRL/L	5.5 BRL/L	6 BRL/L	6.5 BRL/L	7 BRL/L
100 BRL/MWh	30,903,517	39,583,886	48,264,256	56,944,625	65,624,995	74,305,364
150 BRL/MWh	26,194,416	34,874,786	43,555,155	52,235,525	60,915,894	69,596,264
200 BRL/MWh	21,485,316	30,165,685	38,846,055	47,526,424	56,206,794	64,887,163
250 BRL/MWh	16,776,215	25,456,585	34,136,954	42,817,324	51,497,693	60,178,063
300 BRL/MWh	12,067,115	20,747,484	29,427,854	38,108,223	46,788,593	55,468,962
350 BRL/MWh	7,358,014	16,038,384	24,718,753	33,399,123	42,079,492	50,759,862
400 BRL/MWh	2,648,914	11,329,283	20,009,653	28,690,022	37,370,392	46,050,761
450 BRL/MWh	(2,060,187)	6,620,183	15,300,552	23,980,922	32,661,291	41,341,661
500 BRL/MWh	(6,769,287)	1,911,082	10,591,452	19,271,821	27,952,191	36,632,560
550 BRL/MWh	(11,478,388)	(2,798,018)	5,882,351	14,562,721	23,243,090	31,923,460
600 BRL/MWh	(16,187,488)	(7,507,119)	1,173,251	9,853,620	18,533,990	27,214,359
650 BRL/MWh	(20,896,588)	(12,216,219)	(3,535,849)	5,144,520	13,824,890	22,505,259
700 BRL/MWh	(25,605,689)	(16,925,319)	(8,244,950)	435,420	9,115,789	17,796,159

3.4. Return on investment

The ROI was calculated using diesel costs as a baseline to be compared with new technologies (Table 4). All operational and investment costs to calculate the saving comparing technologies were considered. Additionally, the carbon credit benefit was included in total benefit for BEV and FCEV technologies. The calculation resulted in negative results for all scenarios, except in the LNG solution with a ROI of 81%, from an estimated investment of 17.4 million USD and a return of 31.4 million USD. The BEV ROI result was -4%, from an estimated investment of 46.3 million USD and a return of 44.4 million USD. The CNG ROI result was -8%, from an estimated investment of 17.4 million USD and a return of 16 million USD. The FCEV gave the worst result, with ROI -123%, from an estimated investment of 49 million USD and a negative return of -11.3 million USD.

Table 4. Return on Investment calculation of different technologies compared to diesel.

Item	Unit	Diesel	Electric	Fuel cell	CNG	LNG
General Premises						
Total distance	Km	112,785,863	112,785,863	112,785,863	112,785,863	112,785,863
Total volume	Ton	36,655,405	36,655,405	36,655,405	36,655,405	36,655,405
OPEX						
Fuel Cost	USD/lifetime	95,484,065	13,185,481	61,825,439	61,727,072	46,295,304
Maintenance cost	USD/lifetime	18,948,025	13,534,304	18,948,025	18,948,025	18,948,025
Insurance cost	USD/lifetime	739,500	1,953,630	2,035,800	1,087,500	1,087,500
Manpower cost	USD/lifetime	70,920,247	71,898,458	70,920,247	70,920,247	70,920,247
Total Opex (5 years)	**USD**	**186,091,837**	**100,571,873**	**153,729,511**	**152,682,844**	**137,251,076**
Total cost per Km	**USD/Km**	**1.65**	**0.89**	**1.36**	**1.35**	**1.22**
Total cost per ton	**USD/ton**	**5.08**	**2.74**	**4.19**	**4.17**	**3.74**
CAPEX						
Truck cost	USD/lifetime	24,650,000	65,121,000	67,860,000	36,250,000	36,250,000
Filling station cost	USD/lifetime	-	5,880,000	5,800,000	5,800,000	5,800,000
Total CAPEX (5 years)	**USD**	**24,650,000**	**71,001,000**	**73,660,000**	**42,050,000**	**42,050,000**
Total cost per Km	**USD/Km**	**0.22**	**0.63**	**0.65**	**0.37**	**0.37**
Total cost per ton	**USD/ton**	**0.67**	**1.94**	**2.01**	**1.15**	**1.15**
CAPEX + OPEX						
Total cost per Km	USD/Km	1.87	1.52	2.02	1.73	1.59
Total cost per ton	USD/ton	5.75	4.68	6.20	5.31	4.89
Total cost in 5 years	USD	210,741,837	171,572,873	227,389,511	194,732,844	179,301,076
Difference cost (fuel saving cost)			**39,168,964**	**(16,647,674)**	**16,008,993**	**31,440,761**
Carbon credit benefit						
Diesel emissions (entire chain)	kg CO2eq/L	3.41				
Total Fuel consumption (fleet 5 years)	L	84,199,584				
Total diesel emissions (5 years)	T CO2	287,121				
Carbon credit cost	USD/T	18.56				
Total benefit carbon credit	**USD**		**5,328,011**	**5,328,011**		
ROI Calculation						
Total Benefit (fuel saving costs + carbon credit)	USD		44,496,975	(11,319,663)	16,008,993	31,440,761
Investment (new technology - diesel)	USD		46,351,000	49,010,000	17,400,000	17,400,000
ROI	**%**		**-4%**	**-123%**	**-8%**	**81%**

