INTERNATIONAL CERTIFICATION IN MANAGEMENT OF RAIL AND METRO RAIL SYSTEMS

CERTIFICAÇÃO INTERNACIONAL EM GESTÃO DE SISTEMAS FERROVIÁRIOS E METROFERROVIÁRIOS

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CHALLENGES OF DECARBONIZATION PROGRAM IN BRAZILIAN RAIL SYSTEMS: A STUDY OF THE HEAVY HAUL AND PASSENGER RAILWAY

BRASÍLIA
JANUARY, 2024

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Final project presented to Deutsche Bahn as a partial requirement for obtaining the International Certification in Metro and Railway Systems

Area: Rail and Metro Systems

BRASÍLIA
JANUARY, 2024

We dedicate this extraordinary achievement to our beloved families, to the SEST SENAT system for crucial support, to the Institute of Transport and Logistics - ITL and to the Deutsche Bahn (DB) Rail Academy for imparting invaluable knowledge. Gratitude to our companies that supported us, allowing us to achieve the International Certification. To every team member, this triumph is ours.

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Each member of our team, coming from different companies, brings a unique wealth of experience and skills to this collective endeavor. We want to express our deep appreciation for the companies that supported us by giving time and resources to this program (INFRA S.A., SUPERVIA, TRENSURB and VALE). Your contributions were essential to our training and success on this challenging journey.

"The true sign of intelligence is not knowledge but imagination."
(ALBERT EINSTEIN)

ABSTRACT

This study delves into the challenges and opportunities surrounding the transition of energy matrices, with a focus on decarbonization in railway systems, specifically examining heavy haul and passenger transportation. The Carajás Railway serves as a case study, illuminating its diverse initiatives towards adopting more sustainable energy sources.

By scrutinizing the current railway energy landscape, we emphasize both economic and environmental implications. In the realms of heavy haul and passenger transportation, we identify unique challenges and propose context-specific solutions.

The in-depth analysis of the Carajás Railway not only unveils its transition actions but also reveals obtained results, offering valuable insights for other railway systems contemplating similar changes.

Exploring the operational impact of electric and hybrid locomotives in railway transport, this study evaluates benefits and inherent challenges. Regulatory approaches are meticulously examined, highlighting necessary measures for supporting new energy source adoption.

Considering infrastructure complexities and investments associated with this transition, we conclude by anticipating future trends and innovations that will shape the railway industry during this global energy transition. This study provides a concise yet comprehensive understanding for researchers, industry professionals, and policymakers invested in the sustainability and efficiency of railway systems.

Keywords: Railway Energy Transition, Heavy Haul and Passenger Transportation, Sustainable Energy Adoption, Decarbonization Efficiency of Railway Systems.

RESUMO

Este estudo investiga os desafios e oportunidades em torno da transição de matrizes energéticas com foco em descarbonização em sistemas ferroviários, examinando especificamente o transporte de cargas e de passageiros. A Estrada de Ferro Carajás serve como um estudo de caso, iluminando suas diversas iniciativas para a adoção de fontes de energia mais sustentáveis.

Ao examinar o atual cenário energético ferroviário, enfatizamos as implicações econômicas e ambientais. Nos domínios do transporte *heavy-haul* e de transporte de passageiros, identificamos desafios únicos e propomos soluções específicas para cada contexto.

A análise aprofundada da Estrada de Ferro Carajás não apenas revela suas ações de transição, mas também revela os resultados obtidos, oferecendo *insights* valiosos para outros sistemas ferroviários que almejam mudanças semelhantes.

Explorando o impacto operacional de locomotivas elétricas e híbridas no transporte ferroviário, este estudo avalia benefícios e desafios inerentes. As abordagens regulatórias são meticulosamente examinadas, destacando as medidas necessárias para apoiar a adoção de novas fontes de energia.

Considerando as complexidades de infraestrutura e os investimentos associados a essa transição, concluímos antecipando tendências e inovações futuras que moldarão a indústria ferroviária durante esta transição energética global. Este estudo fornece uma compreensão concisa e abrangente para pesquisadores, profissionais da indústria e formuladores de políticas que investem na sustentabilidade e eficiência dos sistemas ferroviários.

Palavras-chave: Transição Energética Ferroviária, Transporte de Carga e de Passageiros, Adoção de Energia Sustentável, Descarbonização, Eficiência dos Sistemas Ferroviários.

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SUMMARY

1 INTRODUCTION

1.1 Overview of global initiatives and challenges in reducing carbon emissions

The commitment to global decarbonization has been a longstanding endeavor, driven by the insights and warnings of esteemed researchers across the world. Numerous initiatives, spanning decades, reflect a collective effort to address the pressing need for sustainable practices and reduce carbon emissions on a global scale.

