UNIVERSIDADE ESTADUAL PAULISTA
"JÚLIO DE MESQUITA FILHO"
INSTITUTO DE PESQUISA EM BIOENERGIA

PROGRAMA INTEGRADO (UNESP, USP E UNICAMP) DE PÓS-GRADUAÇÃO EM BIOENERGIA

A TOTAL COST OF OWNERSHIP COMPARISON OF LOG TRUCK DECARBONIZATION IN PULP MILLS SUPPLY CHAIN

ÂNGELO CONRADO DE ARRUDA MOURA

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Tese apresentada ao Instituto de Pesquisa em Bioenergia de Rio Claro, Universidade Estadual Paulista, com parte dos requisitos para obtenção do título de Doutor em Ciências.

Orientador: Prof. Dr. Saulo Philipe Sebastião Guerra
Coorientador: Prof. Dr. Humberto de Jesus Eufrade Júnior

March
2024

M929t

Moura, Ângelo Conrado de Arruda

A total cost of ownership comparison of log truck decarbonization in pulp mills supply chain / Ângelo Conrado de Arruda Moura. -- Rio Claro, 2024

81 p.

Tese (doutorado) - Universidade Estadual Paulista (UNESP), Instituto de Pesquisa em Bioenergia, Rio Claro

Orientador: Saulo Philipe Sebastião Guerra

Coorientador: Humberto de Jesus Eufrade-Júnior

1. Log hauling. 2. Pulp mill. 3. Carbon emissions. 4. Renewable energy. 5. Monte Carlo simulation. I. Título.

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CERTIFICADO DE APROVAÇÃO

Título: A total cost of ownership comparison of log truck decarbonization in pulp mills supply chain

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Rio Claro, 28 de março de 2024.

I dedicate this work to my beloved wife, Ludmila, and my son Antonio.

ACKNOWLEDGMENTS

Gratitude fills my heart as I acknowledge the invaluable support and blessings that have illuminated my journey:

Firstly, to the divine for the boundless grace and blessings that have surpassed my expectations.

To my cherished wife, Ludmila, whose unwavering love, care, and belief in me have been my guiding light through every endeavor.

To my son, Antonio, a precious gift from above, whose presence brings boundless joy to our lives.

To my late father, Dorival, and my mother, Vera, for their unwavering dedication and sacrifices in nurturing and providing me with endless opportunities.

To my mentor, Ph.D. Professor Saulo Philipe Sebastião Guerra, whose friendship, guidance, and unwavering support have been instrumental in shaping my journey.

To Ph.D. Professor Michel Brienzo, for his steadfast support and exemplary leadership in program coordination.

To my co-advisor, Ph.D. Professor Humberto de Jesus Eufrade Júnior, for the guidance and fundamental support in my doctorate.

To the esteemed faculty and staff at Faculdade de Ciencias Agronômicas (FCA/UNESP), for their unwavering availability and support.

To my colleagues in the PhD program, whose camaraderie and collaboration have enriched my experience profoundly.

To all those who contributed through reviews, suggestions, and participation in surveys, your invaluable contributions have been deeply appreciated.

“For the Lord gives wisdom; from his mouth come knowledge and understanding; He stores up sound wisdom for the upright; he is a shield to those who walk in integrity." (Proverbs 2:6-7).

“Success is going from failure to failure without losing enthusiasm.”

(Winston Churchill)

ABSTRACT

Global carbon dioxide (CO_2) emissions from energy combustion and industrial processes have increased by more than 80% in the last 30 years. Many efforts are being made to set policies and international targets to reduce Greenhouse Gas Emissions (GHG). Globally, transport accounts for 30% of final energy consumption and still has only 4.1% based on renewable sources (REN21, 2023). Thus, decarbonization is a critical challenge, especially in long-distance heavy duties vehicles, as non-fossil fuel technologies are not mature enough for large-scale implementation. A broad list of alternative fuel technologies is being developed and gradually introduced, from ethanol, bioDiesel, Hydrotreated Vegetable Oil (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 from the planted forest as the primary and renewable power source, energy self-sufficiency, and generating surplus, usually sold to the market. On the other hand, Diesel consumption in log transportation is the highest in the pulp production chain. Therefore, this study analyzed the potential application of promising low-emission heavy-duty trucks for log transportation in a Brazilian pulp industry integrated into the pulp mill energy generation. Due to the uncertainty of several variables, a sensitivity analysis was performed to check costs and benefits using the Monte Carlo simulation. The results show the Electric truck option with lower Total Cost of Ownership (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. Despite lower TCO, the Electric truck option has a negative Return on Investment (ROI), meaning the investment is higher than the benefits. The Liquified Natural Gas (LNG) solution was the only one that had a positive ROI. Although Electric Heavy Duty Truck (BEV) still does not have a positive ROI, it is the simplest solution to connect with energy from pulp mills and is expected to have the highest market share. Therefore, it can potentially be the first position in renewable truck options in pulp mill 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 (CO2) provenientes da combustão de energia e de processos industriais aumentaram 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). Globalmente, os transportes representam 30% do consumo final de energia e ainda têm apenas 4,1% baseados em fontes renováveis (REN21, 2023). Assim, a descarbonização é um desafio crítico, 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. Uma vasta lista de tecnologias de combustíveis alternativos está a ser desenvolvida e gradualmente introduzida, desde etanol, biodiesel, óleo vegetal hidrotratado (HVO), biometano, gás natural (comprimido ou liquefeito), células eléctricas de hidrogénio, híbridos e veículos totalmente eléctricos. O setor de papel e celulose tem como fonte de energia primária e renovável as fibras de madeira da floresta plantada, autossuficiente em energia e geração de excedentes, geralmente vendidos ao mercado. Por outro lado, o consumo de Diesel no transporte de toras é o maior da cadeia produtiva de celulose. Portanto, este estudo analisou a aplicação potencial de caminhões pesados de baixa emissão para transporte de toras em uma indústria brasileira de celulose integrada 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 a simulação de Monte Carlo. Os resultados mostram a opção de caminhão elétrico com menor Custo Total de Propriedade (TCO) por quilômetro, 1,52 USD/Km; opções de gás GNL, 1,59 USD/Km e GNV, 1,73 USD/Km; Diesel com 1,87 USD/Km e maior custo para Fuel Cell, com 2,02 USD/Km. As principais variáveis que impactaram os resultados foram custos de combustível e distância. Apesar do menor TCO, a opção de caminhão elétrico tem um retorno sobre o investimento (ROI) negativo, o que significa que o investimento é maior do que os benefícios. A solução de Gás Natural Liquefeito (GNL) foi a única que teve um ROI positivo. Embora o Caminhão Pesado Elétrico (BEV) ainda não tenha um ROI positivo, é a solução mais simples para conectar-se à energia das fábricas de celulose e espera-se que tenha a maior participação de mercado. Portanto, pode potencialmente ser a primeira posição entre as opções de caminhões com menor emissão, para operação em fábricas de celulose no médio e longo prazo.

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

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LIST OF ABBREVIATIONS

CO_2 – Global carbon dioxide

GHG – Greenhouse gas emissions

NOx – Nitric Oxide gas

PM – Particulate Matter

COP – United nations climate change conference

NDC – Nationally determined contributions

LT – LEDS-long-term Strategies

NZE – Net zero emissions

IPCC – Intergovernmental panel on climate change

FCEV – Full cell electric vehicles

BEV – Battery electric vehicles

HVO – Hydrotreated vege table oil

ICE – Internal combustion engine

GVW – Gross vehicle weight

HDV – Heavy-duty vehicles

HDT – Heavy-duty trucks

LDT – Light -duty truck

MDT – Medium-duty truck

CNG – Compressed natural gas

LNG – Liquified natural gas

FCV – Fuel cell vehicles

FAME – Fatty acid methyl ester

FT – Fischer-tropsch synthesis

GTL – Gas-to-liquid

BTL – Biomass-to-liquid

TTW – Tank-to-wheel

WTT – Well-to-tank

TCO – Total cost of ownership

ROI – Return on Investment

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1 INTRODUCTION

Global carbon dioxide (CO_2) emissions from energy combustion and industrial processes have steadily increased by over 80% in the last 30 years (IEA, 2022a). Many efforts are being made to set policies and international targets to reduce Greenhouse Gas Emissions (GHG), started mainly by the Paris Agreement, an international treaty on climate change established at the United Nations Climate Change Conference (COP21) in 2015, which set a primary goal to hold the global average temperature increase below 2°C above pre-industrial levels. The countries were committed to communicating their actions to reduce GHG emissions, called Nationally Determined Contributions (NDCs), and formulating Long-Term Strategies (LT-LEDS) (UNFCC, 2015).

Many other global meetings and treaties have been made, from the Paris Agreement to set actions targeting net zero emissions. In November of 2022, the Conference of the Parties of the UNFCCC in Egypt, COP27, took place. Among several discussions around climate change, the carbon economy, and global temperature targets, some of the main announcement results were the Union European, 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 (UNFCC, 2022). Organizations are also discussing and proposing strategies to achieve those targets, as the International Energy Agency (IEA) published 2021 its Net Zero by 2050: A Roadmap for the Global Energy Sector (IEA, 2021).

The sharing of final energy consumption is similarly distributed among three main groups: buildings at 33%, industry at 33%, and transport at 30%. Decarbonization in transport is a significant global challenge, especially in long-distance heavy duties vehicles, as non-fossil fuel technologies are not mature enough for large-scale implementation. However, according to the Renewables Global Status Report, the transport globally still has only 4.1% based on renewable sources, the lowest share among the end-use sector, and represents nearly a third of total final energy consumption (REN21, 2023).

However, several initiatives are under development for vehicles with low carbon emissions. The Energy Policy Act of 1992, U.S. Public Law 102-486, has defined alternative fuels 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, P-Series fuels (USDOT, 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, a widely used renewable fuel made from corn, sugar cane, and other plant materials used in vehicles blended with gasoline. BioDiesel, a renewable fuel produced by vegeTable oil, animal fats, or cooking oil for Diesel engines, is already largely used in some countries. Natural gas is already abundant for domestic use. Hydrogen, used in vehicles known as full cell electric vehicles (FCEV), still in development or demo applications, uses a similar principle as electric ones, storing energy as hydrogen, which is later converted to electricity by the fuel cell. Electricity is used directly in electric-powered vehicles, called Battery Electric Vehicles (BEV) (AFDC, 2023a). There are other emerging options, such as Biobutanol, Dimethyl ether, Methanol, Renewable hydrocarbon biofuels, and Hydrotreated Vegetable Oil (HVO), as a “drop-in” substitute for fossil-Diesel.

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

This industry has made many improvements in the last decades, with its chemical cycle almost closed, becoming energy self-sufficient, and selling surplus power to the market. The planted forest supplies the raw material not just for the pulp, as fiber, but also for energy through biomass (residues, branches, and bark) and the lignin as the primary source burnt in the recovery boiler (in black liquor format). All the improvements and parameters that impacts this well-developed industrial process are well explored in several studies in the literature. With the new energy source trucks being developed, following the demand to reduce gas emissions globally, combined with the energy generation capacity of pulp mills, it may become a great opportunity as a new technology breakthrough to the sector.

General Objective: this research aimed to analyze the potential application of promising low-emission heavy duty trucks for log transportation in a Brazilian pulp industry, integrating the technology into the mill energy scheme.

Specific Objectives:

- Investigate the energy balance in a modern pulp mill to determine the surplus capacity availability and the other destinations that may compete with the use in logistics.
- Understand variability in wood log transportation. How do different routes, drivers, and percentages of paved and unpaved roads impact the transportation cycle, and how do these parameters impact logistics energy efficiency.
- Mapping and analyze the new low-carbon emission truck technologies to understand maturity levels, potential adoption barriers, and feasibility for log transportation. To give a sense of application readiness to the sector.
- Accomplish the calculation for the integrated solution using risk analysis using the Monte Carlo method to mitigate the uncertainty of unknown variables and establish potential feasibility limits.

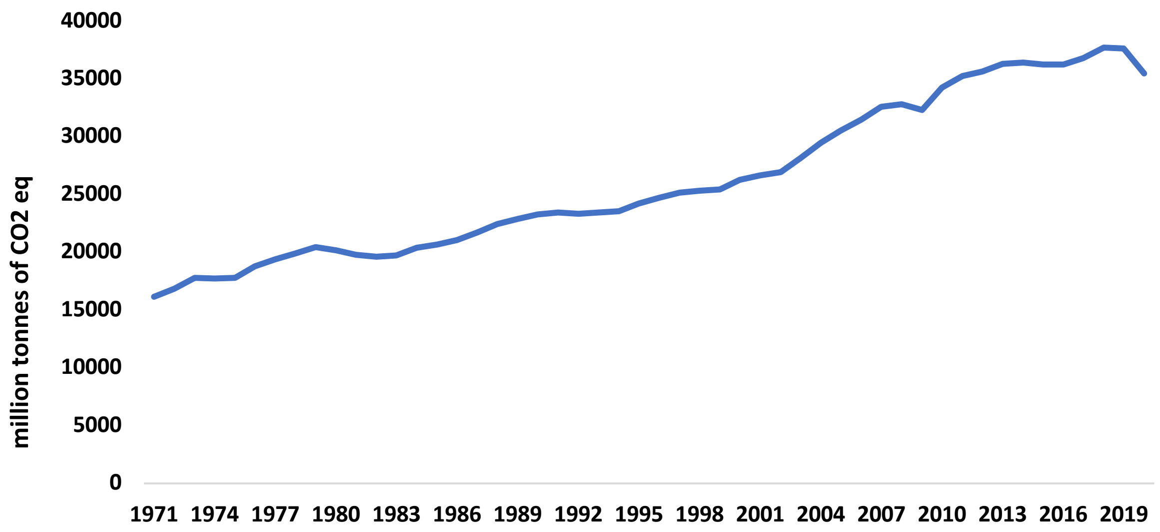
2 LITERATURE REVIEW

2.1 The greenhouse gas emissions challenge

Since the 18th century industrial revolution, humans have searched for power from different fuel sources to meet the world's growing population's needs. Over the years, technology has evolved to increase capacity but has not focused on long-term consequences (SINGULARITY UNIVERSITY, 2019).

According to the International Energy Agency dataset, the GHG emissions from fuel combustion have steadily increased, accounting for a 52% increase in the last 30 years of this time series (1990-2020), Figure 1.

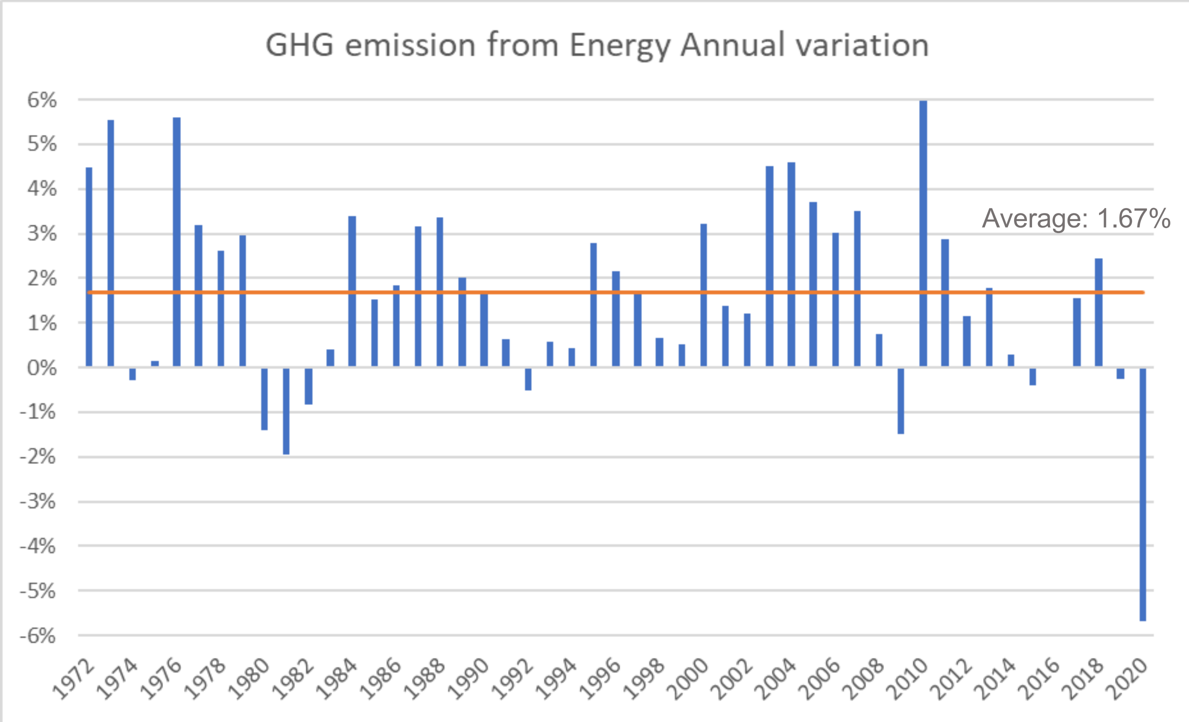
Figure 1. Greenhouse Gas Emissions (GHG) total emissions from energy



Source: Prepared by the author (IEA, 2022c).

However, the annual average increment had more variation, with some peaks, positive, like 5.96% from 2009 to 2010, and negative -5.68% from 2019 to 2020. The annual average for the whole period is 1.67%, Figure 2.

Figure 2. Greenhouse Gas Emissions (GHG) emissions from energy, annual variation



Source: Prepared by the author (IEA, 2022c).

Several international agreements involving countries and international organizations have been established to reduce GHG emissions. The first central Conference was the United Nations Conference on the Human Environment, held in Stockholm in 1972. Another remarkable event involving countries in bilateral and multilateral events was crucial in limiting emissions. The Montreal Protocol, realized in 1987, restricts chemicals that can damage the ozone layer, like hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs). The United Nations Framework Convention on Climate Change (UNFCCC) happened in New York in 1992, which set a target for gas emissions reduction for industrialized countries for the first time. The Kyoto Protocol, the world's first GHG reduction treaty, was realized in 1997, with a target of 5% for 2008-2012. The Paris Agreement, one of the well-known ones, happened in 2015, with the primary objective of maintaining the global temperature increase below two degrees Celsius, above pre-industrial levels and trying to limit it to 1.5 degrees. The international groups, as the world's major advanced economies (G7) and significant economies (G20), not exclusively but also addressed GHG emissions reduction.