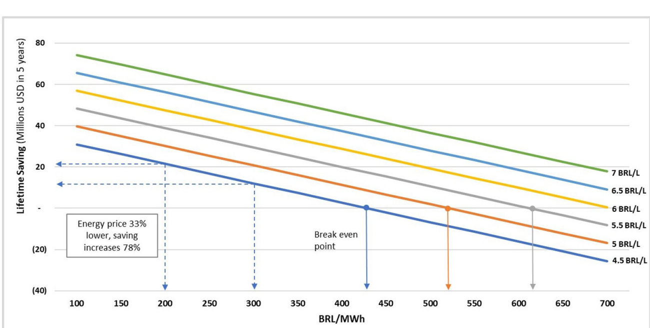

Figure 6. Breakeven point of different diesel price scenarios

4. DISCUSSION

The results present the lower TCO per kilometer from BEV, lower than the diesel, used as a technology baseline comparison in this study. This is mainly due to the lower cost of fuel compared to diesel, despite of the higher acquisition cost. A TCO study for alternative solutions implementations in Europe presents a BEV with higher cost compared to diesel for the 2023 application scenario. The same study gave a lower cost for BEV, but for application in 2030, due to the estimated decrease in investment cost (Basma & Rodríguez, 2023). The reason is because the forest application already presents lower cost using BEV, due to much lower energy cost, considering the pulp mill as the energy generator and supplier. Other studies commonly use standard energy market costs. The static result from TCO present lower cost of CNG and LNG trucks, compared to the diesel, in the same way as BEV; even when having higher investment cost, because the fuel cost is lower than diesel. However, in this analysis the pulp mill as the fuel supplier was not considered; only the investment cost of the filling station adaptation to gas. For the mill integration the "green" gas generation is possible, but it would require more complex changes and higher investments in the mill. Therefore, this technology scenario is subjected to the gas availability close to the using point and price fluctuation.

Consistent with findings from other studies (Xie et al., 2023; International Energy Agency, 2023a), the total cost of ownership (TCO) for fuel cell electric vehicles (FCEVs) remains higher than that of conventional diesel trucks. This is primarily due to significantly higher capital costs for fuel cell trucks and associated infrastructure, which are not sufficiently offset by savings in fuel expenses or the value of carbon credits (International Energy Agency, 2023b). Similar to gaseous fuels such as CNG and LNG, the fuel supply chain for hydrogen is more complex and less mature compared to diesel or electricity (International Renewable Energy Agency, 2022).

Battery electric vehicles (BEVs) show a lower TCO on average, as also noted in McKinsey & Company (2022) and CALSTART (2021) but exhibit a negative return on investment (ROI) in this study. This implies that the total financial and environmental benefits fall short of the total investment costs. CNG trucks present an ROI like BEVs: although they offer fuel cost savings compared to diesel, these savings are modest and offset by mid-range vehicle prices—positioned between diesel and BEV options. FCEVs report the most negative ROI; a result of their combination of the highest upfront costs and a relatively small differential in fuel cost compared to diesel, as observed in studies by the ICCT (Xie et al., 2023) and U.S. Department of Energy (2023).