The Paris Agreement reached at COP21 of the UNFCCC in 2015 calls for stabilizing global average temperature at well below 2 °C above pre-industrial levels. This target requires global zero net GHG emissions at some point in the second half of this century. The countries that signed this agreement have to present to the UNFCCC by 2020 a long-term low emission development strategy (La Rovere *et al.*, 2019).

In October 2018, the Intergovernmental Panel on Climate Change (IPCC) issued a warning that the world needs to reduce global greenhouse gas (GHG) emissions by 45% by around 2030 and reach net-zero emissions by 2050 to avert the worst impacts of climate change (IPCC, 2018). Various commitments and initiatives continue to unfold globally, representing a collective effort undertaken by nations at different levels. This global movement reflects a shared responsibility and recognition of the critical need for concerted action in addressing challenges related to sustainability and carbon reduction.

In alignment with this statement and other pervasive media coverage, the urgency of addressing climate change has become a prominent narrative, underscoring the imperative for immediate and comprehensive action. Within this narrative, decarbonization has emerged as a critical and overarching strategy that extends its reach across various sectors, each playing a crucial role in global efforts to mitigate climate change, especially in the transport sector.

As underscored by widespread media reports and several scientific publications, the transport sector stands out among the diverse contributors to climate change. Transport sector is a major contributor to global warming and consequent climate change, directly by harmful emissions in exhaust gases from vehicles powered by fossil fuels, and indirectly by consuming electricity or liquid fuels derived from fossil fuels (van der Meulen & Möller, 2017). On a worldwide basis, the transport sector today is responsible for almost one-third of final energy demand and nearly two-thirds oil demand. It is also responsible for nearly one-quarter of global carbon dioxide emissions from fuel combustion and is a major contributor to air pollution, particularly in urban areas (International Energy Agency & Union of Railway, 2019). Its role in the emission of greenhouse gasses is substantial, and addressing this aspect becomes paramount in the broader strategy of transitioning to a low-carbon future.

The challenges within the transport sector are intricate. Despite technological advancements and increasing awareness of environmental issues, the sector continues to be a significant contributor to greenhouse gas emissions. However, when scrutinizing the sector, it becomes evident that a nuanced analysis, especially when considering various modes of transportation, reveals disparities in their greenhouse gas emission profiles. Some modalities fare worse than others in terms of GHG emissions.

Taking this in consideration, railways are among the most efficient and lowest emitting modes of transport. With a strong reliance on electricity, it is also the most energy diverse. Rail networks carry 8% of the world's motorized passenger movements and 7% of freight transport, but account for only 2% of energy use in the transport sector (International Energy Agency & Union of Railway, 2019). A rough comparison, to illustrate the rail efficiency, one container train powered by four diesel locomotives emits six times less CO_2 than a fleet of 260 trucks needed to transport the same number of containers (California Air Resources Board, 2020).

Given that rail stands out as one of the most efficient modes of transportation, an important question arises: If rail is already relatively clean, why is it important to address its carbon footprint? (WSP, 2023). This question is important because the rail has to be thought entirely, as an Ecosystem Perspective. During operation, railways account for 0.4% of greenhouse gas emissions from transportation according to the European Environment Agency (2022). Emissions also arise from the construction of the railway network, the manufacture of the rolling stock, its maintenance and ultimate disposal (International Energy Agency & Union of Railway, 2019).

Therefore, a comprehensive evaluation of rail across its entire lifecycle, especially regarding emissions, is imperative. This becomes particularly relevant given the increasing demand for cleaner transportation, solidifying rail's crucial position in the intrinsic decarbonization of the transport sector and its pivotal role in curbing energy demand from other transportation modes. However, it remains essential to consider the complete lifecycle of rail emissions. This thorough examination is critical because, despite being an energy-intensive sector, rail inherently operates with efficiency and environmental friendliness.

1.2 The specific role of the transport sector in contributing to climate change

The importance of rail extends beyond its operational efficiency to include its crucial role in diminishing energy demand from other transportation modes. Nevertheless, concentrating solely on operational emissions and linking consumption directly to emissions might create a surface-level perception of reduction. Such an approach neglects the broader lifecycle impact, potentially masking the authentic environmental gains achieved by these actions.

The significance of rail in terms of emissions is evident when considering that, if all passenger and freight services currently carried by rail switched to road vehicles, such as cars and trucks, the global oil demand from transport today would be 16% higher, increasing the total GHG emissions from transport by 12% or 1.2 Gt of CO_2-eq (International Energy Agency & Union of Railway, 2019).