Additionally, the United Nations annual meetings of UNFCCC, known as COP (Conference of the Parties), bring representatives from different countries to discuss and negotiate on emissions and climate policies. The latest one, COP28, occurred in Dubai, United Arab Emirates, from 30 November until 12 December 2023 (UNFCC, 2023). In COP28, the main resolutions were, calls for an end of all direct and indirect fossil fuel subsidies, at national, EU and global levels, by 2025 the latest, support a global target to triple renewable energy and double energy efficiency by 2030, with a tangible phasing out of fossil fuels, halting all new investments in fossil fuel extraction (EUROPEAN PARLIAMENT, 2023).

During this time, countries have implemented policies targeting GHG emissions reduction, mainly following international treaties. One example of independent action came from the world's biggest economy, the United States, which created a federal law in 1992, The Energy Policy Act of 1992, U.S. Public Law 102-486, to address various aspects of energy production, consumption, and conversation. The wide range of topics includes provisions for energy efficiency, renewable energy, alternative fuels, etc. (USDOT, 1992).

Regarding gas emissions control targets, it is essential to mention Brazil’s commitment to the Paris Agreement, signed in 2015. The Brazilian NDC begins with the positive results already achieved reducing greenhouse effect gases and establishes even more ambitious commitments. Brazil adopted reducing target emissions by 37% by 2025, compared to the levels of 2005, and is suggesting that emissions may be reduced by up to 43% by 2030 (MINISTRY OF FOREIGN AFFAIRS, 2020).

Despite climate change's existential threat to humankind, it can be fought with innovation, creating some economic opportunities. Disruptive innovation has the potential to generate growth, create jobs, and open new avenues for investment. Moreover, climate change can save humanity by accelerating global efforts to reduce greenhouse gas (GHG) emissions (FAYOLLE, 2019).

The global final energy consumption in 2020 presents a well-balanced distribution, with the most significant consumers being industry consumers at 33% and buildings at 33%. The following sectors are Transport, with 30%, and Agriculture, with 3%. The renewables sharing among those sectors are Industry, with the biggest percentage of renewable energy, with 16.8%; second Buildings, and Agriculture, with

15.5%; and last position with Transport, which accounts for only 4.1% from renewable sources (REN21, 2023).

As the energy demand tends to increase and is expected to double by 2050, the energy source also must change shortly. It is projected that renewable energy will account for more than 50% of the power supply post-2035, a break from past fossil fuel-based generation (MCKINSEY, 2019).

The renewable energy capacities forecast was reviewed with the largest ever upward due to the first global energy crisis created by Russian's invasion of Ukraine, creating unprecedent opportunities for renewables. The estimates are to grow over 2022-2027 by almost 2400 GW, which is equal to China's capacity in 2022. The estimate is that renewable energy will increase by over 10% in the forecast period, reaching 38% in 2027 and becoming the largest source of energy (IEA, 2022b).

Energy demand comes from different sectors; manufacturing is the largest energy consumer. Modern manufacturing with robots, assembly lines, and smart supply chains demonstrates that the future trend of energy demand share must not change. Therefore, the energy cost is also crucial for business, which drives the need for renewable energy, becoming feasible when innovations in clean energy are moving toward a world powered by 100% renewable energy sources (SINGULARITY UNIVERSITY, 2019).

According to IEA report, Tracking Clean Energy Progress 2023, in the 2023 edition 3, is considered fully "on track", which means the realization progress to achieve net zero CO_2 is according to the IEA's Net Zero Emissions by 2050 Scenario (NZE). Not all components are entirely on track at the global level, but the progress of clean energy is considered to be on apparent acceleration. For instance, Global Electric vehicle sales grew by 55%, more than 10 million units, with manufacturing capacity sufficient to achieve 2030 requirements; Nuclear capacities was added by 40%, with new 8 GW installed; Heat pumps reached 11% sales growth; Electrolyser, installed capacity increase more than 20%, with potential to reach 3 GW in 2023; finally, the Energy efficiency of the economy grew more than twice of previous year level. Despite fast progress, in areas where clean energy technologies are already available, with costs falling, a complete transition to net-zero will all areas decarbonizing and rapid innovation to bring to market clean technologies. Especially in areas where emissions are more complex to address, such as heavy industry and long-distance transport (IEA, 2023a).

2.2 The road transportation background

Road transportation represents, by far, the leading freight modal. In the U.S. market in 2022, trucking freight accounts for 65% of total freight weight and 73% of the total value, 8.5 times higher than railed volume (USDOT, 1992).

Truck classifications are typically based on the maximum loaded weight of the truck, typically using the gross vehicle weight rating (GVWR). In the U.S., are considered heavy-duty trucks weighing more than 11.8 tonnes, class 7, from 11.8 to 14.96 tonnes, and class 8, for more than 14.96 tonnes (AFDC, 2023b). In Europe, Category N is the classification for vehicles having at least four wheels and for good transportation. The Heavy-Duty trucks are N2, vehicles not exceeding 12 tonnes, and N3, vehicles exceeding 12 tonnes (EUROPEAN COMMISSION, 2023). Table 1, from the IEA publication, presents a comparison summary of categories in different countries.

Table 1. Trucks classification in the United States, European Union, China, and Japan

United States		European Union				China		Japan			
Vehicle Category	Weight (t)	Vehicle Category	Weight (t)	Trailers & semitrailers	Weight (t)	Trucks Weight (t)	Tractors Weight (t)	Trucks Category (t)	Weight (t)	Tractors Category	Weight (t)
		N1	< 3.5								
2b	3.86 - 4.54	N2	3.5 - 12	O1	< 0.75	3.5 - 4.5	3.5 - 18	1-4	3.5 - 7.5		
3	4.54 - 6.35					4.5 - 5.5					
4	6.35 - 7.26			O2	0.75 - 3.5	5.5 - 7					
5	7.26 - 8.85					7 - 8.5		5	7.5 - 8		
6	8.85 - 11.79					8.5 - 10.5		6	8 - 10		
7	11.79 - 14.97			O3	3.5 - 10	10.5 - 12.5		7	10 - 12		
8a	14.97 - 27.22	N3	> 12			12.5 - 16		8	12 - 14	1	< 20
						16 - 20	18 - 27	9	14 - 16		
						20 - 25		10	16 - 20		
8b	> 27.22			O4	> 10	25 - 31	27 - 35	11	> 20		
						> 31	35 - 40				
							40 - 43			2	> 20
							43 - 46				
							46 - 49				
							> 49				

Source: IEA (2017).

In Brazil trucks are classified by weight and number of axles, with weight splited in light, semi-heavy and heavy loads. The light ones are dedicated to urban delivery and semi-heavy and heavy are used in several types. The legislation is defined by National Traffic Council, “Conselho Nacional de Transito (Contran), through legal resolution nº 882/2021 (CONTRAN, 2021). The semi-heavy is called as “Truck”, is a 6x2 with 14 meters length and GVW from 10-14 tons. The heavy duty uses the tractor and trailer, with several configuration depending on number of axles, being the main ones: 2 axles trailer and simple axle tractor, 18.15 meters and GVW 33 tons; 3 axles trailer and simple axle tractor, 18.15 meters and GVW 41.5 tons; 7 axles trailer and doule axle tractor, known as “Bitrem”, 19.80 meters and GVW 57 tons; 9 axles trailer and double axle tractor, know as “Rodotrem”, 30 meters and GVW 74 tons (GESTRAN, 2022).

According to the Global Market Insights consultancy report, the Heavy-Duty Trucks market siz surpassed USD 250 billion in 2022. The mining and oil and gas sector intensifies the demand, especially in the Middle East and Africa. The Diesel-powered heavy-duty trucks dominate with 80% of the industry share in 2022, with main benefits such as higher torque and power for cargo on long distances and availability of a vast network of refueling stations (GMI, 2023).

Transport still has the lowest percentage of renewable energy compared to the other sectors, with only 4.1% (REN21, 2023). The forecast still expected sluggish growth, from 9% in 2020 to 15% in 2027, not in line with the European Union’s expected 29% for 2030. To overcome the gap, countries must implement more aggressive transport decarbonization programs, including biofuels and BEVs (IEA, 2022b).

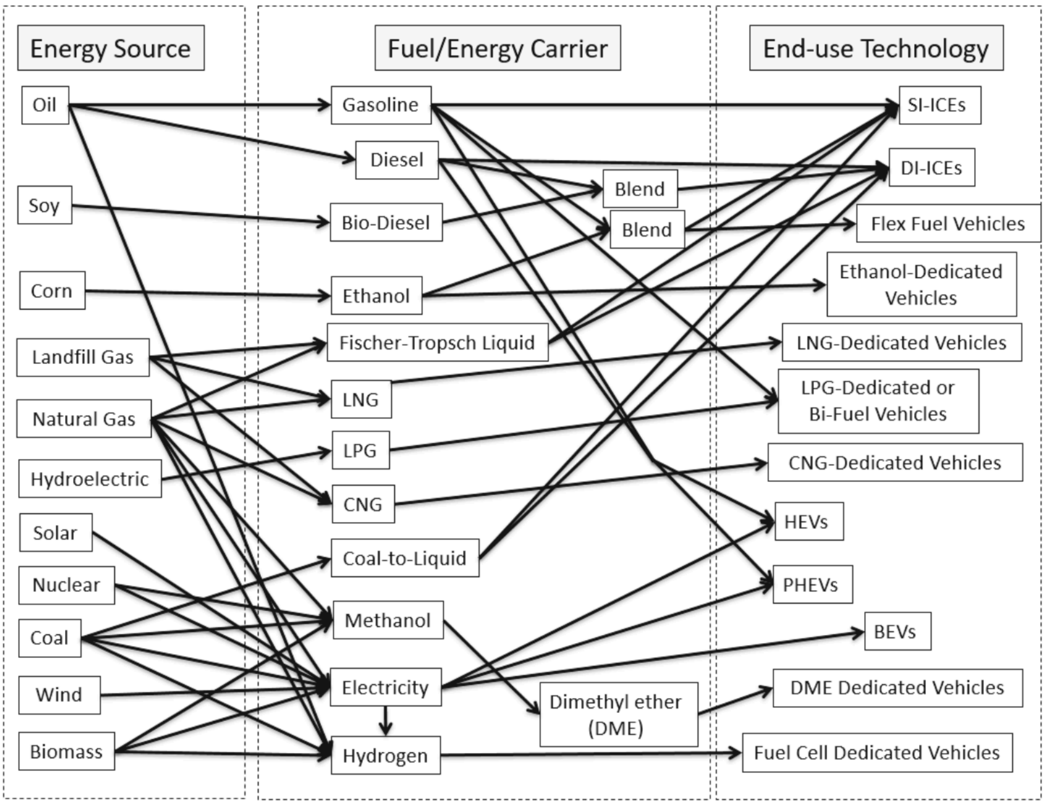
There are several emerging technologies (NASEM, 2020), but they are still immature. Among the many reasons for slow adoption, linked to the challenges of technology development, is the market size. The higher volumes must affect decreasing unit prices. For example, EVs in China cost 9% more than Internal Combustion Engine (ICE) vehicles, whereas in the United States and Europe, it is more than 50% (REN21, 2023).

According to the Mckinsey consultancy report, the new trucks with different sources of power engines are under development at various levels and present a real potential for changing this matrix. The analyses indicate that most commercial vehicles can reach cost parity with Diesel-powered trucks within the next ten years, assuming a continued battery cost and power density improvement. The most cost-effective application seems to be in the light-duty truck (LDT) segment that drives a relatively constant distance of 100 to 200 kilometers per day, which is enough range but avoids high battery costs (MCKINSEY, 2017).

The powertrain comprises the engine and drivetrain, which kinematically couples it to the wheels. The internal combustion engine (ICE), fuelled by Diesel, is the dominant prime mover for Heavy-Duty Vehicles (HDVs).

The type of end-use technology has a broad list which comes from different energy sources. Targeting the reduction of GHG emissions, the life cycle analysis of vehicle/fuel systems is an essential factor to consider. End-use technology emissions must be compared, as well as the full scope of the emissions (or energy) associated with the manufacturing, use, and disposal of HDVs (Figure 3). For example, the GHG emissions from electric HDVs are zero. However, the total GHG emissions along the chain can be higher if the electricity is produced using a substantial amount of mineral coal (TAMAYAO et al., 2015).

Figure 3. Potential fuel and technology pathways for HDVs



Source: NASEM (2020).

Therefore, a broad list of alternative fuel technologies is being developed and gradually introduced, from ethanol, bioDiesel, HVO, biomethane, natural gas (compressed or liquified), electric hydrogen fuel cells, hybrids, and fully electric vehicles. Energy matrix change involves technology development, market acceptance, industry conversion, refilling infrastructure, countries' regulation, and government incentives. Not to mention the traditional fossil fuel lobby and the time it takes for industry adaptation in a healthy economic way, the higher volumes must affect decreasing unit prices.

Natural gas is composed mainly of a mixture of paraffinic hydrocarbons such as methane, ethane, propane, and butane, and its availability and favorable price compared to Diesel are the main factors behind the trends in growth utilization. The Intergovernmental Panel on Climate Change (IPCC) predicts that the most significant energy consumers by 2050 will continue to be North America, followed by Europe and China (STETTLER et al., 2019).

Natural gas is used in two formats: compressed natural gas (CNG) and liquified natural gas (LNG). Compressed natural gas (CNG) heavy-duty vehicles work like gasoline vehicles with internal combustion engines. Many heavy-duty natural gas vehicles have engine functions like gasoline engines, with spark-ignited natural gas systems, but some are like Diesel engines with compression injection. The natural gas is stored in fuel tanks or cylinders, usually behind the vehicle's cab, which is safer but sometimes below the powertrain. The CNG fuel system transfers high-pressure gas from the tank through the fuel lines, with a pressure regulator to control the pressure to a level compatible with the engine fuel injection system. Finally, the fuel is introduced to a manifold or combustion chamber, mixed with the air, and then compressed and ignited by a spark plug (AFDC, 2023a).

BioDiesel fuels, or “renewable Diesel fuels, " are produced through transesterification, separating glycerine from fat or vegeTable oil. It is a mix of Fatty Acid Methyl Esters (FAMEs). The process generates two products: methyl esters, the chemical name for bioDiesel, and glycerine, a product sold for soap fabrication and other products (NASEM, 2020).

BioDiesel fuels are gaining traction with growing utilization, especially in the most significant producer countries, and precisely, Hydrotreated Vegetable Oils (HVO) are a drop-in fuel that can be used in Diesel cycle engines without damage in any proportions. The HVO is produced from the hydrogenation of oils, resulting in a mixture of paraffin-based hydrocarbons, free of sulphuric and aromatic compounds, with a high cetane content. The HVO can also be produced from biomass through a Biomass-to-liquid process via Fischer-Tropsch (FT) synthesis when lignocellulosic materials such as wood biomass can be converted into syngas by gasification. Finally, the gas is transformed into a long chain of hydrocarbons by FT synthesis, and then hydrotreatment or hydrocracking is required as the final refining step to obtain the fuel (PETRY; MOURA; FRANIECK, 2021).

The HVO cold properties can be adjusted to local requirements by changing the process severity or by additional catalytic processing. The cetane number of HVO is very high, and other properties are very similar to the gas-to-liquid (GTL) and biomass-to-liquid (BTL) Diesel fuels produced by Fischer-Tropsch (FT) synthesis, as seen in Table 2.

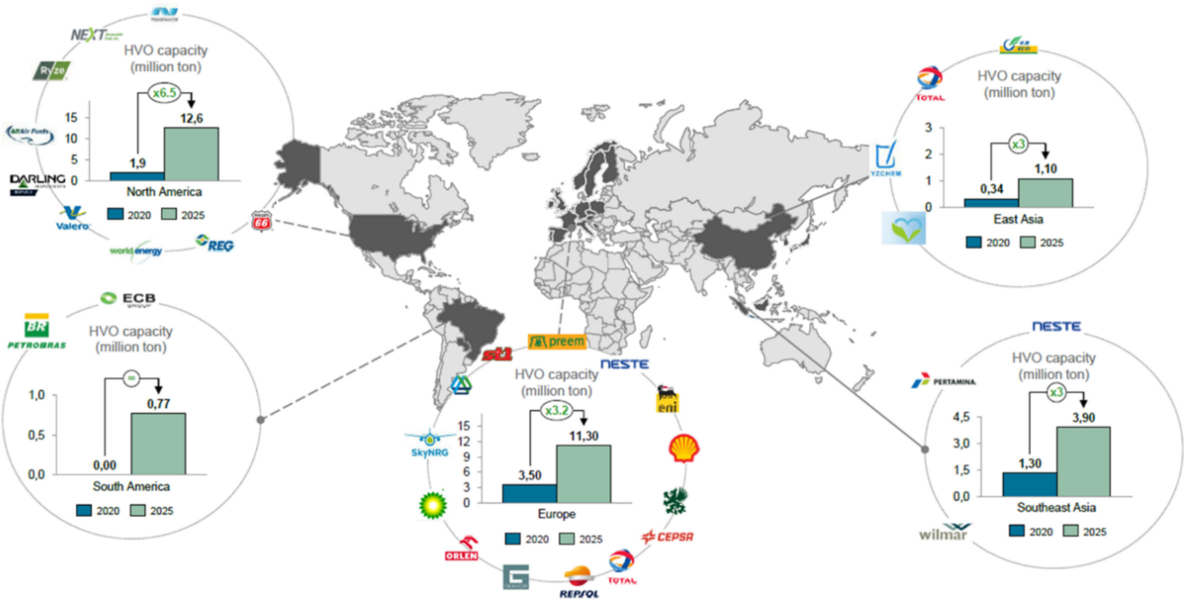
Table 2. HVO typical properties, European EN 590:2004 Diesel, and FAME

Property	HVO	EN 590 (summer grade)	FAME (from rape seed oil)
Density at 15ºC (kg.m^{-3})	775 … 785	~ 835	~ 885
Viscosity at 40ºC (mm^{2}.s^{-1})	2.5 … 3.5	~ 3.5	~ 4.5
Cetane number	~ 80 … 99	~ 53	~ 51
Distillation range (ºC)	~ 180 … 320	~ 180 … 360	~ 320 … 370
Cloud point (ºC)	-5 … -25	~ -5	~ -5
Heating value, lower (MJ.kg^{-1})	~ 44.0	~ 42.7	~ 37.5
Heating value, lower (MJ.L^{-1})	~ 34.4	~ 35.7	~ 33.2
Total aromatics (wt-%)	0	~ 30	0
Polyaromatics (wt-%)(1)	0	~ 4	0
Oxygen content (wt-%)	0	0	~ 11
Sulphur content (mg.kg^{-1})	< 10	< 10	< 10
Lubricity HFRR at 60ºC (um)	< 460	< 460	< 460
Storage stability	Good	Good	Very Challenging

Source: Aatola et al. (2008).