Sensitivity analysis reveals considerable variability in TCO and, consequently, total benefits across all technologies—ranging from 1 to 5 times the average results. This aligns with findings from World Energy Council (2022), which emphasized the critical role of uncertain parameters (e.g., fuel prices, infrastructure availability, and vehicle utilization rates) in shaping outcomes. Notably, BEV scenarios demonstrate only positive variation, highlighting their potential resilience to input variability. These results underscore the importance of detailed planning and risk management when evaluating technology adoption, especially under conditions of high input uncertainty.

Despite the negative ROI observed in the current analysis, battery-electric vehicles (BEVs) remain the most promising diesel replacement in the medium term—typically defined in energy transition literature as a 5-to-10-year period—due to their lower total cost of ownership, operational efficiencies, and robust outcomes in sensitivity analyses. This trend is noticed by expert's opinion and confirmed by the market movement. It seems the market is not moving in a disruptive way as per international agreements and governments targets, with logistics still having the lowest renewable utilization sharing in 2023 (REN21, 2023). The technology transition is complex not only about technology readiness, but also related to market scale, refilling infrastructure and others. However, the market movement towards low emission solutions is slow, but consistently moving upwards. In a six years old study from McKinsey consultancy, which mapped parity of diesel and electric trucks, especially in the light duty category for ten years (McKinsey & Company, 2017). Nevertheless, from that moment until nowadays, several brands already offer solutions for heavy duty category off the shelve with more than 60 tons GVW and a performance at around 500 kilometers.

Considering that the implementation's region characteristics must influence the cost benefit, in Brazil the HVO should be considered as a potential alternative. The HVO can be produced from renewable sources, as wasted cooking oil, but also from an important Brazilian vocation: biomass from residues of eucalyptus plantation and animal fats considered as a drop-in fuel, which does not require any changes in vehicles configuration (Petry et al., 2021). Despite Brazil's abundant renewable sources, the adoption of Hydro-treated Vegetable Oil (HVO) faces significant barriers. The main challenges include the absence of regulatory recognition by ANP, which currently does not authorize HVO commercialization, and the lack of inclusion in the RenovaBio program, preventing access to carbon credits (Petry et al., 2021; Greenea, 2021). Additionally, there are no HVO production facilities in operation, and required refinery upgrades demand high investment with little policy support or market certainty. The fuel distribution infrastructure is also unprepared for HVO, and domestic demand remains low due to limited awareness and no price advantage over conventional fuels. Moreover, Brazil's feedstocks are often diverted to biodiesel or exported to regions with established HVO markets, like Europe and Asia, which have clear mandates and incentives (International Renewable Energy Agency, 2021). These factors together limit the scalability and economic viability of HVO, despite its technical advantages as a drop-in renewable diesel.

5. CONCLUSION

The results show that technologies with better TCO per kilometer, especially the Electric truck option, have the lowest cost per kilometer. There are several factors influencing the cost benefit of technology replacement; such as items related to investments and operational costs, with fuel costs and distance being the main ones. Despite lower TCO, the Electric truck option has a negative ROI, meaning the investment is higher than the benefits. The second lowest TCO compared was the LNG solution, which was the only one having positive ROI. However, the latter seems to be the less likely scenario to be implemented, due to higher complexity of fuel supply in Brazil and fewer manufacturers with that option. The carbon credit increases total benefits but cannot be a feasible solution as a standalone factor. It is important to consider the high sensitivity from operational costs, especially with regards of electric; as the relation between diesel cost and pulp mill energy potentially can change from a negative to a positive impact. Although the electric option is still not positive with current investment costs, it has the potential to obtain the first position in renewable trucks option in pulp mill operations in the medium to long term. The electric truck looks like the simplest solution to connect with the energy from pulp mill, to benefit from the surplus generated, and this technology is expected to have the highest market share.

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AUTHOR CONTRIBUTIONS

ACAA: conceptualization, data curation, formal analysis, writing; SPSG: conceptualization, supervision, methodology.