Improving the efficiency of rail emissions, especially in the context of extensive rail networks featuring massive heavy-haul trains, is a challenging endeavor. As already been highlighted, while these heavy-haul trains outperform any other terrestrial equivalent transport in terms of efficiency, the substantial reliance on liquid fuels derived from oil, combined with the widespread use of internal combustion engines, constitutes a formidable obstacle in attaining emission reduction targets within this transport mode.

To effectively address the environmental impact of the transport sector, a comprehensive approach to decarbonization is required. This involves promoting and adopting sustainable alternatives such as electric vehicles powered by renewable energy, investing in public transportation infrastructure, and incentivizing the use of cleaner technologies. Policymakers, industry stakeholders, and the public all play crucial roles in driving this transformative change within the transport sector.

This study delves into the challenges and opportunities of the decarbonization program in Brazilian rail systems, focusing on both heavy-haul and passenger transportation sectors. The pressing global need to reduce carbon emissions provides the backdrop for this investigation, underscoring the imperative for cleaner and more sustainable energy sources. To anchor these considerations, the Carajás Railway, a rail network that is under concession to Vale, in Brazil serves as a compelling case study, offering insights into effective decarbonization strategies within the Brazilian context.

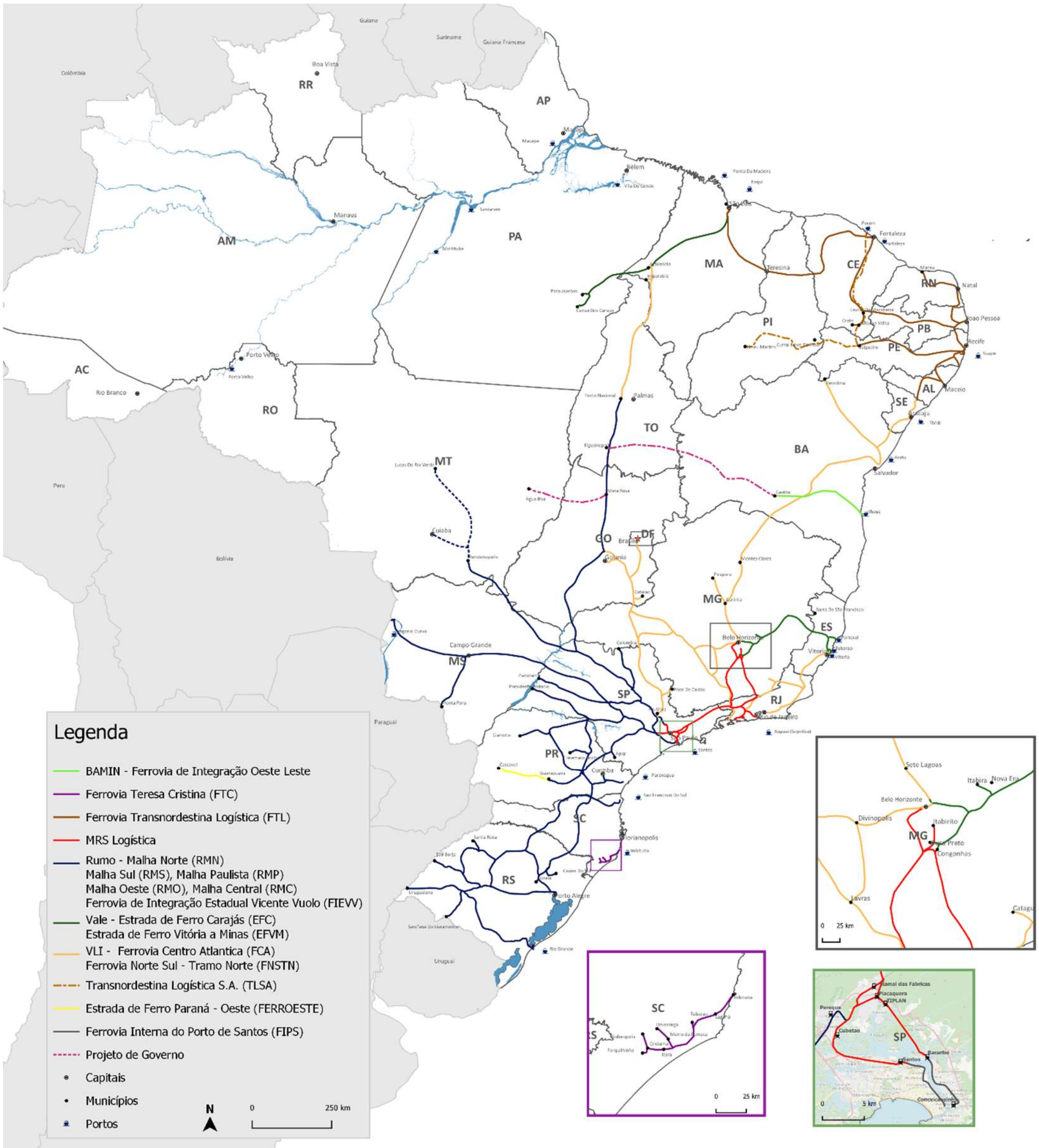
1.3 Contextualizing the challenges of decarbonization in Brazilian rail systems