The HVO global production in 2019 was 7 billion liters and is expected to continuously increasing, mainly from Singapore and the United States. In Europe, bioDiesel production might decrease as the storage capacity is already saturated, and the price has fallen quicker than the cost of feedstocks, challenging bioDiesel production. In this way, most of the production from France, Germany, Spain, and the Netherlands might come from HVO (Figure 4). New HVO plants are projected to increase by 2025, triple in the Europe Union and Asia and six times in the US compared to 2020 (GREENEA, 2021).

Figure 4. Installed and announced HVO production units



Source: Greenea (2021).

Hydrogen fuel cells are electric vehicles that use hydrogen stored in pressurized tanks, with onboard fuel cells for power generation. The fuel cell vehicles (FCV) powertrains are hybrids because they capture the braking energy in stores in a battery. Hydrogen-powered trucks benefit from higher density when stored in tanks, making the cost less sensitive to weight and range.

The energy density compared with batteries is much higher, six times higher per unit of volume and 300 times by unit of weight (IEA, 2017). The hydrogen can be refueled with two technologies: with gaseous hydrogen, at 350 or 700 bars, with hydrogen in the liquid stage (sLH2), and with cryo-compressed (CcH2) (H2 MOBILITY, 2023).

Regarding the adoption of renewable fuel HDVs, despite some barriers that slow down the targets defined in the international agreements for decarbonization, there is a clear growing trend. For instance, the current electric heavy-duty truck production is dominated by China, with 85% of global sales in 2022 and estimated sales in 52,000 units (including medium-duty), representing 4% of total sales in China. The Chinese electric vehicles are also being sold in other countries, from Latin America, North America, and Europe (IEA, 2023b).

Most batteries are produced in Asia due to their dominance in lithium iron phosphate (LFP) battery chemistries. However, European Union's truck manufactures already started announcing investments in battery production facilities for heavy-duty packs, like Volvo, about a 2.7 GWh plant in Sweden (IEA, 2023b).

For some applications, the average battery capacity has increased from 2019-2022, like transit buses with a 31% increase and shuttle buses with a 45% increase. However, heavy-duty trucks have no clear trend, with only a 6% increase (IEA, 2023b).

The potential application of new truck technologies must be diversified according to the country's energy availability. For instance, the expansion of hydrogen production in 2022-2027 is expected to be led by China, followed by Australia, Chile, and the United States, representing two-thirds of the dedicated capacity for hydrogen production. BioDiesel is expected to grow its consumption at around 22%, 35,000 million liters per year, over 2022-2027, with the United States, Canada, Brazil, Indonesia, and India responsible for 80% of global expansion (IEA, 2022b).

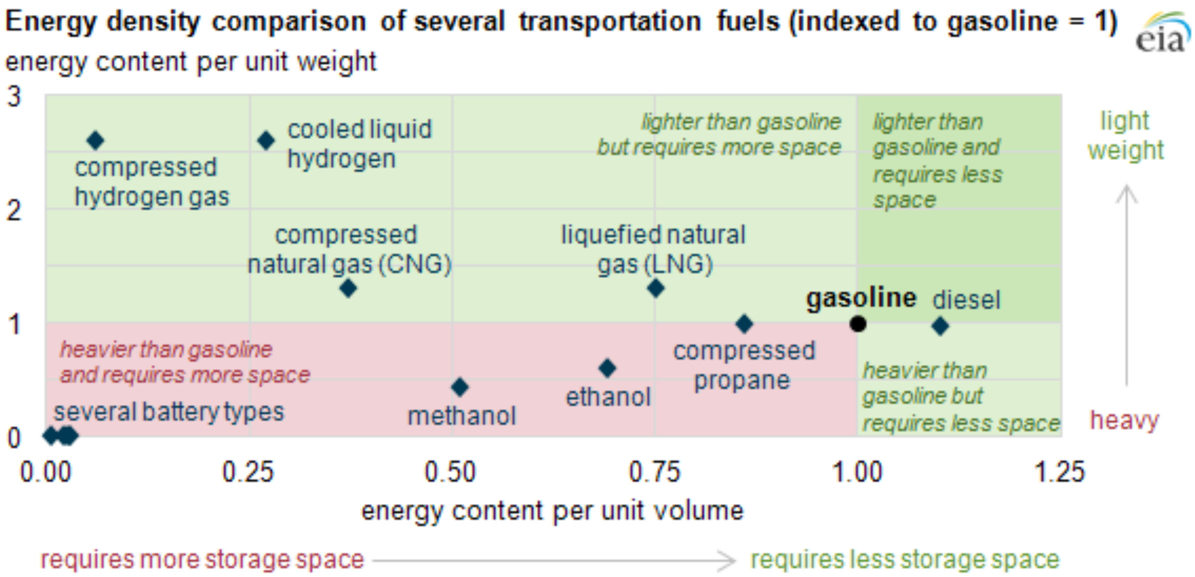
As fuel consumption is a consequence of multiple factors, there is a complexity in defining the influence of each component and defining between several options of new technologies. Besides the engine/powertrain type, other factors affect fuel consumption and GHG emissions, like engine and drivetrain efficiencies and moving constancy, which is affected by highway speed, trailer aerodynamics, and tire rolling resistance (NASEM, 2020). Collier et al. (2019) found that HDVs had lower consumption when running at higher speeds and that driving behavior had an impact. Trucks driving at or below the optimum speed, between 54 and 60 miles per hour, generally displayed better fuel economy.

The research conducted in a Norwegian company by Walnum et al. (2015) explored diverse factors that can influence fuel consumption, such as load weight, trailer type, route, brake horsepower, average speed, automatic gearshift use, cruise-control use, use of maximum torque, use of running idle, driving in highest gear, brake applications, number of stops and rolling without engine load. They concluded that the variables related to infrastructure have a more significant influence, 10 to 12 times higher than the ones attributed to driving behavior. However, when appropriate control is applied to the infrastructure variables, driving behavior can reduce fuel consumption.

Another complexity to lowering fuel consumption is related to the correct power dimensioning, defining the optimum vehicle size for each application, and balancing fuel consumption and transportation demand. Walnum et al. (2015) found an average increase of 0.58 liters per 10 km compared to 700 Hp with 500 Hp. However, the horsepower cannot be undersized, which may cause an increase in consumption because the truck needs to run at nearly 100% torque.

Energy density becomes essential when comparing alternative fuel technologies (Figure 5). The weight and size of storage can compete directly with the payload and space available to transport people and freight. Therefore, large storage, for instance, can make technology less efficient, even considering cheaper fuels (EIA, 2013).

Figure 5. Comparison of the energy density of different fuels



Source: EIA (2013)

Figure 5 presents several fuels' energy densities per weight and volume. The energy per weight of natural gas (CNG or LNG) is close to 15% higher than Diesel, indicating that natural gas can offer less weight for the same amount of energy. However, because of the significantly lower density of natural gas, which is 1,000 times lower than Diesel, it must either be compressed to 200-300 bar (CNG) or liquified through cooling to -162°C (LNG). With that, it increases volumetric energy density to be stored in the vehicle using cylinders. LNG is around 600 times denser than natural, which means it can offer 2-3 times more energy for the same tank capacity, consequently increasing vehicle range. LNG energy content per unit volume is higher than CNG; however, it is lower than Diesel, using more space on the vehicle compared to the traditional Diesel options (STETTLER et al., 2019).

Regarding electric vehicles, the fuel cells powered by hydrogen can double the fuel economy compared to similar gasoline vehicle size. The battery-powered ones can achieve even higher economy rates, around four times Diesel. However, the energy density per volume of hydrogen and various battery types, such as lithium-ion, lithium polymer, and nickel-metal hydride, are still much lower than Diesel, making it not efficient and does not compensate for the fuel economy, limiting the driving range (EIA, 2013).

2.3 Renewable energy emissions

The GHG emissions from biofuels will vary according to each production pathway and related raw material, including the whole supply chain, from cultivation of the feedstock (crop-based) to processing, transport, and distribution.

Considering a near-zero CO_2 emission, biofuels are not the best option because the number of production chains still emit a reasonable amount of CO_2. The liquid and gaseous electrofuels only partially reduce the pollutant Nitric Oxide gas (NOx) and Particulate Matter (PM), despite CO_2 reductions. Nevertheless, the bioDiesel, for instance, increases NOx and decreases PM strongly. The HVO can reduce both NOx and PM emissions. The natural gas vehicles will vary according to the technology used (BREUER et al., 2021).

Table 3 shows the percentage indices of emissions for alternative fuels concerning Diesel parameters of $CO_{2\text{-eq}}$, PMc, and NOx. On TTW emissions (g/Km), there is a reduction trend from Diesel to hybrid Diesel, bioDiesel, HVO, LNG, electric, and hydrogen (KLEIN et al., 2020).

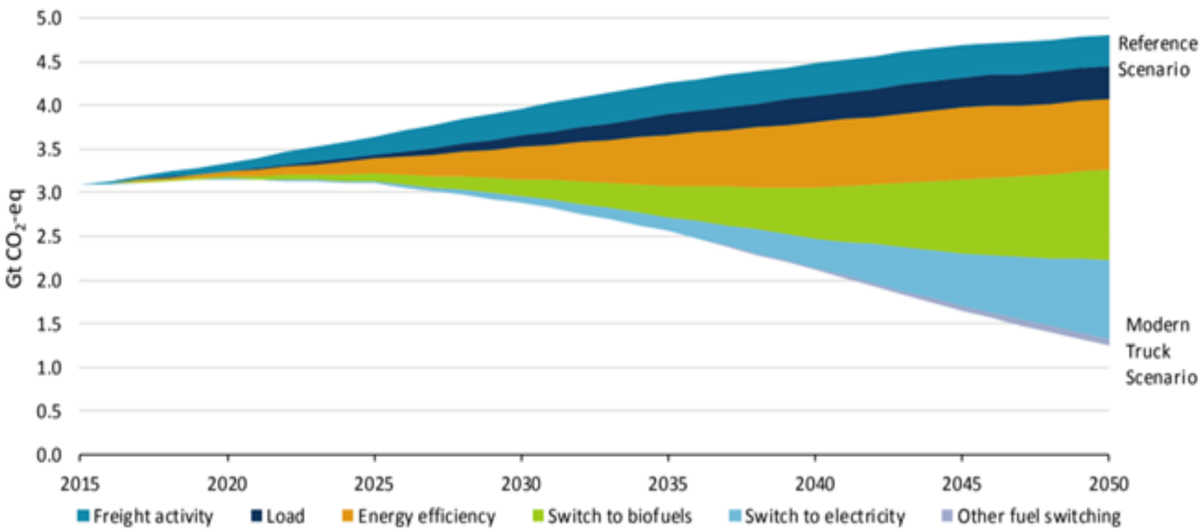
Table 3. Percentage indices for alternative fuels compared with Euro VI vehicles

Fuel/technology	TTW MJ/km	TTW emissions (g/km) CO_2-eq.	TTW emissions (g/km) PM_c	TTW emissions (g/km) NO_x	WTW emissions (g/km) CO_2-eq.	WTW emissions (g/km) PM_c	WTW emissions (g/km) NO_x
Diesel, Euro VI*	12.87	901	0.013	1.634	1186	0,059	2,1
Index of average 2018 diesel rel. to Euro VI							
Diesel, average 2018	99%	99%	211%	175%	99%	123%	159
Index (Euro VI = 100)							
Diesel, Euro V**	H: 95% L: 98%	H: 95% L: 98%	H:270% L:112%	H: 121% L: 216%	H: 95% L: 98%	H: 133% L: 102%	H: 116% L: 201%
Diesel, Euro VI	100%	100%	100%	100%	100%	100%	100%
Diesel, plug-in hybrid, Euro VI	91%***	80%	80%	100%	97%	91%	103%
GTL, Euro V	100%	103%	100%	100%	104%	104%	102%
Biodiesel, Euro VI, 97% FAME-3% HVO	100%	2%	100%	100%	16%	202%	111%
HVO, Euro VI	100%	2%	100%	100%	11%	202%	111%
LNG, Euro VI	113%	97%	100%	50%	91%	49%	58%
BioLNG, Euro VI	113%	6%	100%	50%	36%	50%	51%
Electric, average mix	47%****	0%	0%	0%	70%	48%	29%
Electric, wind/solar	47%****	0%	0%	0%	2%	0%	0%
Hydrogen	71%	0%	0%	0%	80%	294%	59%
Hydrogen, electrolysis with wind/solar/hydroelectric	71%	0%	0%	0%	7%	0%	0%

Source: Klein et al. (2020).

Combining different measures, are expected to reduce emissions of modern trucks by about 50% in 2015-2050 (Figure 6). Around 18% of GHG reductions come from truck activity reduction, 12% from increased loads, the use of biofuels accounting for 25%, and the switch to electricity adding 16% (IEA, 2017).

Figure 6. GHG emissions in the Modern Truck Scenario



Source: IEA (2017).

Table 4 presents some reference values of GHG emissions for various biofuels from the European Union Fuel Quality Directive (FQD) and California's LCFS, expressed in grams of CO_2 equivalent per MJ of fuel (g $CO_{2\text{-eq}}$/MJ). By comparison, emissions from Diesel amount to 74.1 g CO_2/MJ, with an additional 12 g CO_2/MJ to 17 g CO_2/MJ from well-to-tank emissions (IEA, 2017).

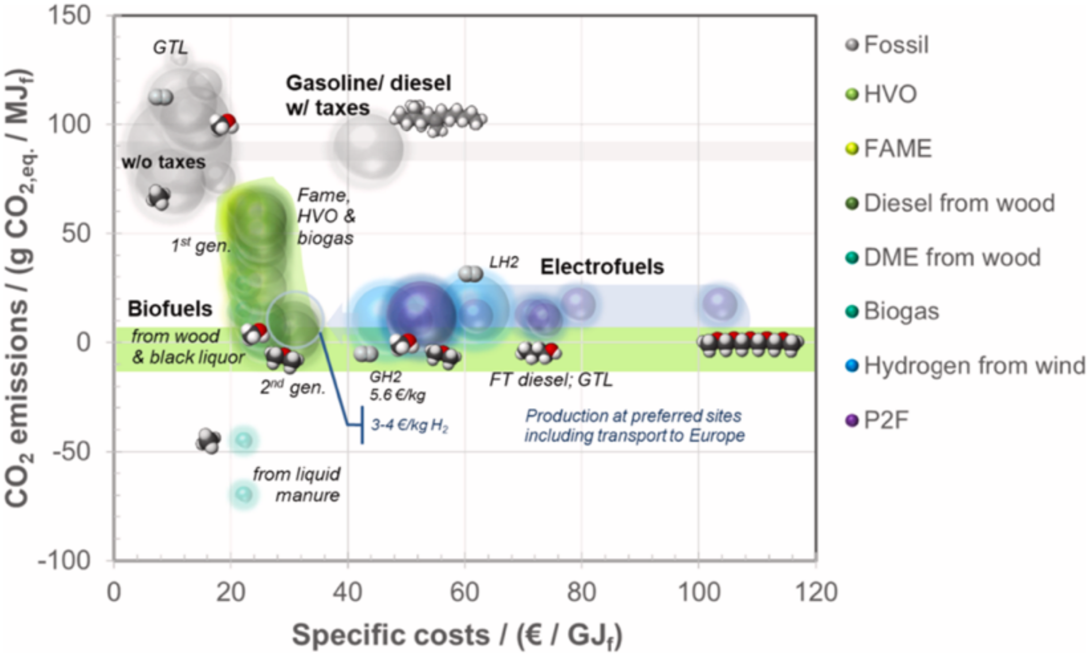
Table 4. Regulatory GHG emissions for biofuels

Fuel (feedstock)	GHG emissions range (g CO2-eq/MJ)		Comment
	EU FQD	California LCFSB	
Biodiesel (crops)	32-54	49-55	EU FQD range dependent on feedstock and process fuel. LCFS values for rapeseed- and soybean-based fuels certified in 2016.
Biodiesel (wastes/residues)	10	< 30	EU FQD value for waste vegetable or animal oil feedstocks. LCFS values for UCO, corn oil and animal fat feedstocks
HVO (crops)	27-50	No data	Rapeseed, sunflower and palm oil feedstocks considered. There is limited use of crop-based HVO within California's LCFS
HVO (wastes/residues)	No data	10-50	UCO and tallow feedstocks. No EU FQD value is available.
Biomethane (anaerobic digestion)	12-17	< 30	EU FQD values for MSW and manure feedstocks. LCFS values for wastewater sludge and dairy biogas
Fuel ethanol (crops)	23-57	20 to > 100	EU FQD values for wheat, corn, sugar beet and sugar cane feedstocks. LCFS values include credits for the production of co-products.

Source: IEA (2017).

The costs of renewable fuels are fundamental in the economic profiles of HDVs. According to Breuer et al. (2021), fossil fuels cost 10-20 euros/GJf, while biofuels are between 20-30 euros, hydrogen at 45, and electrofuels at 53-100 (Figure 7).

Figure 7. CO_2 emissions and costs for different fuels



Source: Breuer et al. (2021).

2.4 Refilling infrastructure of new energy solutions

One crucial factor to be considered in adopting new fuel technologies for HDVs is the refueling time and infrastructure availability to make it sustainable in a regular day-to-day operation, avoiding excessive downtime that can affect transportation cycle time (Van Grinsven et al.,2021).

The LNG refueling stations are rapidly growing, and expansions are planned in several regions, especially in Europe, China, and India, from investments and government incentives, also motivated by LNG and Bio-LNG production increases. In 2022, Europe already accounted for more than 400 stations, with estimates of 750 units by 2025 and more than 2000 by 2030, with Germany having the highest growth from 3 to 70 stations from 2018 to 2022 (VOLVO, 2022).

In India, the Ministry of Petroleum and Natural Gas, with the Society of Indian Automobile Manufacturers Association (SIAM), has planned 1000 new refueling stations for LNG by 2024. One of the actions is to achieve the 15% share of natural gas target in India's energy mix by 2030 (FINANCIAL EXPRESS, 2021).

In 2018, China already accounted for 2.552 refuelling LNG sites, almost 13 times increase from 200 units in 2011 (YUAN, 2019). According to Sharafian et al. (2017), China's LNG refueling infrastructure reported 3.200 units in 2015, with an expressive growth rate from 100 units in 2010.