As highlighted in the previous introduction, as the global community grapples with the escalating impacts of climate change, the challenges of decarbonization become increasingly apparent. This section contextualizes these challenges within the specific framework of Brazilian rail systems. Factors such as the country's unique geographical features, diverse transportation needs, and existing energy infrastructure will be considered to provide a nuanced understanding of the hurdles and complexities involved in reducing carbon emissions in this sector.

The Brazilian railway mode stands out for its high capacity to transport goods over long distances. This is attributed to the inherent characteristics of rolling stock and its relationship with infrastructure. In the maps related to the Brazilian Railway Infrastructure, the various track gauges are represented based on their usage in different networks. In this context, it is noted that Brazil currently has a network of 29,074 km, with 76.0% in metric gauge, 22.2% in broad gauge, and 1.8% in mixed gauge. In Brazil, in particular, the significance of the railway mode is evident through the connectivity it provides between production zones and locations for exporting (ports) and processing mineral and agricultural commodities. Considering data from 2017, the most prominent cargoes in terms of transported volume are iron ore, soybeans, and corn, accounting for 77.3%, 4.5%, and 3.3% of the total volume moved in the country that year, respectively. The remaining percentage is distributed among other transported goods, representing 14.9% of the total volume. Within this group of 89 commodities, those that stand out in terms of volume moved include sugar, coal, cellulose, diesel oil, steel products, and pig iron (CNT, 2023).

The vast continental dimensions of Brazil have posed challenges for expanding the rail network. Nevertheless, investments have been initiated, particularly following the privatization process of the Brazilian heavy haul railway system. Since the concession cycle in the 1990s, there have been substantial investments in restructuring operations and modernizing rolling stock and railway infrastructure. These investments have led to increased transportation production and enhanced safety, consequently reducing the number of accidents. In the period from 2006 to 2017 alone, there was a notable increase of 57.4% in the volume of goods transported. In Figure 1.1, the representation of the Brazilian heavy haul railway system, encapsulating the intricate network that spans the vast expanse of the country.

Figure 1.1 - Brazilian heavy haul railway system



Source: (ANTF, 2023)

In general, as is the case globally, decarbonizing the rail sector presents a significant challenge, especially when considering the extensive dimensions and the specific types of loads and trains, as exemplified in the context of the Brazilian railway. Moving away from oil in the transportation sector is not as simple as an electric vehicle in every driveway. Electric vehicles work well for many applications, but for others, oil's nature as an energy-dense liquid is more difficult to replace (Gross, 2020).

Why does oil dominate the transportation sector? The reason is simple — fuels made from oil have attributes that make them nearly ideal transportation fuels. Modes of transport don't just carry their passengers or freight; they also carry the fuel required to make the journey. Thus, the ideal transportation fuel is energy dense — meaning that it contains a lot of energy for its weight and volume. Petroleum-based fuels meet this criterion. Liquid fuels enabled the development of the internal combustion engine, which powers the overwhelming majority of today's transport. Finally, liquid fuels are ideal for transportation because they are easy to move from production to storage to final use in a vehicle — they can be easily pumped into an on-board tank (Gross, 2020).

Addressing emissions in such a diverse and expansive rail network demands thoughtful strategies and innovative solutions to meet the dual goals of environmental sustainability and efficient transportation. Brazil has searched for energy alternatives to petroleum diesel with the purposes of mitigating environmental impacts caused by the use of oil products and increasing energy safety. Moreover, an alternative and renewable energy source such as biodiesel plays an important role in lessening the country's dependence on diesel and lowering its CO_2 emissions (Murta *et al.*, 2023.). Moreover, the government encourages the use of new biofuels, such as bio-oil and biokerosene, while increasing the mandatory mixture of biodiesel in mineral diesel (up to 20%) (Gonçalves *et al.*, 2020).