The U.S. Department of Energy provides complete data on refueling stations for several fuel types (Table 5). The biggest refueling network is Ethanol, with 63.055 units. The new energy sources are BioDiesel (B20) plus Renewable Diesel accounts with more than 2,000 units, CNG and LNG with 1,508 units, and Hydrogen with only 74 units (AFDC, 2023).

Table 5. Available refueling stations in the U.S. per fuel type

Fuel Type	Avaible units
Ethanol (E85)	63055
Propane (LPG)	2777
Biodiesel (B20 and above)	1610
Compressed Natural Gas (CNG)	1411
Renewable Diesel (R20 and above)	571
Liquefied Natural Gas (LNG)	97
Hydrogen	74

Source: AFDC (2023).

Regarding hydrogen, the most prominent initiative to provide refilling infrastructure comes from H2 Mobility Deutschland GmbH, a company established in Germany in 2015. Important players in this sector are shareholders such as Shell, Daimler Truck, Hyundai, Air Liquide, Linde, OMV, and Total Energies. H2's mobility ambition is to enable hydrogen utilization in mobility as the largest refueling station operator worldwide. The first phase goals are to establish the network in seven German metropolitan areas (Hamburg, Berlin, Rhine-Ruhr, Frankfurt, Nuremberg, Stuttgart, and Munich), with stations PV and LDV to refuel up to 8 kg of H_2 at 700 bar CGH_2 for small vehicles, and HDVs with 350 CGH_2 (H2 MOBILITY, 2023).

The BEV refueling requires that the charging is done following the economics of the electric grid by minimizing the demand and maximizing charging during off-peak, low-rate periods. The hardware includes transformers, electrical switchgear, charges plug, civil construction infrastructure, networking, and management via software. The charge types need to match the vehicle needs, as Level 3 DC charging is a broad category that delivers DC instead of AC, eliminating the need for on-vehicle conversion and providing charging at up to 350 kW or higher (NACFE, 2023).

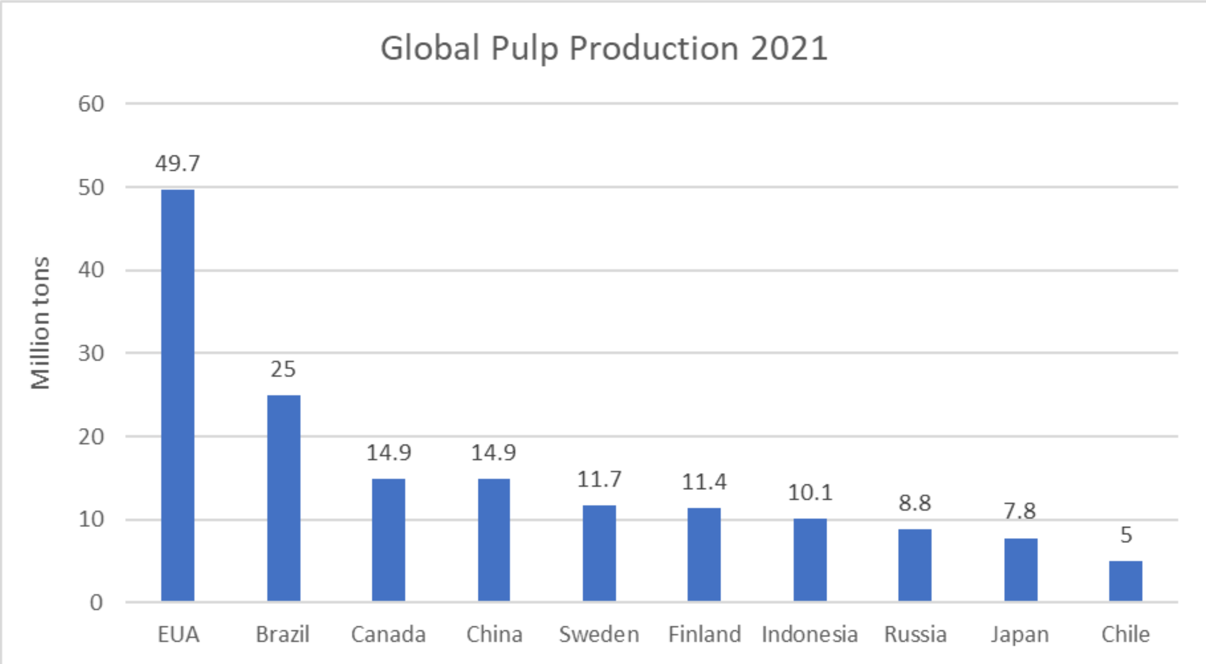
2.5 The planted tree industry and pulp production

According to the FAO (2023), the planted forest represents 3% of the global forest area, covering 131 million hectares. In the past 30 years, from 1990-2020, the planted forest area has increased by 123 million hectares. The highest share of planted forest for commercial use and restoration is in South America, with more than 90%. Tree plantations may produce a broad array of wood-based products for use in the building, commodity, and energy sectors. Despite turning woody biomass into energy is not being used massively because of costs compared to the fossil fuels, predictions points to increase usage of biomass energy in the next decades (GYANARANJAN et al., 2022).

The planted forest sector is very relevant in the Brazilian economy, responsible for 1.3% of Brazil's GDP, with a gross income of 260 billion Brazilian reais in 2022, maintaining historical trend of growth above Brazilian GDP. Account in 2022 with 9.94 million hectares, 76% eucalyptus plantation and 19% pine plantation, performing the highest productivity worldwide, with estimate 32.7 m^3/ha/year (over bark), average cycle of 6.7 years, from Eucalyptus and estimate 30.9 m^3/ha/year (over bark), average cycle of 16.3 years, from Pine. This sector generates 2.6 million jobs, direct and indirect, with activities for industrial purposes in more than 1,000 municipalities. The energy generated in the sector comes from 86% renewable sources, including biomass and black liquor (IBA, 2023).

Brazil's pulp production (Figure 8) reached 25 million tons in 2022, second in the global rank, after the United States which produces approximately 50 million tons. The most significant share comes from short fibers, which is 21.9 million tons. In 2022, Brazil remain the first global pulp exporter, performing US$ 8.4 billion exported, with China and Europe as the main destinations, with 40% and 30%, respectively (IBA, 2023).

Figure 8. Global pulp production 2021



Source: IBA (2023).

Carbon monitoring is implemented in 81% of Brazilian companies through inventories to measure the emissions and retention, from fundamental pillars such as stocked carbon in natural and production forests, removing carbon by planted and natural forests during their growth, avoided emissions by utilization of renewable energies and stocked carbon in wood products. The estimated amount of carbon stocked from 9.94 million hectares of planted forest is 1.82 billion tons of equivalent carbon dioxide. This represents around 38% of total emissions in the United States in one year, 4.7 Gt in 2022, or 60% of yearly emissions of Buildings globally, around 3Gt, 2021 and 2022 (IEA, 2022a). The 6.73 million hectares of natural forests are also used for conservation stocks, plus 2.98 billion tons of CO_{2eq} (IBA, 2023).

2.6 Energy balance in the planted tree industry

The invention of the recovery boiler by G. H. Tomlinson in the 1930s was an important milestone in improving the kraft process. The recovery boiler made it possible to burn the liquor, generate steam, and recover the caustic soda from the process, both essential for pulp manufacturing. With that, kraft mills became a nearly closed-cycle process concerning inorganic chemicals (SALMENOJA, 2019).

The pulp and paper industry has been reinventing itself for a long. In the last decades, it has turned into thermoelectric plants, which collaborate with generating electrical energy for the system in which they are inserted. These changes result from much research into electrical and cellulose production equipment, seeking increased efficiency (Oliveira, 2015).

The proper use and application of energy in the pulp manufacturing process is significant for the modern pulp industries, as nowadays, besides pulp, one of the leading products that generate revenue in this segment is electricity, and its correct use represents higher shareholder turnover for the new business opportunity (CGEE, 2013).

The potential of different uses for energy generated in pulp mills, as integration between industry and forest logistics, is a field not explored yet. Looking to the future, this valuable product, electricity, may find a rival product that will dispute the use of lignin and may cause the reduction of energy sold to the market, but this is only an assumption because the future is unpredictable. Energy conservation remains a top priority for investment made by professionals in this segment (Oliveira, 2015).

In 2022, approximately 93% of total waste generated of companies associated with IBA - Brazilian Trees Industry, was used for energy generation and recycling or reuse. The main destination was for energy generation what accounts of 88%. Besides the direct use for energy generation, the residues after tree harvesting are also left in the field, to improve soil properties protecting from erosion and boosting nutrition. The main residue are the trees barks, branches and leaves with 57.8% (Table 6) of total waste share.

Table 6. Waste generated by type, according to destination, in % of total waste

Waste generated during the production process	Share of Total (%)
Bark, branches and leaves	57.8
Sawdust	21.7
Woodchips	6.6
Black liquor	5.7
Lime Sludge and boiler ash	1.0
Oils, grease, and agrochemical packaging	0.2

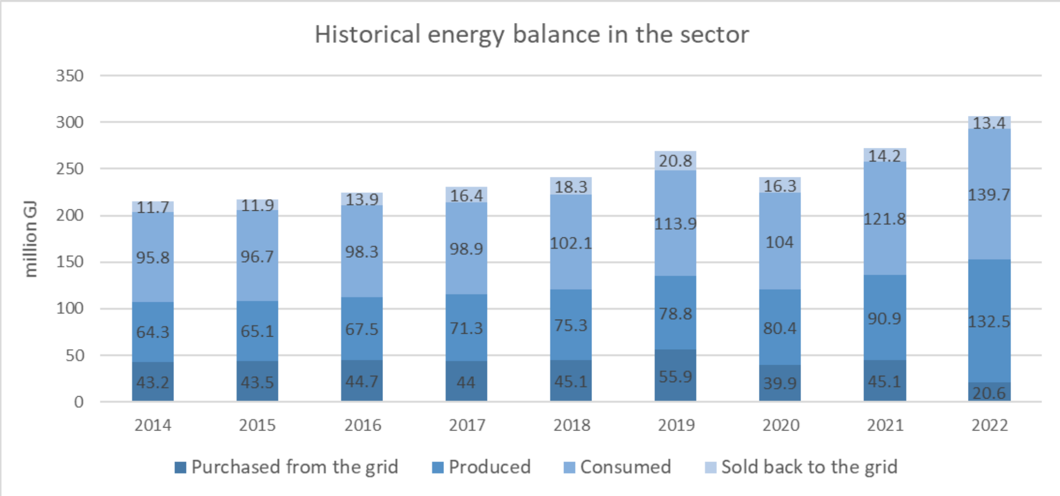
Source: IBA (2023).

Regarding the energy matrix, planted forest in Brazil is a global reference. In 2022 were produced 132.5 million of Giga Joules (GJ), representing 74.6% of total sector demand (121.8 million GJ), selling to the network 14.2 million of GJ, quantity enough to supply a 1.37 million habitant’s city per one year (IBA, 2022).

Most of the pulp industry's energy comes from wood lignin in the black liquor, which is burned in the chemical recovery boiler. Burning this fuel generates thermal energy that is widely used in the pulp manufacturing process for heating and electric power generation (VILLARROEL, 2011).

Figure 9 shows the positive energy balance from the planted tree industry in Brazil. From 2014 until 2022, the energy produced was 75% of total demand, and 39% of the demand was purchased from the grid. Therefore, an energy surplus was sold back to the grid of 136.9 million GJ for the same period, representing 19% of the production (IBA, 2023).

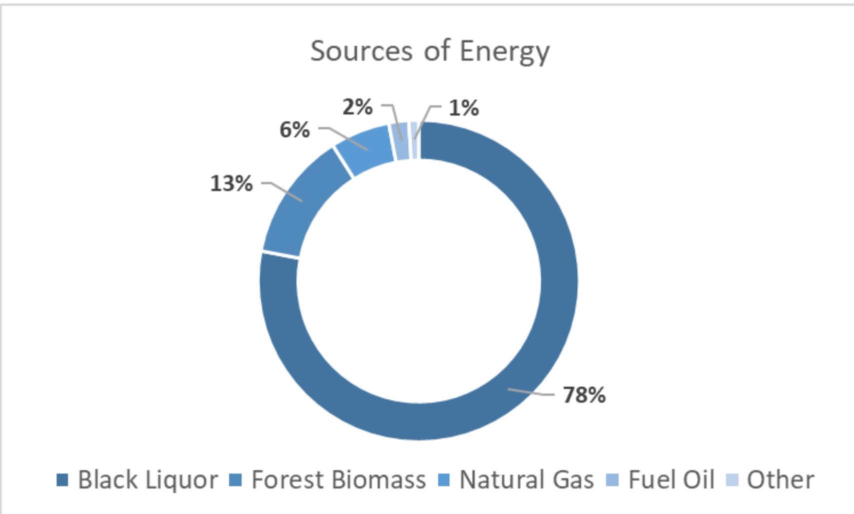
Figure 9. Historical energy balance in the sector, 2014–2022.



Source: IBA (2023).

In 2022, the leading companies in the planted forest industry reported their energy efficiency as part of their agenda. Renewable sources mainly supply the energy share. The primary energy source was an internal residue, black liquor with 78%, followed by forest biomass, with 13% (Figure 10), totaling 91% from renewable sources (IBA, 2022).

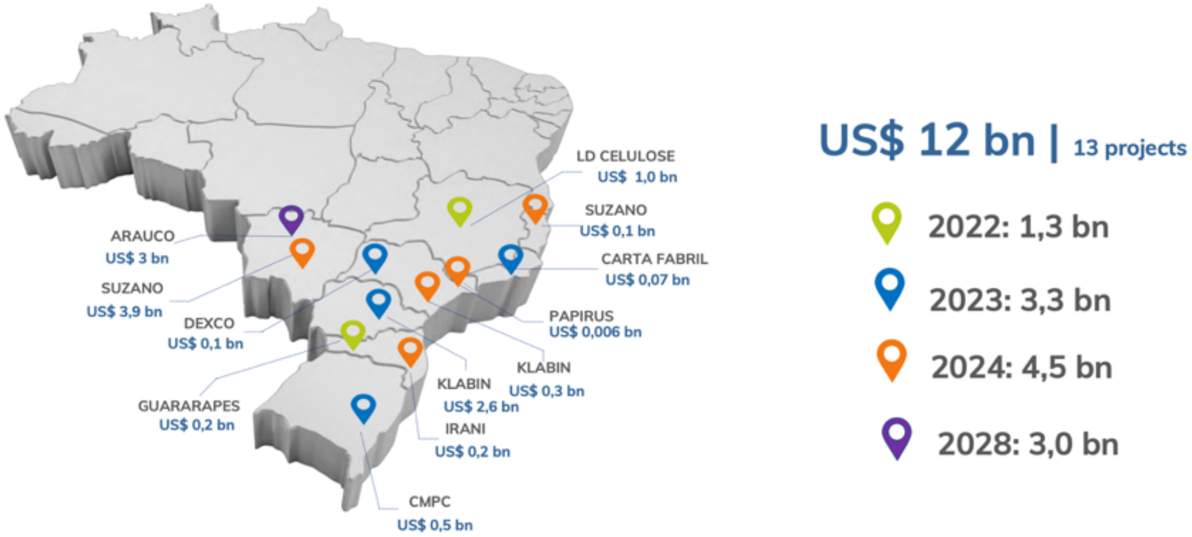
Figure 10. Sources of energy in the planted tree sector in Brazil in 2022



Source: IBA (2023).

The planted tree industry in Brazil is very relevant to the Brazilian economy, mainly pulp and paper production, which is still in expansion. By 2028, it is expected to have at least 13 new plants in operation, which are currently construction in progress, with a total investment in the sector of US$ 12 billion. As seen in Figure 11, the investments are spread in different regions, from central west, central, south, and southeast (MALINOVSKI, 2023).

Figure 11. The forestry sector in Brazil.



Source: Malinovski (2023).

2.7 Monte Carlo simulation

The Monte Carlo method is a mathematical technique used to estimate possible outcomes of uncertain variables, through a computational algorithm that uses ramdon sampling repeatedly to obtain likelihood range of results. The method was invented by John von Neumann and Stanislaw Ulam during World War II, to improve decision making under uncertain conditions (IBM, 2024).

The main steps to perform the Monte Carlo simulation are: establish the mathematical model, from business formulas to scientific equations, to define an equation which combines inputs variables and outputs. Determine the input values, choosing the inputs and it’s probability distributions. Create a large dataset of random samples, of size in a range of 100,000 to produce accurate results. Set up the Monte Carlo software and run the simulation. Analyse the simulated results, using statistical tools to calculate parameters such as mean value, standard deviation (AWS, 2024).

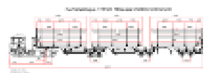
The inputs variables probability distribution can be estimated with historical data or defined using expert opinion, or from previous knowledge (Lumivero, 2024).

3 MATERIALS AND METHODS

3.1 Study object

This study considers the feasibility of replacing heavy-duty Diesel trucks with alternative options with renewable-based energy in a fictious hypothetical pulp mill in the State of Mato Grosso do Sul, Brazil. The pulp mill produces 2.5 million tons annually, with an average surplus energy generation of 180 MWh and an average radium distance from the mill to the field of 80 Km. For log hauling in Brazil is used several composition types, which definition depends on different factos as roads dimensions, slope, paved or unpaved, as per list on Table 7.

Table 7. Composition types used in log hauling in Brazil

Composition Type	**GVW** (ton)	**Tare** (ton)	**Net weight** (ton)	**m3/trip**	**Layout**
"Romeu e Julieta"	56	19	37	46.3	
Bitrem	57	20	37	43.5	
Tritrem	77.7	24	52	63.2	
Pentatrem	120	34.15	85.85	107.3	
Hexatrem	200	53.65	116.35	154.5	

Source: Author (presented on HarvestTech 2021, April 2021 Rotorua, NZ).

For this study was considered the most common tractor and trailer combination used in Brazilian pulp mills, the three-wagon truck well known in Portuguese as “tritrem” (Figure 12). The composition consists of a 6x4 tractor truck at around 440 Hp, with a total gross weight of 74 tons and a total payload of 52 tons.

This application considers two innovation breakthroughs, which will be studied in an integrated way. The new truck technology, identifying the feasibility of main options, existing and most promising ones; and the pulp mill integrated in the wood supply logistics, as the fuel supplier. The pulp mill can generate different fuel types using several pathways, as shown in Figure 3. However, due to the complexity of the mill side, this study will concentrate the analysis only on the scenario of the mill supplying electric vehicles.