In conclusion, contextualizing the challenges of decarbonization within the Brazilian rail systems reveals a complex interplay of geographical, infrastructural, and operational factors. The vast dimensions of Brazil, coupled with the intricate nature of the railway network spanning over 29,000 km, contribute to the difficulty of transitioning to more sustainable practices. The significance of the rail mode in connecting production zones to export locations, particularly for vital commodities like iron ore, soybeans, and corn, underscores its crucial role in the nation's economic landscape. Overcoming these challenges demands innovative solutions, especially in the face of the unique characteristics of Brazilian rail transport. Initiatives post-privatization, in the case of heavy haul rail systems, have propelled investments, resulting in noteworthy increases in transportation production and safety enhancements. However, the journey toward decarbonization is multifaceted, requiring thoughtful strategies to balance environmental sustainability with the efficient transportation demands inherent in Brazil's diverse and expansive rail network. The pursuit of alternative energy sources, such as biodiesel, is indicative of the nation's commitment to mitigating environmental impacts and increasing energy security. With ongoing efforts, Brazil aims to navigate the complexities of decarbonizing its rail systems, contributing to the global endeavor for a more sustainable and resilient transportation sector.

1.4 Objective

The main objective of this study is to present the challenges and opportunities surrounding the transition of energy matrices in railway systems, specifically examining heavy haul and passenger transportation. The Carajás Railway serves as a case study, illuminating its diverse initiatives towards adopting more sustainable energy sources in heavy haul transportation. The work also has the specific objective to analyze the passenger railway decarbonization scenario in Brazil.

1.5 Document Structure

The present document is divided into five chapters. The first chapter is a brief introduction, contextualization of the problem approached and objectives of the study. In Chapter 2, we present a case study of the Carajás Railway, highlighting the initiatives and outcomes of its decarbonization endeavors to broader discussions on sustainable rail practices in Brazil. Subsequently, in Chapter 3, we focus on the challenges inherent in decarbonizing passenger transportation. The challenges of regulations and legislation shaping the adoption of alternatives in the energy transition in Brazil's rail sector are indicated in Chapter 4. Finally, in Chapter 5, the conclusions are drawn.

2 CASE STUDY: CARAJAS RAILWAY AND VALE'S DECARBONIZATION EFFORTS

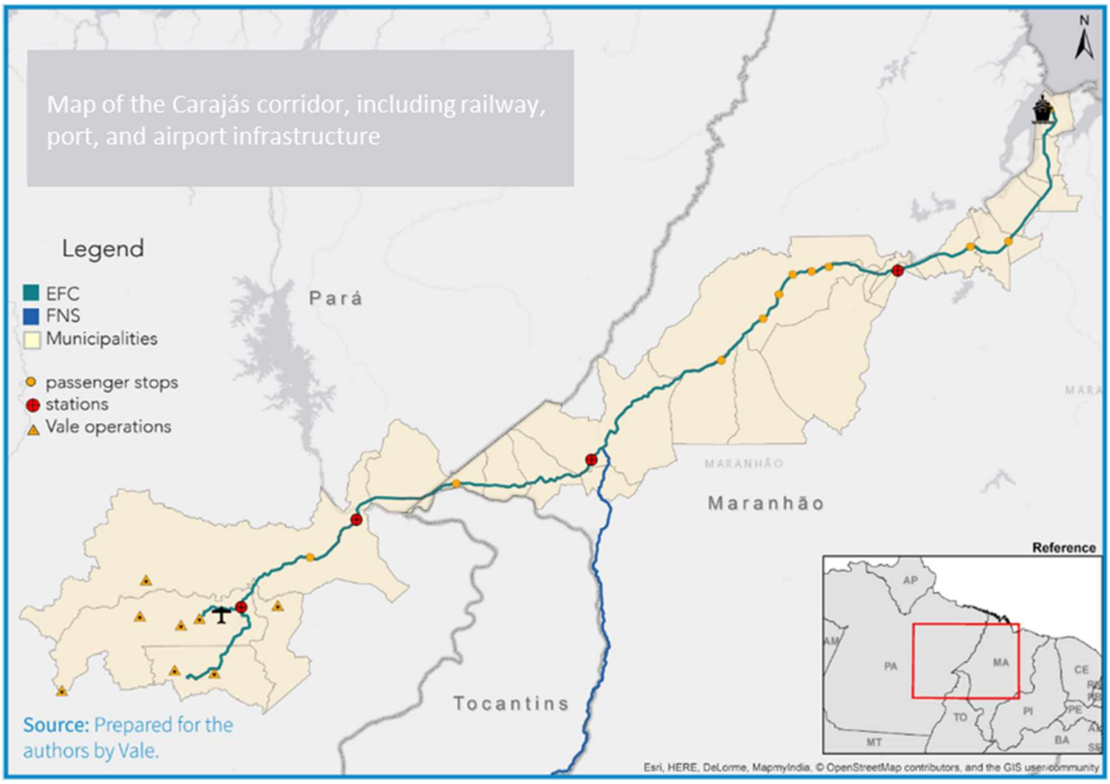
2.1 Background and significance of the Carajás Railway

Central to this study is the Carajás Railway, which serves as a pivotal case study within Brazil's ongoing decarbonization efforts. This subsection introduces the historical background and significance of the Carajás Railway, emphasizing its strategic position in the national transportation network. By highlighting the initiatives and outcomes of its decarbonization endeavors, this presentation establishes the Carajás Railway as a rich source of insights applicable to broader discussions on sustainable rail practices in Brazil.