Four alternative solutions were considered as replacements 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 12. Three-wagon log truck in Brazil.

Source: Author.

3.2 Methodology

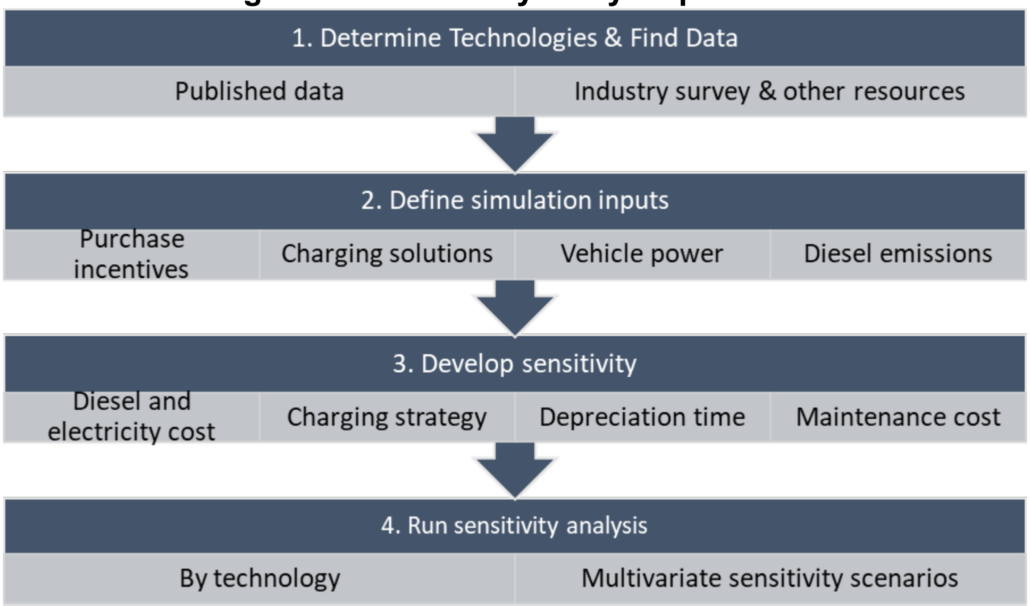
This analysis aims to check the potential feasibility of alternative energy solutions for heavy-duty trucks by simulating different parameters from truck solutions and pulp mill energy information. To achieve this goal, a multivariate analysis was run, comparing the Total Cost of Ownership (TCO) of new truck 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. The impact of CO_2 emissions was also estimated for both cases.

As the historical data of renewable energy HDVs are still not available, it was used the best references from manufacturer technical catalogs and scientific studies to determine the value of main parameters, such as refilling infrastructure, investment costs, estimate energy efficiency, and others, and used the sensitivity analysis to minimize the uncertainty, following Figure 13 scheme.

It was performed a market screening, checking all the manufacturer's options available in the market or under development, reviewing the literature to map initial trials data, and performing an expert survey to map the stage and potential trends on implementation.

The Monte Carlo simulation was done for the sensitive analysis on TCO using @Risk 8.5.2 software, Industrial Edition, Student license, from Lumivero/Palisade. The simulation was run using variations in several inputs, like costs as trucks, fuel, maintenance, insurance, drivers wage, and others related to the operational efficiency, as distance, loading/unloading time, empty or loaded speed, refilling time. It was selected variables that cause higher uncertainty, especially related to the technology maturity and early-stage adoption, to determine the probability of output results and provide the rank of the variable with higher interference. A total of 5 million scenarios were performed from a combination of 100 simulations, and 50,000 iterations were made in each simulation.

Figure 13. Sensitivity analysis process.



Source: adapted from Sattterfield; Nigro (2020).

3.3 TCO parameters

It was used the main variables that influences a truck's TCO, as those related to the technology replacement, like truck and battery cost, the hauling cycle time, and parameters related to the mill production, which influences transport demand and energy supply, as per the list shown in Table 8.

Table 8. Analysis inputs/outputs

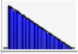
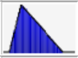
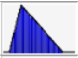
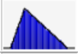
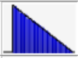
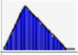
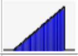
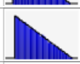
Group	Item	Unit	Source*
Inputs			
General Premises	Truck depreciation	years	Author's previous experience
	Battery lifetime	years	Author's previous experience
	Filling station depreciation	years	Author's previous experience
	Filling station ratio	# trucks/station	Author's previous experience
	Carbon credit cost	$USD/ton	Author's previous experience
	Diesel emissions (entire chain)	kg CO2eq/L	-
	Truck power / model	kWh	-
	Available power for operation (per charge)	kWh	CAMPOS, 2016
	Truck payload	ton	-
Mill demand & Energy Balance	Pulp mill production	Million ton/year	-
	Specific consumption	m^3 wood/ton pulp	FOELKEL, 2017
	Ton x m^3 factor	#	FOELKEL, 2017
	Wood demand ton	ton/year	-
CAPEX (investments)	Truck price	USD	ICCT, 2023a
	Filling station	USD	Author's previous experience
	Additional batteries	USD	Author's previous experience
OPEX (operational costs)	Fuel cost	USD/L, USD/kWh, USD/kg	- ZAPAROLLI, 2013 - Author's previous experience
	Consumption factor on/off road	#	Author's previous experience
	Consumption on road (mix full and empty)	km/L, km/kWh, km/kg, km/m^3	Author's previous experience
	Consumption off road (mix full and empty)	km/L, km/kWh, km/m^3	Author's previous experience

	Consumption on road (mix full and empty)	kWh/km, kg/km	Author's previous experience
	Consumption off road (mix full and empty)	kWh/km, kg/km	Author's previous experience
	Maintenance cost	USD/km	ICCT, 2023b
	Driver cost	USD/month	AGENCIABRASIL, 2024
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	%	-

* Inputs data source comes from public references, expert knowledge, and author's previous experience.

For the sensitivity analysis using @Risk software, the variables with higher uncertainty were selected to check their potential impact on the cost per km and total benefit. The variables, distribution model, and intervals are listed in the system report in Figure 14.

Figure 14. Sensitivity analysis inputs

	Input	Graphs	Function	Minimum	Maximum	Mean	Std Dev
1	Minimum wage (BRL)		RiskTriang(1412,1412,1553.2,RiskName("Minimum wage (BRL)"),RiskStatic(1412))	1,412.00	1,552.63	1,458.99	33.25
2	Fuel Cost - Diesel (BRL)		RiskTriang(4.5,5.5,6.5,RiskName("Fuel Cost - Diesel (BRL)"))	4.5098	6.4941	5.5011	0.4080
3	Fuel cost - Elect (BRL)		RiskTriang(0.14,0.2,0.3,RiskName("Fuel cost - Elect (BRL)"),RiskStatic(0.14))	0.14025	0.29968	0.21340	0.03306
4	Fuel cost - FCV (BRL)		RiskTriang(19.4,24.25,29.1,RiskName("Fuel cost - FCV (BRL)"),RiskStatic(24.25))	19.4340	29.0504	24.2661	1.9741
5	Fuel Cost - CNG (BRL)		RiskTriang(1.75,2.25,4,RiskName("Fuel Cost - CNG (BRL)"))	1.7548	3.9927	2.6653	0.4816
6	Fuel Cost - LNG (BRL)		RiskTriang(1.75,2.25,4,RiskName("Fuel Cost - LNG (BRL)"),RiskStatic(2))	1.7514	3.9846	2.6709	0.4834
7	Annual Insurance %		RiskTriang(0.01,0.03,0.05,RiskName("Annual Insurance %"),RiskStatic(0.03))	0.010152	0.049834	0.030021	0.008171
8	Carbon credit cost (BRL/ton)		RiskTriang(70,90,150,RiskName("Carbon credit cost (BRL/ton)"),RiskStatic(90))	70.285	149.354	103.509	17.071
9	Diesel truck cost (USD)		RiskTriang(170000,170000,204000,RiskName("Diesel truck cost (USD)"),RiskStatic(170000))	170,000.10	203,935.93	181,375.29	8,002.12
10	Electric truck cost (USD)		RiskTriang(398700,443000,531600,RiskName("Electric truck cost (USD)"),RiskStatic(443000))	399,240.50	530,910.40	457,784.54	27,547.75
11	Full cell truck cost (USD)		RiskTriang(421200,468000,561600,RiskName("Full cell truck cost (USD)"),RiskStatic(468000))	421,348.60	560,596.68	483,496.28	29,110.70
12	CNG truck cost (USD)		RiskTriang(200000,250000,250000,RiskName("CNG truck cost (USD)"),RiskStatic(250000))	200,273.12	249,999.99	233,313.37	11,765.48
13	LNG truck cost (USD)		RiskTriang(200000,250000,250000,RiskName("LNG truck cost (USD)"),RiskStatic(250000))	200,036.58	249,999.21	233,351.38	11,808.81
14	Filling station cost		RiskTriang(1000000,2000000,2000000,RiskName("Filling station cost"),RiskStatic(2000000))	1,001,556.93	1,999,991.40	1,667,116.06	235,737.27
15	Truck payload (ton)		RiskTriang(49.4,52,52,RiskName("Truck payload (ton)"),RiskStatic(52))	49.4134	52.0000	51.1349	0.6091
16	Consumption factor on/off road (%)		RiskTriang(0.35,0.44,0.55,RiskName("Consumption factor on/off road (%)"),RiskStatic(0.44))	0.35068	0.54966	0.44682	0.04099
17	Maintenance cost Diesel (USD/Km)		RiskTriang(0.1512,0.168,0.1848,RiskName("Maintenance cost Diesel (USD/Km)"),RiskStatic(0.168))	0.151220	0.184760	0.167999	0.006854
18	Maintenance cost BEV (USD/Km)		RiskTriang(0.108,0.12,0.132,RiskName("Maintenance cost BEV (USD/Km)"),RiskStatic(0.12))	0.108058	0.131904	0.120009	0.004903
19	Maintenance cost FCEV (USD/Km)		RiskTriang(0.1512,0.168,0.1848,RiskName("Maintenance cost FCEV (USD/Km)"),RiskStatic(0.168))	0.151299	0.184728	0.168000	0.006875
20	Maintenance cost CNG (USD/Km)		RiskTriang(0.1512,0.168,0.1848,RiskName("Maintenance cost CNG (USD/Km)"),RiskStatic(0.168))	0.151234	0.184605	0.167956	0.006841
21	Maintenance cost LNG (USD/Km)		RiskTriang(0.1512,0.168,0.1848,RiskName("Maintenance cost LNG (USD/Km)"),RiskStatic(0.168))	0.151249	0.184673	0.168022	0.006870
22	Distance (Km)		RiskTriang(64,80,112,RiskName("Distance (Km)"),RiskStatic(80))	64.109	111.789	85.342	10.021
23	Operational efficiency (%)		RiskTriang(0.657,0.73,0.803,RiskName("Operational efficiency (%)"),RiskStatic(0.73))	65.745%	80.263%	72.996%	2.979%
24	Off road empty (Km/h)		RiskTriang(22.4,28,33.6,RiskName("Off road empty (Km/h)"),RiskStatic(28))	22.4286	33.5492	28.0046	2.2891
25	Off road loaded (Km/h)		RiskTriang(16,20,24,RiskName("Off road loaded (Km/h)"),RiskStatic(20))	16.0206	23.9744	19.9976	1.6314
26	On road empty (Km/h)		RiskTriang(48,60,72,RiskName("On road empty (Km/h)"),RiskStatic(60))	48.083	71.979	60.007	4.894
27	On road loaded (Km/h)		RiskTriang(44,55,66,RiskName("On road loaded (Km/h)"),RiskStatic(55))	44.036	65.960	55.008	4.476
28	Loading time (h)		RiskTriang(1.2,1.5,1.8,RiskName("Loading time (h)"),RiskStatic(1.5))	1.20336	1.79690	1.50031	0.12175
29	Unloading time (h)		RiskTriang(1,1.25,1.5,RiskName("Unloading time (h)"),RiskStatic(1.25))	1.00107	1.49800	1.25023	0.10234
30	Refilling time - Dies(h)		RiskTriang(0.08,0.08,0.096,RiskName("Refilling time - Dies(h)"),RiskStatic(0.08))	0.080000	0.095859	0.085335	0.003768
31	Refilling time - Electric (h)		RiskTriang(0.16,0.16,0.192,RiskName("Refilling time - Electric (h)"),RiskStatic(0.16))	0.160000	0.191879	0.170632	0.007533
32	Net energy price BRL/MW		RiskTriang(10,100,700,RiskName("Net energy price BRL/MW"),RiskStatic(100))	11.40	699.79	269.52	153.11

3.4 Co_2 emissions calculation

The CO_2 emissions estimates were calculated following three steps. First, the truck emissions factors (median score reference of 3.41 kg of CO_2 per liter) should be identified. Second, multiply the distance by the truck emissions factor—finally, convert to metric tons by dividing by 1,000,000 (MATHERS, 2015).

$$\text{Total emissions (T } CO_2\text{)} = \frac{\text{Fuel consumption (L) x Kg CO2-eq}}{1000}$$

3.5 Return on investment calculation (ROI)

The Return on Investment (ROI) was calculated using the original formula created by Donaldson Brown (FLESHER at all, 2013). The indicator is calculated by the relation between net profit and investment spent (INVESTOPEDIA, 2023).

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

3.6 Experts survey

In order to understand how log logistics experts forecast new HDV technology applications and main trends in the future, a non-disclosure online survey was performed. The survey was sent using Google Forms to experts worldwide in different areas, such as logistics operators, pulp mill engineers, wood supply managers, researchers, and others. Table 9 describes the questions requested.

Table 9. Application trends of renewable HDVs in forest operations.

Expert Profile Characterization	• Personal data*: complete name, affiliation, and position • Where is the country of your working scope? • What is the core activity of your institution? • What is the sector of your work? • Do you have any work in Forestry business? • What is your main role? • How long have you been working with logistics?
Trends assumptions (considering heavy duty application)	• Does your company have ongoing actions, or is studying, for low carbon emission alternatives to diversify the energy matrix for HDVs? • In your opinion what is the most prominent technology to replace Diesel in the short term, 1-3 years? • In your opinion what is the most prominent technology to replace Diesel in the medium term, 3-5 years? • In your opinion what is the most prominent technology to replace Diesel in the long term, 5-10 years? • In your opinion what is the most prominent technology to replace Diesel in the long term, >10 years? • What are the main challenges do you consider, for decision making whether to adopt new technologies in the short term?

*Non-disclosure data, respecting the privacy of the participants.

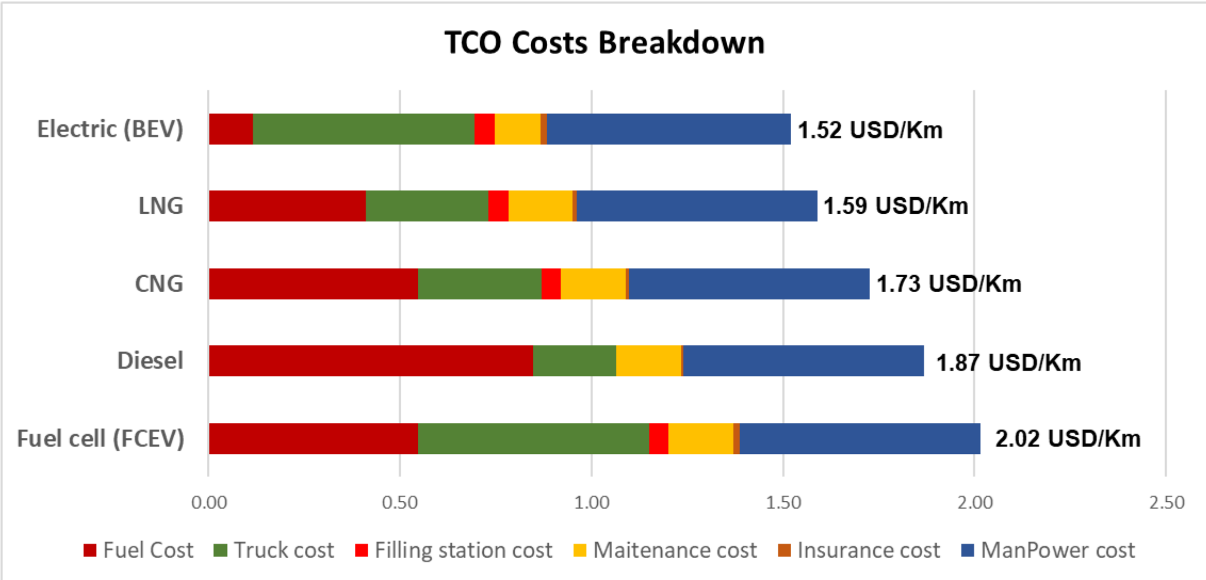
4 RESULTS

4.1 Total cost of ownership results

The TCO result is expressed by the cost per kilometer calculated for each solution. The lowest estimated cost is the BEV, at 1.52 USD/km, followed by gas trucks, LNG, at 1.59 USD/km, and CNG, at 1.73 USD/km. In the sequence comes the technology “baseline,” the Diesel truck estimated at 1.87 USD/km, and the highest cost is the FCEV, Hydrogen truck, with 2.02 USD/km.

Fuel and investment costs, trucks, and filling stations contributed the most to the final cost per kilometer (Figure 15). Maintenance and insurance costs had a lower impact on total costs and did not differ much between the technologies. The workforce contributed to one of the highest costs; however, it is almost the same for all solutions.

Figure 15. TCO costs breakdown



Besides the static numbers from the standard calculation, each TCO is presented in a range of potential values, according to the probability distribution, from performing Monte Carlo simulation. The summary results are listed in Figure 16, including minimum, maximum, mean, and standard deviation values. The probability followed the same rank as found in the static calculation, having the lowest minimum for BEV, CNG, LNG, Diesel, and 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 maximum, with lowest maximum according to the solution with lowest static, mean, and minimum, meaning the curves are positioned following the same static rank, with no higher variation for some specific technology, despite differences in standard deviation.

Figure 16. TCO outputs statistics

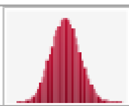
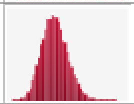
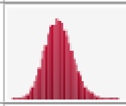
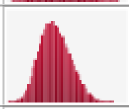
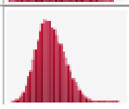
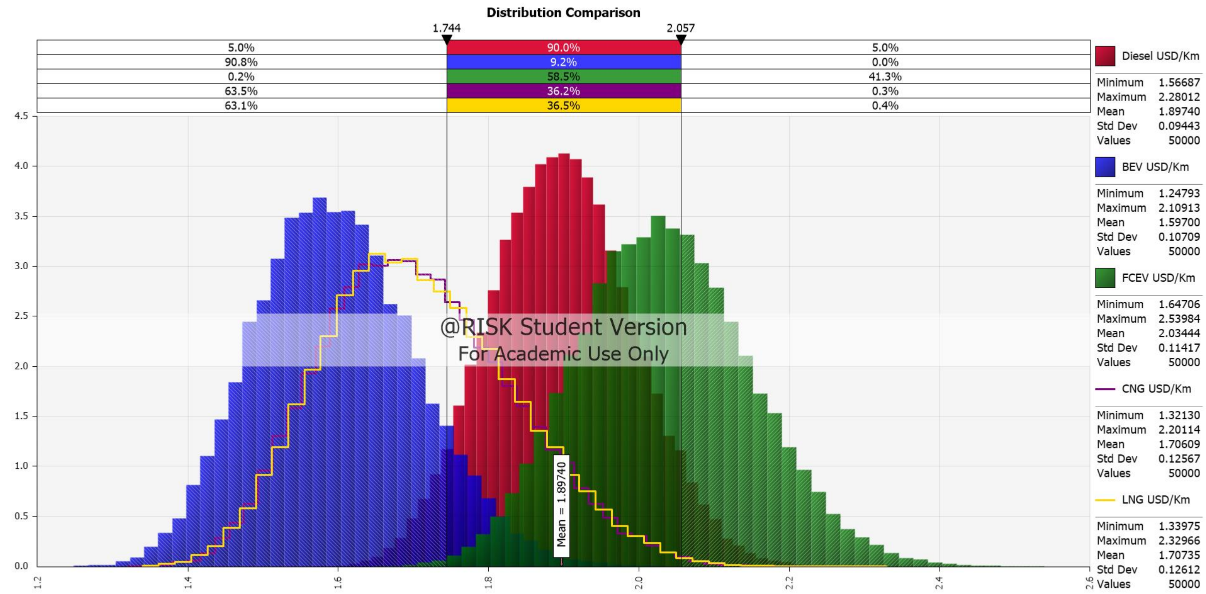
Output	Graphs	Minimum	Maximum	Mean	Std Dev
Diesel USD/Km		1.56687	2.28012	1.89740	0.09443
BEV USD/Km		1.24793	2.10913	1.59700	0.10709
FCEV USD/Km		1.64706	2.53984	2.03444	0.11417
CNG USD/Km		1.32130	2.20114	1.70609	0.12567
LNG USD/Km		1.33975	2.32966	1.70735	0.12612

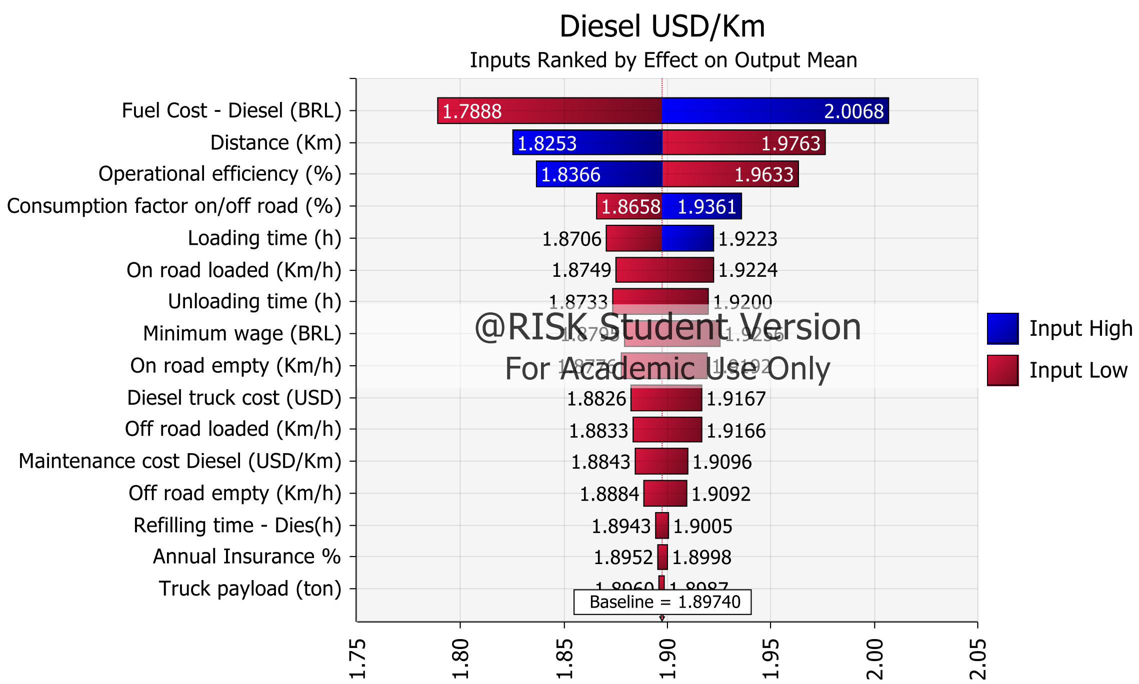
Figure 17 presents the probability distribution curves of cost/km for all alternatives. The chart is considering Diesel trucks as reference, with 90% confidence interval between 1.744 USD/km and 2.057 USD/km. Using the same Diesel interval plot, the BEV presents 90.8% probabliblity to be smaller than 1.744 USD/km and 0% of being higher than 2.057 USD/km. positioned more to the left representing potentially the lowest costs. The gas alternatives, CNG and LNG are also positioned to left side, being lower potential costs compared to the Diesel, with 63.5% and 63.1% to be lower than 1.744 USD/km, and 36.2% and 36.5% to be in the same interval as Diesel, respectively. The FCEV having higher estimate cost also has it’s curved positioned with provability of higher costs compared to the Diesel, with 58.% within same interval as Diesel, and 41.3% probability to be higher cost.

Figure 17. Probability distribution curves of cost/km



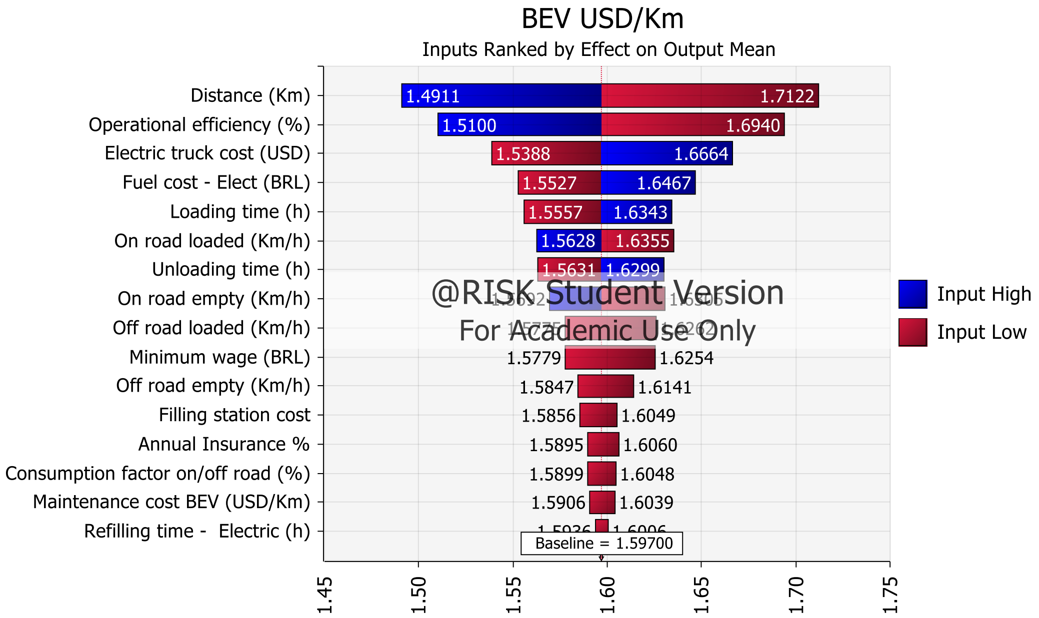
For the Diesel truck, the main parameter impacting the results was the Diesel cost, which alone can varies the cost/km range from 1.78 to 2.00. The second parameter was the distance, and the third was the operational efficiency. The truck price appears only in the tenth position. The rank and impact from all inputs with variation are listed in Figure 18.

Figure 18. Cost/km Inputs ranking of Diesel truck.



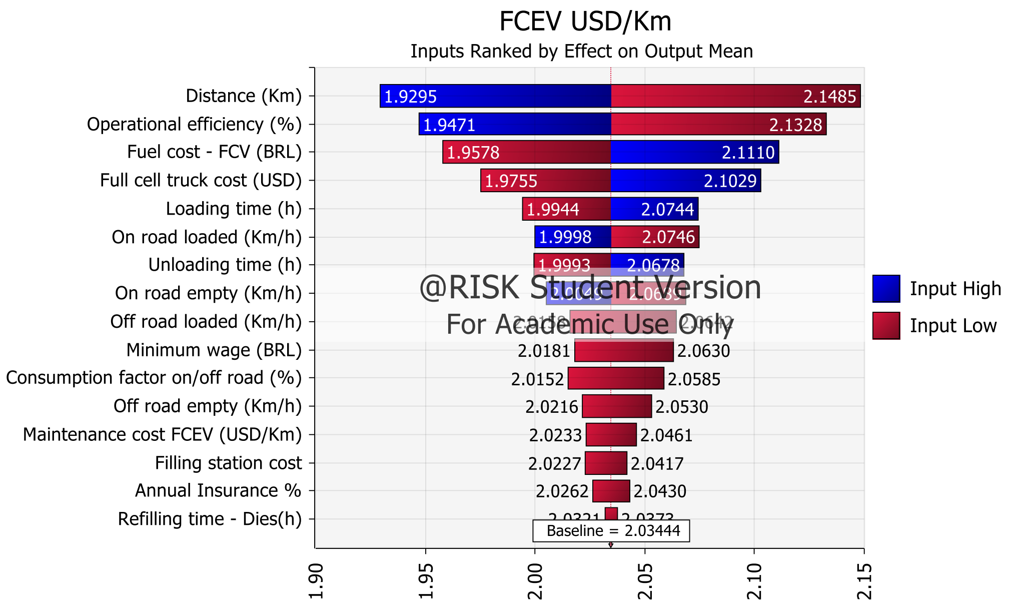
The parameters impacting the results of BEV are presented in Figure 19. The main ones were: first, the distance; second, the operational efficiency; and third and fourth, related to the new technology, the truck price and fuel cost. The filling station cost and refiling time did not appear among the initial ten positions.

Figure 19. Cost/km inputs ranking of electric truck.



The parameters impacting the results of FCEV are presented in Figure 20. The main ones were: first, the distance; second, the operational efficiency; and third, fuel cost, with truck price in the fourth position.

Figure 20 Cost/km inputs ranking of electric truck.



The parameters impacting the results of CNG are presented in Figure 21. The main ones were: first, the fuel cost; second, the distance; and third, operational efficiency. The truck price appears in the seventh position.

Figure 21. Cost/Km inputs ranking of compressed natural gas truck.

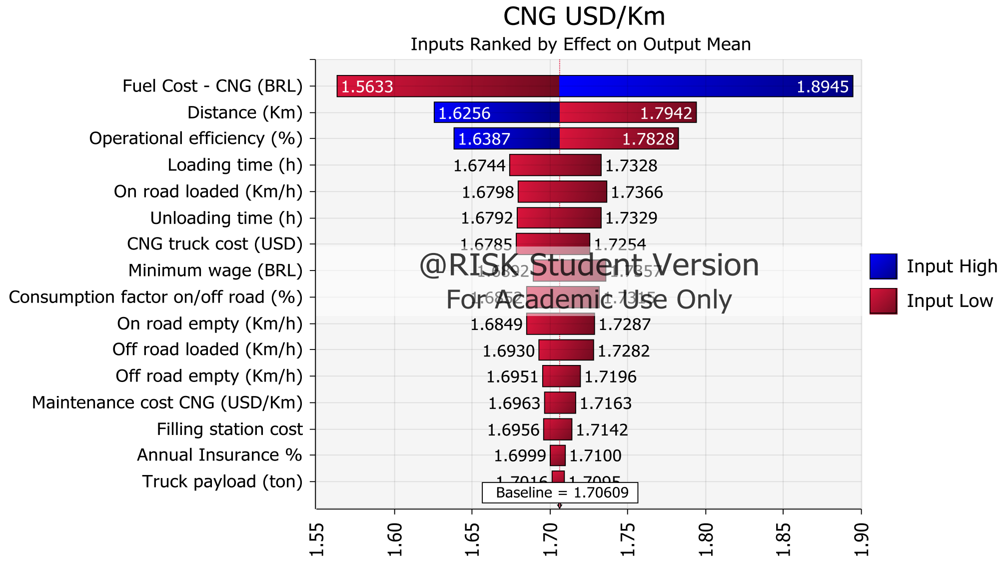
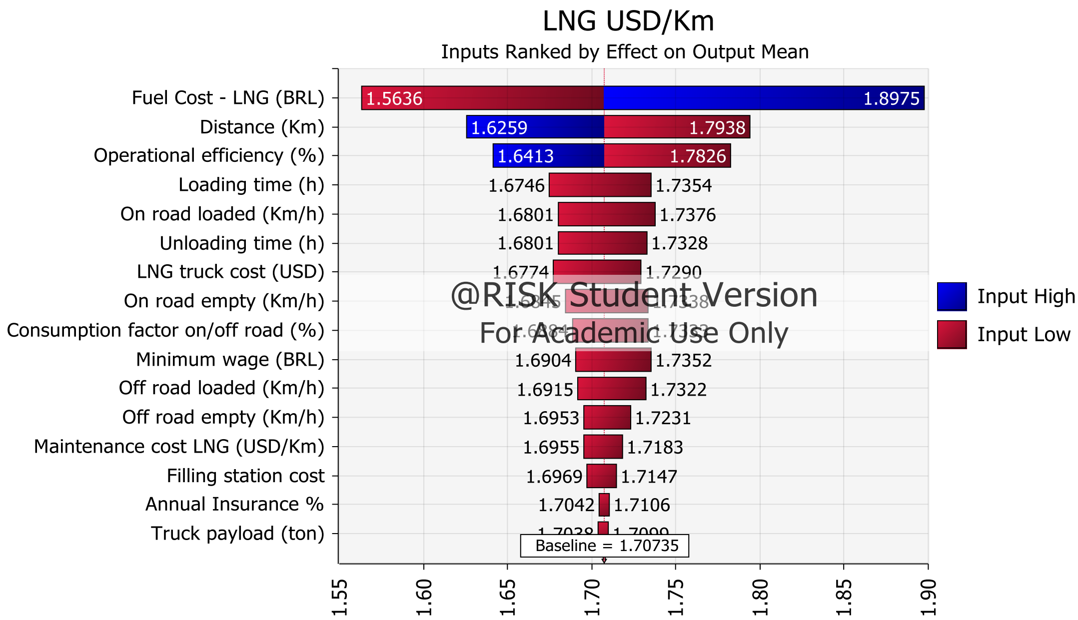


Figure 22 presents the parameters impacting LNG's results, and like the final TCO distribution, the rank is also nearly the same as the CNG truck. The main ones were the fuel cost, the distance, and operational efficiency. The truck price appears in the seventh position.

Figure 22. Cost/km inputs ranking of liquified natural gas truck.

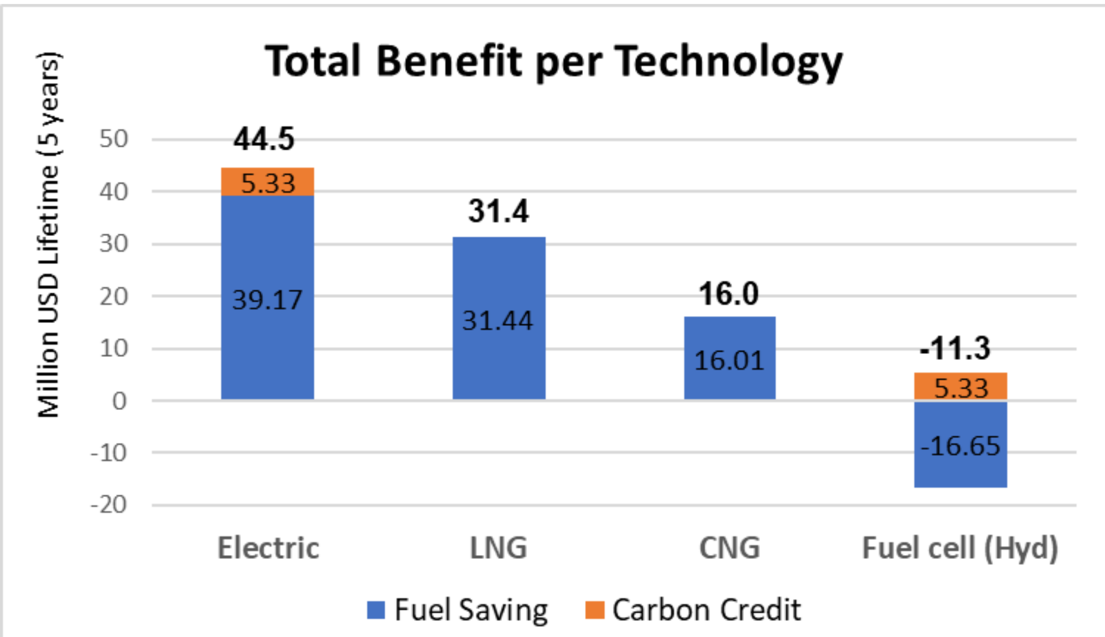


4.2 Benefits of technology replacement

This section presents the total benefit from technology replacement, which mainly considers the unitary cost variation between new technology and Diesel, from TCO calculation USD/km and carbon credit values. For the total benefit of technology transition, the unitary TCO difference times total kilometers to be run with the complete fleet in its lifetime of 5 years. 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 23, and summary of the sensitivity analysis in Figure 24. According to the static results, the higher benefit comes from BEV, accounting for 44.5 million USD in 5 years of operation, 39.17 million USD from fuel cost savings, and 5.33 million USD from carbon credit. The gas trucks, LNG, and CNG present savings of 31.4 and 16.0 million, respectively, from fuel cost savings only. Both technologies were not considered as they do not entirely have carbon benefits. Finally, the FCEV presented a negative -11.3 million USD result from higher fuel costs. The carbon credit was considered as the technology do not have CO_2 emissions at all. However, there is insufficient benefit to compensate for the higher energy cost.