The discovery of the Carajás iron ore reserves in 1967 prompted the Brazilian Federal Government to acknowledge their pivotal role in the regional development plan. This comprehensive initiative aimed to foster extractive industries, agriculture, and manufacturing while attracting migrants to the area. Initially, the state-owned Brazilian company, known as Companhia Vale do Rio Doce (CVRD or Vale), played a central role in these endeavors. However, in 1997, Vale underwent privatization and was subsequently rebranded as Vale S.A. in 2007. This transition marked a significant shift in the corporate landscape, aligning with broader economic strategies and global market dynamics.

Part of the challenge in exploring the region fell under the purview of CVRD (Companhia Vale do Rio Doce), and one of its key components, the Carajás Railway (EFC), began operations in August 1982, playing a pivotal role in this strategic vision. The railway spans over 978.0 km of broad gauge tracks, a significant portion now duplicated, with a remarkable transport capacity of 230 million metric tons per annum (Mtpa) dedicated to iron ore. This extensive network constitutes 3.4% of the total Brazilian railroad infrastructure (CNT, 2023), strategically connecting with the Port of Itaqui (MA) and the networks of Ferrovia Transnordestina Logistica (FTL) and Ferrovia Norte-Sul (FNS). EFC fleet, comprising 300 locomotives (from 3600Hp up to 5800Hp) and 21,212 wagons. Among its diverse cargo portfolio, iron ore emerges as the primary commodity transported, underscoring the railway's essential role in the Brazilian context. EFC's cargo distribution underscores 98% dedicated to the transport of iron ore and the remaining 2% allocated to various other goods. One of its most remarkable feats is the operation of the world's largest regular-service train, featuring 330 wagons, each weighing around 104 tons, that exceeds 36,000 tons per train, predominantly composed of iron ore.

Figure 2.1: Carajás Railway - EFC (Estrada de Ferro Carajás)



Source: Columbia Center on Sustainable Investment (2020)

Of particular relevance from a shared-use perspective, Vale offers passenger services on the EFC, making it Brazil's longest railroad with passenger services. According to data from VALE, EFC transported 320,200 passengers in 2022. Passenger trains transport around 1,200 passengers each and have the priority of circulation over cargo trains (Columbia Center on Sustainable Investment, 2020).

2.2 Vale's initiatives and strategies for decarbonizing rail operations

In 2020, Vale announced an investment of between US $4 and $6 billion to reduce its direct and indirect emissions (scopes 1 and 2) by 33% by 2030. Today, Vale's rail network represents 10% of the company's carbon emissions. The initiative is one more step towards achieving the goal of zero emissions net carbon emissions by 2050, in line with the ambition of the Paris Agreement to limit global warming to below 2°C by the end of the century (Wabtec Corporation, 2023).

Since 2017, Vale company, has been unwavering in its commitment to decarbonize operations, with also emphasis on its expansive rail network among other numerous decarbonization initiatives. The company also committed to reducing its net emissions from its value chain (scope 3) by 15% by 2035.

The company has not only set emission reduction targets across Scopes 1, 2, and 3 but has translated these commitments into initiatives to curtail carbon emissions. For a clear understanding of emission scopes and associated initiatives, consult the following topics, summarizing insights available in the company's website publications, offering a succinct overview:

- Scope 1 - encompasses direct greenhouse gas (GHG) emissions stemming from operational activities, notably the combustion of fossil fuels in mines and plants, and fugitive emissions from equipment. Mitigating these emissions involves employing solutions such as fuel substitution, alternative processes, electric or battery equipment solution and implementing energy efficiency programs.
- Scope 2 - where the focus is on indirect emissions from purchased or acquired electricity, in order to achieve sourcing 100% of its electricity consumption in Brazil from renewable sources by 2025.
- Scope 3 - encompassing all other indirect emissions that occur in the value chain, Vale is targeting a 15% reduction by 2035. This includes emissions associated with purchased goods and services (like the production and transportation of fuel), capital goods (manufacturing and transportation of locomotives and rail infrastructure), and both upstream and downstream transportation and distribution.

Key initiatives for rail decarbonization within these scopes include fleet modernization, operational optimization through advanced technologies, fuel diversification with biofuels, hydrogen, green ammonia and significant investments in rail infrastructure upgrades. In this manner, Vale, through these initiatives, goes beyond mitigating its direct emissions and actively engages with the broader rail ecosystem fostering collaboration with stakeholders, and pioneering innovations through partnerships with various manufacturers and suppliers.

2.3 Vale Rail Decarbonization - First Steps: Challenges and lessons learned

2.3.1 Vale's Battery Electric Locomotives Prototypes Overview

In its journey toward energy transition, Vale has explored the realm of locomotive prototypes powered exclusively by batteries. The initial step in this exploration involved forming partnerships with two distinct suppliers, marking an ambitious endeavor to disrupt the market and introduce environmentally-friendly locomotives. The first two prototypes, initially designed for switch yard operations, were procured from the American company Progress Rail and the second one from Chinese company CRRC. The Battery Electric Locomotive (BEL), named Joule and ordered from Progress Rail, found its purpose on the EFVM (Estrada de Ferro Vitoria-Minas), the rail concession of Vale in the southeast of Brazil. While the second BEL, named Amazonas, was designated for use on the EFC.

Figure 2.2 - Progress Rail BEL “Joule” for EFVM (received in July 2020)

Source: (VALE, 2020)

Both locomotives were engineered with the capability to be charged through a reverse pantograph, as illustrated in Figure 2.3.

Figure 2.3 - CRRC BEL with battery charger and reverse pantograph for EFC (received in April 2022)

Source: Photograph is from the author's personal archive

2.3.2 EFC’s BEL, Challenges and Lessons Learned

Disrupting the rail market is not an easy task. The amount of energy required, combined with the operational rigidity of the system, presents significant obstacles for those seeking to introduce new technologies or approaches. Several factors contribute to the difficulty of disrupting the rail industry:

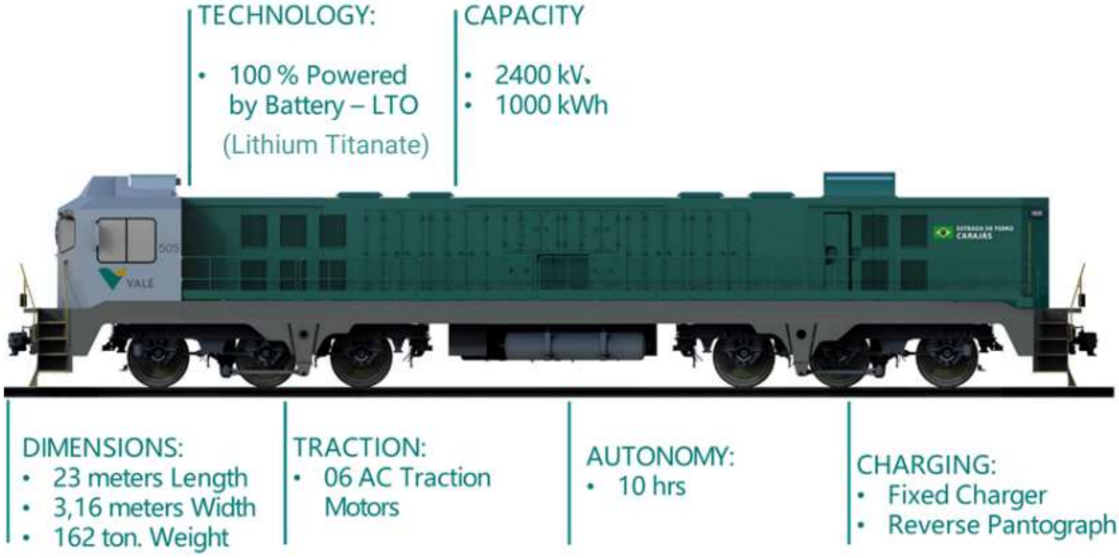
- High Energy Needs: Trains rely a lot on electricity or diesel. Changing this while keeping things efficient and eco-friendly is a big task.
- Not Flexible: Rail networks are fixed, so they can't easily adapt to unexpected situations and new requirements.
- Existing Infrastructure: Established infrastructure creates inertia and makes it difficult to implement sweeping changes.
- Rules and Regulations: Strict safety rules add complexity and slow down new ideas, especially those that technology that is totally new and without safety track record.
- Resistance from Current Players: Both within the company and in the industry, is significant. Companies already in the game often resist changes that could impact their market share. Internal resistance might come from employees who are unfamiliar with or perceive new ideas as threats.