Figure 23. Total benefit per technology (static results)



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 and FCEV. Except for BEV, all other technologies' minimum was negative. However, the only negative mean was from FCEV.

Figure 24. Total benefit outputs from Monte Carlo simulation

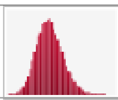
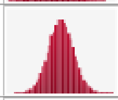
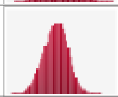
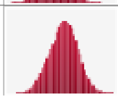
Output	Graphs	Minimum	Maximum	Mean	Std Dev
Total Benefit BEV		1,299,791.98	100,761,462.14	43,747,839.06	12,992,889.92
Total Benefit FCEV		-53,178,425.44	37,988,766.27	-9,795,802.75	11,324,155.76
Total Benefit CNG		-33,938,340.29	81,331,243.49	23,486,227.14	15,145,971.20
Total Benefit LNG		-29,431,721.20	78,031,651.65	23,335,262.42	15,246,637.20

Table 10 summarizes the rank of input that causes a higher impact on the total benefit, with a classification from each group of inputs. Operational cost items, such as fuel costs, are generally over-investments. The Cycle time items, such as distance and operational efficiency, also appear in the first positions. The investment cost appears in the third position for BEV and FCEV scenarios, and the fourth for CNG and LNG, but refiling stations are not in the top five items. The inputs, minimum wage (BRL), annual insurance %, and refilling time (electric truck) did not appear in the first sixteenth positions of any technology scenario.

Table 10. Inputs rank per technology

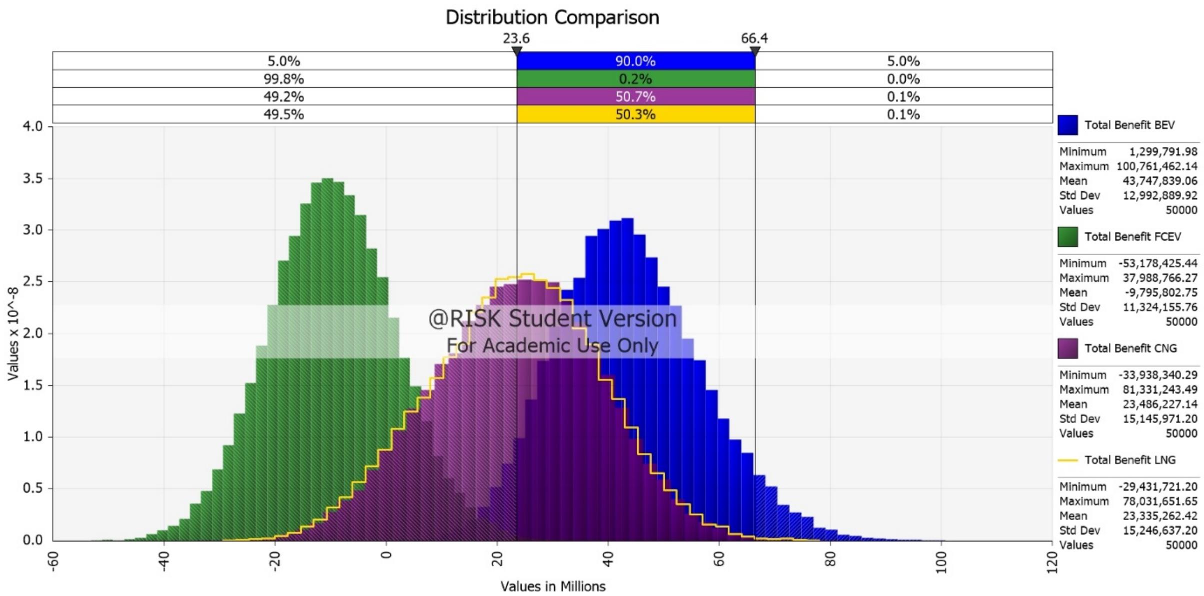
Sequence	Electric	Fuel cell (Hyd)	CNG	LNG
1st	Fuel Cost - Diesel (BRL)	Fuel Cost - Diesel (BRL)	Fuel Cost - CNG (BRL)	Fuel Cost - LNG (BRL)
2nd	Distance (Km)	Fuel cost - FCV (BRL)	Fuel Cost - Diesel (BRL)	Fuel Cost - Diesel (BRL)
3rd	Electric truck cost (USD)	Fuel cell truck cost (USD)	Distance (Km)	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

Figure 25 presents the probability distribution of total benefit for alternative fuels, considering BEV as reference values for 90% Confidence Interval. The BEV total estimate benefit is 23.6 to 66.4 million USD, with 90% of the Confidence Interval. The FCEV -28.3 to 8.9 million USD, with 99.8% probability of benefits below 23.6 million USD. For CNG and LNG similar distribution, CNG -2.1 to 47.7 million USD, with 49.2% probability of benefits below 23.6 million USD, and LNG -2.7 to 47.8 million USD, with 49.5% probability of benefits below 23.6 million USD.

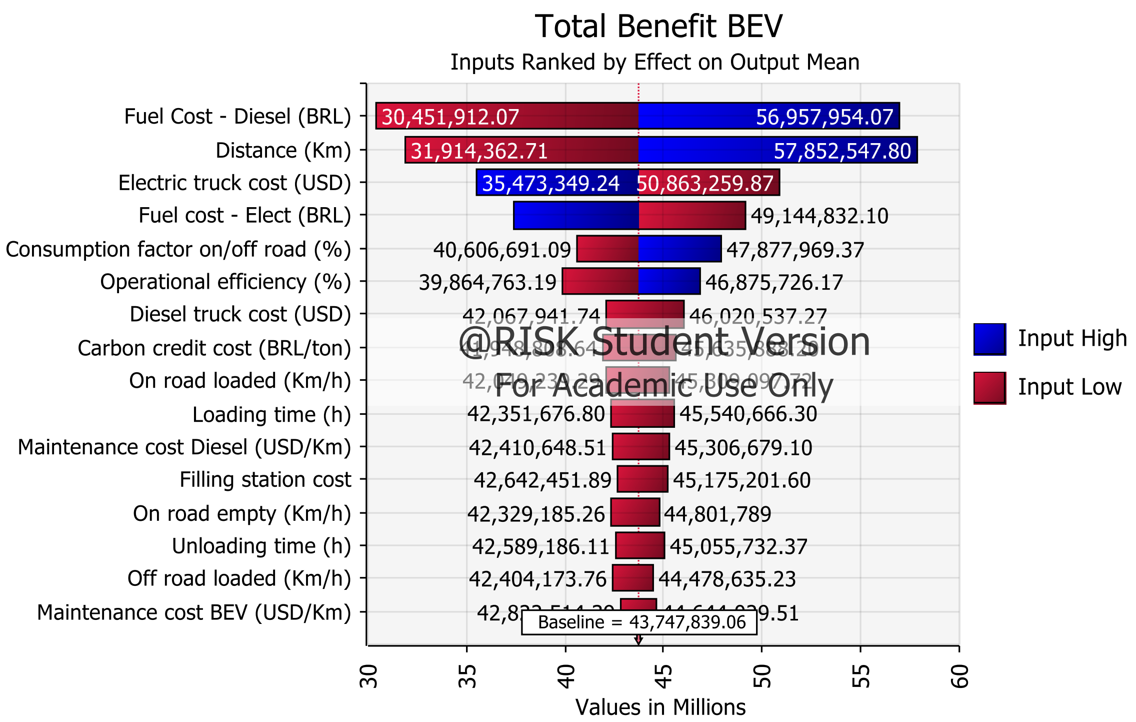
Figure 25. Probability distribution of total benefit from electric truck



Regarding total benefits, not only specific technology inputs impacted the result, but also items from the technology baseline.

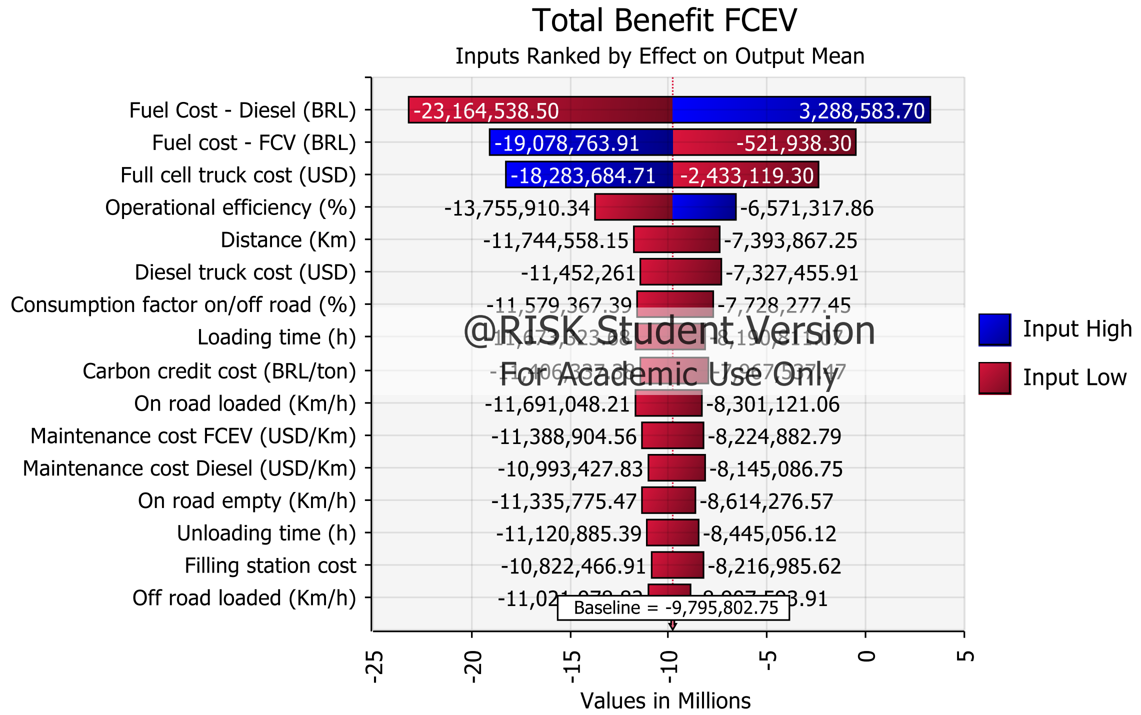
For BEV, the Diesel trucks have influenced the results, as seen in Figure 26. The primary item impacting the result of BEV is the fuel cost of Diesel, followed by distance and electric truck price. The energy cost for electric trucks came in fourth position. The Diesel truck cost appears in the seventh position, and the carbon credit is in the eighth.

Figure 26. Inputs ranking of electric truck total benefit



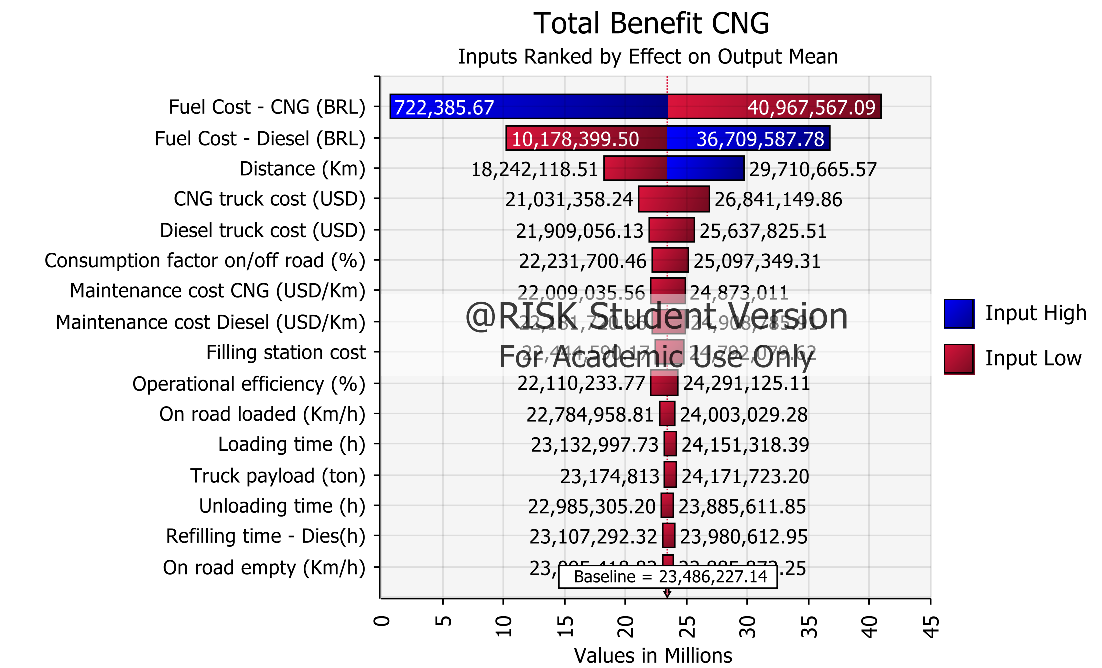
For FCEV, the primary item impacting the result is the fuel cost of Diesel, followed by fuel cost for FCEV and fuel cell truck price, Figure 27. The carbon credit appears in the ninth position.

Figure 27. Inputs ranking of fuel cell hydrogen truck total benefit



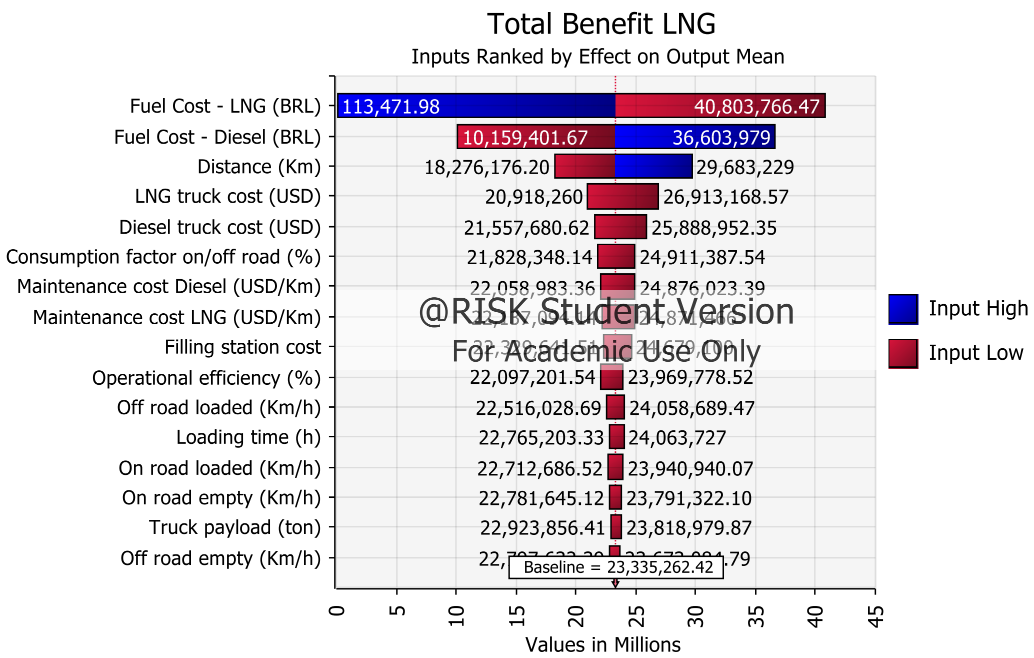
The primary item impacting the result of CNG is the gas cost, followed by Diesel cost and distance, Figure 28. The CNG and Diesel truck prices appear in fourth and fifth position, respectively.

Figure 28. Inputs ranking of compressed natural gas truck total benefit



Similarly of CNG, the primary item impacting the result of LNG is the gas cost, followed by Diesel cost and distance, Figure 29. The LNG and Diesel truck prices appear in fourth and fifth position, respectively.

Figure 29. Inputs ranking of liquified natural gas truck total benefit



4.3 Sensitivity analysis of energy price

Considering the BEV as the highest technology-saving scenario compared to diesel trucks, with fuel costs as the main reason for the results, additional sensitivity analysis was performed to check the benefits of several combinations of Diesel and energy prices.

Table 11, 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 times presented positive benefit, 84.6%.

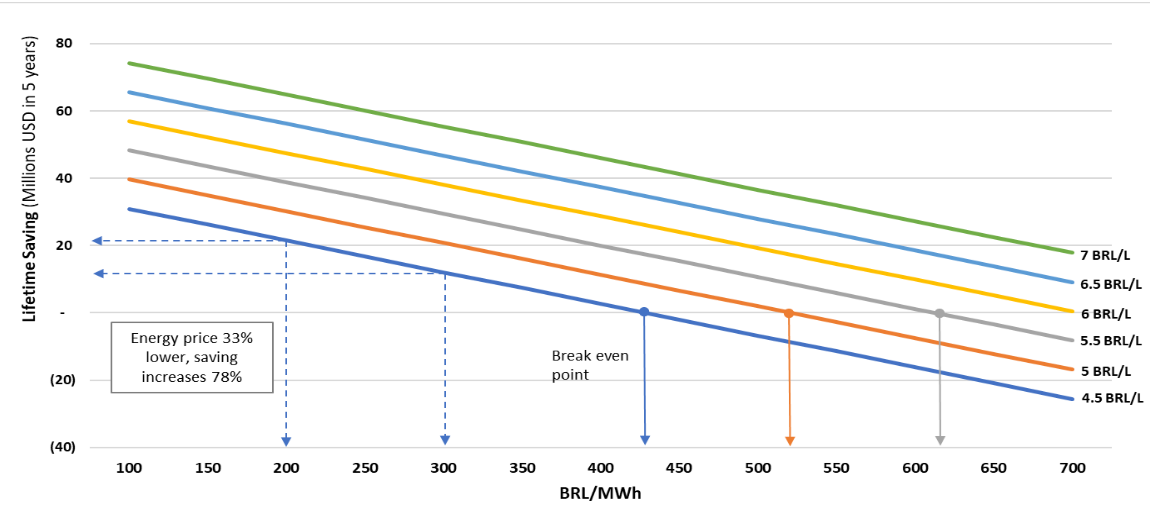
Table 11. Total benefit of electric trucks in different energy and Diesel prices

	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

Figure 30 highlights the breakeven point of Diesel price scenarios of 4.5, 5 and 5.5 BRL/L, which present scenarios with negative results. There is a positive benefit for the 4.5 BRL/L curve when energy prices are lower than 430 BRL/MWh. There are positive benefits for the 5 BRL/L curve when energy prices are lower than 520 BRL/MWh. There are positive benefits for the 5.5 BRL/L curve when energy prices are lower than 610 BRL/MWh. The other Diesel price scenarios have positive benefits independent of the energy price.

The energy price has a significant sensitivity in the results, as seen in the example comparison in Figure 37. For instance, using the Diesel cost curve 4.5 BRL/L, if the energy decreases from 300 to 200 BRL/MWh, which means a 33% reduction, the savings increase from 12.07 to 21.49 million USD, representing a 78% increment.

Figure 30. Energy price vs. five years economy for different prices of Diesel



4.4 Return on Investment

The ROI was calculated using diesel costs as a baseline to compare with new technologies, Table 12. All operational and investment costs were considered to calculate the savings comparing technologies. The carbon credit benefit was also included in the total benefit for BEV and FCEV technologies.

The calculation resulted in negative results for all scenarios, except the LNG solution with an 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 obtained the worst result, with ROI -123%, from an estimated investment of 49 million USD and a negative return of -11.3 million USD.

Table 12. ROI calculation of alternative solutions

Item	Unit	Diesel	Electric	Fuel cell	CNG	LNG
General Premisses						
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 payload	ton	52.00	52.00	52.00	52.00	52.00
Fleet size	#	145.00	147.00	145.00	145.00	145.00
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	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%**

4.5 Expert survey results

In the experts' survey there was a total of 15 respondents, from whose summary profile, the main role is project manager, 40% of them, followed by logistics experts, 27%, then operations manager, 20%, and professors, 20%, as per Figure 31. More than 50% of them have more than five years of experience. The most significant share was among professionals between 1 and 5 years of experience, with 46%. The second group, with 27%, consisted of professionals between 10 and 20 years of experience. The third, with 20% of the participants, had 5 to 10 years of experience, and the latest, with 7%, professionals with 20 to 30 years of experience, Figure 32.

Figure 31. Experts main role

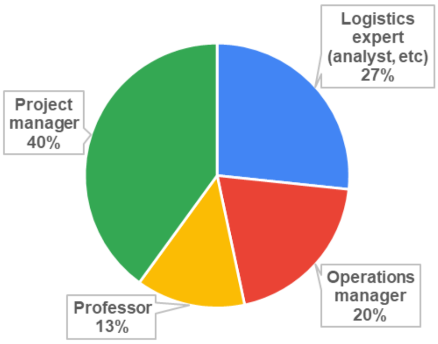
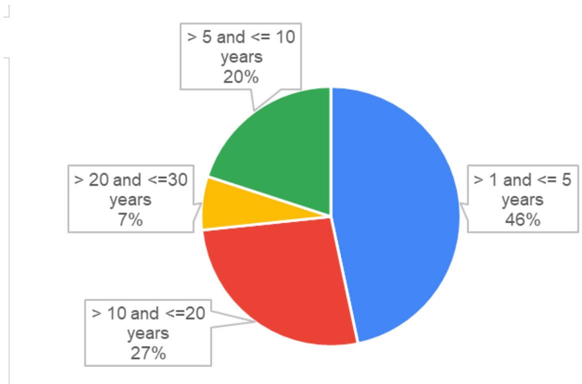
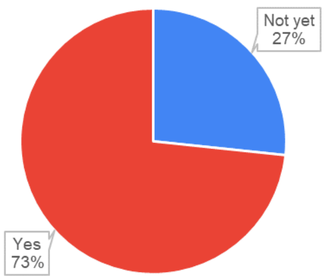


Figure 32. Experts experience in forest logistics



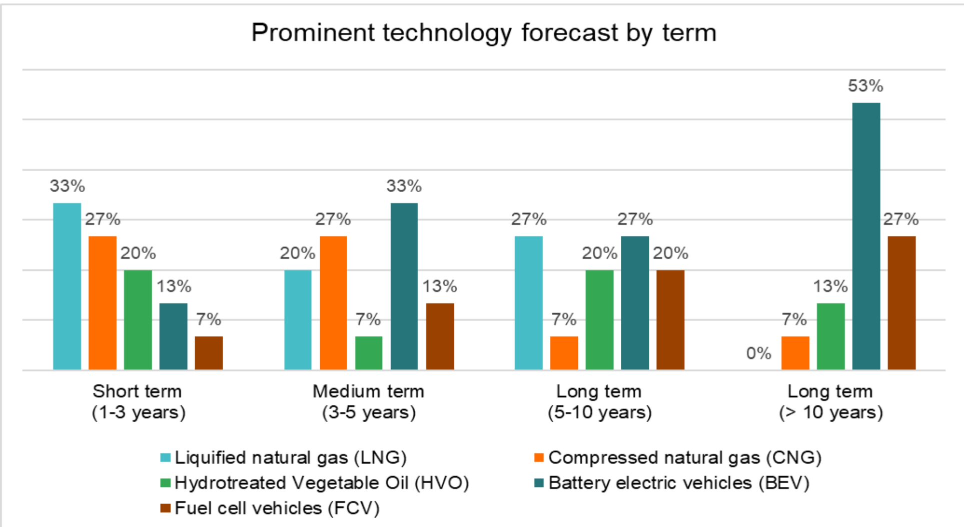
Regarding their affiliations with transportation technologies using renewable sources, most of them informed ongoing initiatives pursuing energy matrix changes, accounting for 73% of respondents, Figure 33.

Figure 33. Affiliation's experts with ongoing initiatives for renewable sources of energy



In their opinion, as expressed in Figure 40, the most prominent technology to replace diesel HD trucks is short to long-term. There is a trend to increase BEV and FCEV over time, with gas options CNG and LNG as the main ones for the short term and a mix of solutions in the medium term, appearing also HVO as a potential candidate. In the short term (1-3 years), the LNG is in the first position with 33% of the participants, followed by CNG with 27%, HVO 20%, BEV 13%, and FCEV 7%. In the medium term (3-5 years), BEV appears in the first position with 33%, followed by CNG 27%, LNG 20%, HVO 7% and FCEV 13%. In the long term (5-10 years) results are pretty similar as medium term, with almost equal sharing, but with increase of HVO, from 7% to 20% and reduction of CNG, from 27% to 7%. For the longest term scenario the highest share is with BEV with 53%, followed by FCV 27%, HVO 13%, CNG 7% and LNG 0%.

Figure 34. Prominent technology forecast by term



4.6 Non-Diesel heavy duty trucks available in the market

Table 13 lists the results of leading manufacturers' existing HDTs alternatives for Diesel. The summarized data comes from the manufacturer's web pages. They already present options powered by different fuels for heavy-duty applications, class 8, with more than 15-ton capacity and above 400 Hp.

The biggest number of options are related to the BEV technology, with seven models found, with Gross Vehicle Weight (GVW) ranging from 37 to 64 tons, minimum distance of 200 km, different options of number of batteries, and charging time around 30, 60 and 90 minutes. However, out of the seven, only two options present 6x4 traction, and for the FCEV technology, four models and 2 were from the same brand. All the options above 400 H, GVW ranging from 37 to 44 tons, minimum distance of 644 km, and charging time 20 minutes, and only one option for 6x4 traction.

Regarding gas solutions, CNG and LNG were found two options each, and all three manufacturers inform their vehicles are compatible with compressed or liquified gas. All the options have 6x4 traction, 60-ton GVW capacity, and 700-1000 km performance.

Table 13. Low-emission trucks are available in the market

Brand	Model	Configuration*	Power	Transmission	GVW	Performance	Maximum speed	Battery capacity	Charging time	Tank Capacity (H2, Gas)	Filling pressure	Data Source
Electric - BEV												
Scania	Options, P, G, R and S	6x2	270-450 KW	not informed	Max 64 ton	200 Km	not informed	624 KW installed, 468 KW useable	not informed	-	-	https://www.scania.com/group/en/home/products-and-services/trucks/battery-electric-truck.html
Volvo	VNR Electric 6x4 Tractor	6x4	455 Hp	Two-speed I-Shift Automated	37 ton	442 Km	109 Km/h	375kWh - 565kWh	4 Batteries: 60 min (80% charging at 250kW) 6 Batteries: 90 min (80%	-	-	https://www.volvotrucks.us/trucks/vnr-electric/specifications/
Mercedes-Benz	eActros 600	not informed	536 Hp	4 speed transmission	40 ton	500 Km	not informed	621 KWh	30 min (80%)	-	-	https://eactros600.mercedes-benz-trucks.com/gb/en/eactros-600/showroom.html, https://insideevs.com/news/691149/mercedes-eactros-
Man	eTGX	6x2		not informed	44 ton	400 Km	not informed	480 KWh	45 min	-	-	https://www.man.eu/de/en/truck/all-models/the-man-tgx/the-man-etgx/overview.html
Nikola	TRE-BEV	not informed	645 Hp	not informed	not informed	531 Km	112 Km/h	733 KWh	90 min	-	-	https://nikolamotor.com/the-nikola-tre-bev-reinventing-short-haul-transportation/
Sany	JS EV 550	6x4	405 KWh	Four-speed automatic	not informed	240 Km	89 Km/h	350 KWh	60 min (90%), or swap battery in 5 min	-	-	https://www.sanyglobal.com/product/truck/semi-trailer_tractor/138/876/
Iveco	IVECO HD BEV	4x2	645 Hp	not informed	44 ton	500 Km	not informed	738 KWh	90 min (80%)	-	-	https://www.iveco.com/en-us/press-room/release/Pages/IVECO-to-produce-and-market-its-Heavy-Duty-Battery-Electric-Vehicle-and-Heavy-Duty-Fuel-Cell-Electric-Vehicle.aspx
Fuel Cell - FCEV												
Hyundai	XCIENT Fuel Cell Tractor	6x4	350 Kw	5-Speed Automatic	37 ton	724 Km	not informed	72 KWh		68.6 Kg	350 / 700 bar	https://ecv.hyundai.com/global/en/products/xcient-fuel-cell-tractor-fcev
Hyundai	XCIENT Fuel Cell Truck	6x2	350 Kw	5-Speed Automatic	42 ton	644 Km	85 Km/h	72 KWh		not informed	350 bar	https://ecv.hyundai.com/global/en/products/xcient-fuel-cell-truck-fcev
Nikola	TRE-FCEV	not informed	536 Hp	not informed	not informed	805 Km	112 Km/h	164 KWh (2 pack)	20 min	70 Kg	700 bar	https://nikolamotor.com/tre-fcev/
Iveco	IVECO HD FCEV		400 KWh	not informed	44 ton	800 Km	not informed	not informed	20 min	70 Kg		
Compressed Natural Gas - CNG												
Scania	13L Otho Cycle For CNG or	6x4	280-460 Hp	not informed	60 ton	400 Km	not informed	-	-	200 m3		https://www.scania.com/group/en/home/products-and-services/trucks/gas-truck.html
Volvo	FH gas-powered, compatible with CNG, LNG, Bio-gas or HVO	6x4	420, 460 or 500 Hp	I-Shift, automated manual transmission	60 ton	1000 Km	not informed	-	-	not informed		https://www.volvotrucks.com/en-en/trucks/trucks/volvo-fh/volvo-fh-gas-powered.html
Liquefied Natural Gas - LNG												
Shacman	CNG Truck (CNG or LNG), models F3000, F2000, M3000	6x4	380 Hp	Fast	not informed	700 Km	not informed	-	-			https://www.shacmanchina.com/shacman-lng-tractor-truck.html
Volvo	FH gas-powered, compatible with CNG, LNG, Bio-gas or HVO	6x4	420, 460 or 500 Hp	I-Shift, automated manual transmission	60 ton	1000 Km	not informed	-	-			https://www.volvotrucks.com/en-en/trucks/trucks/volvo-fh/volvo-fh-gas-powered.html

* Some brands offers different configuration models for the same tractor. In case of 6x4 availability, this summary restricted to inform only this option, used by log hauling.

4.7 Non-Diesel heavy duty trucks trials

It was not found any public register of implementation of heavy duty trucks using alternative fuels in forest logistics operation. Nevertheless, some companies have reported initial trials, aiming to decarbonize their operations. Table 14 presents some tests reported publicly, using different brands and technologies.

Table 14. Alternative heavy duty trucks trials on forest hauling

Company	Country	Technology	Trial Scope	Brand	Configuration	Power	GVW	Performance	Data Source
Fibria / Suzano	Brazil	CNG	presented on Apr 2021	Scania	6x4	410 hp	150 ton	400 km	Author - presented presented on HarvestTech 2021, April 2021 Rotorua, NZ, on behalf of Suzano
James Jones & Sons and Scotlog Haulage	Scotland	BEV	press release on May 2023	Volvo	not informed	not informed	40 ton	not informed	https://www.jamesjones.co.uk/news-and-updates/james-jones-and-sons-to-trial-electric-timber-trucks
Svenska Cellulosa AB aka SCA	Sweden	BEV	press release on Oct 2021	Scania	not informed	not informed	80 ton	not informed	https://www.scania.com/group/en/home/newsroom/press-releases/press-release-detail-page.html/4111621-scania-and-sca-develop-first-80-tonne-electric-timber-truck
Fennel Forestry (Mount Gambier)	Australia	Diesel-powered converted to electric	press release on Feb 2023. 2 years trial	Kenworth	not informed	720 hp	not informed	400-500 km	https://bigrigs.com.au/2023/02/28/australias-first-electric-logging-truck-goes-to-work-in-sa/

5 DISCUSSION

5.1 Total Cost of Ownership Results

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 because of the lower fuel cost compared to Diesel despite the higher acquisition cost. A TCO study for implementing alternative solutions in Europe presents BEV with a higher cost than Diesel for the 2023 application scenario. The same study demonstrates a lower cost for BEV but for application in 2030 due to an estimated decrease in investment cost (ICCT, 2023b). The reason the forest application already presents a lower cost using BEV is due to the much lower energy cost, considering the pulp mill as an energy generator and supplier. Other studies commonly use standard energy market costs. It is important to consider the capacity of all trucks were considered the same for this analysis. For a specific truck model analysis, different capacities must interfere in the results, what can potentially demand more or less truck units.

The static result from TCO presents a lower cost of CNG and LNG trucks than Diesel trucks, in the same way as BEV, even having higher investment cost, and the fuel cost is lower than Diesel. However, this analysis does not consider the pulp mill as the fuel supplier; it is just the investment cost for filling station adaptation to gas. For mill integration, the “green” gas generation is possible but would require more complex changes and higher investments in the mill. Therefore, this technology scenario is subjected to gas availability close to the use point and price fluctuation.

In line with other studies, the TCO estimate for FCEV technology is higher than for Diesel trucks. The much higher investment cost impacted the result and was not compensated by benefits such as lower fuel costs and carbon credits. Likewise, the gas options for the fuel supply are more complex than those for Diesel or electricity.

5.2 Benefits of technology replacement

Despite lower TCO for BEV, the Return on Investment is negative, meaning the total benefit is smaller than the total investment. The ROI for CNG is close to that of

BEV, and the fuel cost is lower than that of Diesel but not as much as that of BEV. However, the truck price is between Diesel and BEV. The FCEV had the lowest ROI negative because of a combination of the highest truck price and a smaller difference in fuel cost compared to the Diesel truck.

The sensitivity analysis presents potential expressive variation in TCO and total benefit for all technologies, ranging from 1 to 5 times the mean results, which implicates in risks of increasing negative results, except BEV, which presents just positive variation. What means for technology application is important to consider all details and reduce the uncertainty of any variable involved.

5.3 Market trends

Despite the negative ROI, there is an indication that the BEV is potentially the most promising technology for replacing Diesel trucks in the medium term. This trend is noticed by expert's opinions and confirmed by the market movement. It seems the market is not moving as disruptive as per international agreements and government 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, batteries discharge, etc.

However, the market movement towards low-emission solutions is slow but consistently upward. A six-year study from McKinsey consultancy mapped the parity of Diesel and electric trucks, especially the light-duty category, in ten years (MCKINSEY, 2017). Nevertheless, from that moment until now, several brands have already offered solutions for the heavy-duty category off the shelves, with more than 60 tons.

Additionaly, besides of ongoing trucks development, some complementary technology has been developed, addressing some bottlenecks for technology implementation. For instance, in the case of BEV, systems to speed up refilling as Swap and Go. Like Janus electric Australia, which uses simple forklift system for fast battery replacement (APAC OUTLOOK, 2023) and Sany group, which has developed an automatic system which storage several batterie units for automatic swap (SANY, 2022).

Considering that the implementation's regional characteristics must influence the cost-benefit, the HVO should be considered a potential alternative in Brazil. The HVO can be produced from renewable sources, such as wasted cooking oil, but also from important Brazilian vocation, biomass from residues of eucalyptus plantation, and animal fats; additionally, it is considered a drop-in fuel, which does not require any changes in vehicles configuration (PETRY; MOURA; FRANIECK, 2021). However, Brazil has no clear production and commercialization plans yet, as expected in the European Union, Asia, and the United States (GREENEA, 2021).

The energy matrix change of HDV has several complications, which makes this process a long-term change. However, a consistent movement towards this direction is noticed. Those improvements will be crucial to achieving emissions reduction or at least mitigating the effects of increasing freight volumes (IEA, 2017).

This study does not cover a more complex logistics integration with pulp mills. For example, gas production by the pulp mill requires plant investments, fuel pathways such as hydrogen plants, and other potential market fuels such as HVO and several bio-Diesel variations. Considering so many fuel production pathways and different truck alternatives, it is an opportunity for several studies on this subject.

6 CONCLUSIONS

- The results show technologies with better TCO per kilometer, especially the Electric truck option, with the lowest cost per kilometer.
- Several factors influence the cost-benefit of technology replacement, such as items related to investments and operational costs, fuel costs, and distance.
- Despite lower TCO, the Electric truck option has a negative ROI, meaning the investment is higher than the benefits, not feasible from financial point of view. The second lowest TCO compared was the LNG solution, the only one with positive ROI. However, it seems the less likely scenario to be implemented due to the higher complexity of fuel supply in Brazil, fewer manufacturers with that option.
- The carbon credit increases total benefits but cannot make a solution feasible as a standalone factor.
- Considering the high sensitivity of operational costs, especially concerning electric, the relationship between Diesel cost and pulp mill energy cost can potentially change from a negative to a positive impact.
- Although electric option is still unfavorable with current investment costs, it can potentially be the first position in renewable trucks option in the medium to long-term pulp mills operations.
- The electric truck looks like the simplest solution to connect with the energy from the pulp mill, benefitting from the surplus generated, and the technology is expected to have the highest market share.

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