An additional challenge for specific projects arises when unforeseen and uncontrollable external factors come into play right at the beginning. Take, for instance, the Vale EFC's BEL project, which commenced just before the outbreak of COVID-19. In this scenario, the challenges related to culture, distance, and technology, alongside the factors mentioned earlier, take on an even greater magnitude.

2.3.3 The Vale EFC's BEL Project

The project involved a prototype switchyard locomotive designed and manufactured by CRRC Zhuzhou Locomotive, a Chinese company. The locomotive battery charger, nevertheless, was designed by Progress Rail, american company, however manufactured in Brazil. The locomotive boasts the following technical characteristics as can be viewed on Figure 2.4 hereafter.

Figure 2.4 - CRRC BEL for EFC (received in April 2022)



Source: Picture adapted based on author's archive.

Selecting the optimal battery for a locomotive environment requires careful consideration of a complex interplay of factors. Critical variables like active material composition, energy density, power output, lifespan, cost, and safety must be meticulously balanced to achieve the desired performance and operational efficiency. These active materials behave in fundamentally different ways, significantly impacting each of these aspects. For example, a battery with high energy density might offer longer range but come at the expense of a shorter lifespan or higher cost.

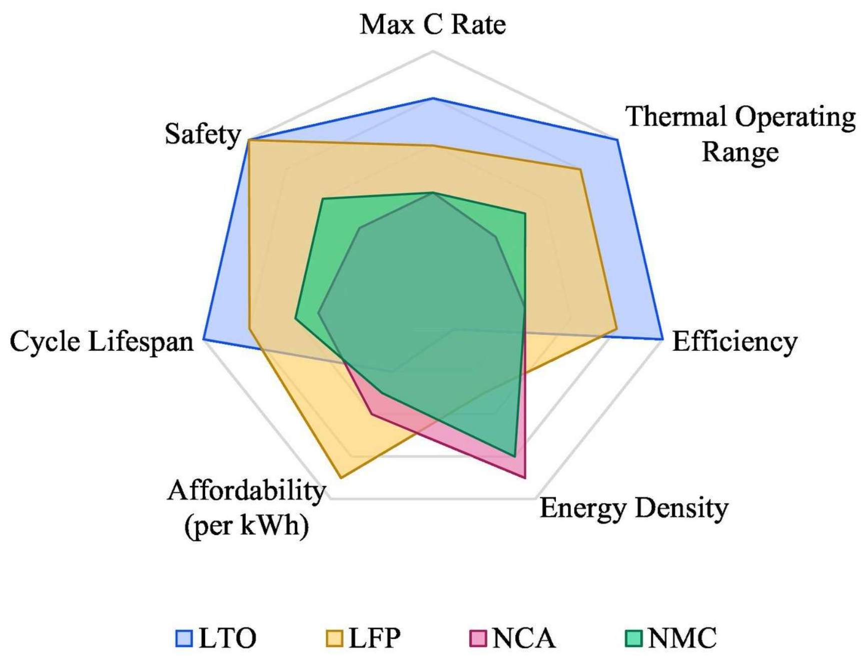
The specific locomotive of Vale EFC, in question, embraces the LTO (Lithium Titanate) battery chemistry, prioritizing crucial factors for its intended application. This choice prioritizes exceptional cycle lifespan and durability, exceeding 10,000 cycles compared to other chemistries as per battery and locomotive manufactured, in line with the wide researchers and publication. This translates to significantly reduced maintenance and replacement costs throughout the locomotive's lifespan.

Additionally LTO batteries boast inherent safety due to their stable chemistry and lack of dendrite formation, minimizing the risk of thermal runaway or fire, a critical factor for heavy-duty applications as can be expected on rail. Furthermore, LTO's ability to handle rapid charging and discharging with high current makes it ideal for applications with frequent bursts of high power demand, such as switching yards locomotives. The wide temperature range compatibility is another advantage, ensuring suitability for diverse operational environments, especially at Vale EFC, in the northwest of Brazil, where the average temperature is 30°C. While LTO comes with the trade-off of lower energy density compared to other options, requiring potentially larger packs for similar travel range, and a currently higher cost, the focus on durability, safety, and performance in demanding environments makes LTO an appropriate option, which was considered in this prototype.

The Figure 2.5 demonstrates the performance comparison of four of the most common commercial battery chemistries: Lithium Titanate (LTO), Lithium Iron

Phosphate (LFP), Nickel Manganese Cobalt (NMC) and Lithium Iron Phosphate (LFP) (Knibbe *et al.*, 2022).

Figure 2.5 - Performance of four of the most common commercial battery chemistries



Source: (Knibbe *et al.*, 2022)

2.3.4 The Vale EFC's BEL Battery Chargers Project

Due to the disruptive nature of the technological change, at that time, acquiring the battery charger from Progress Rail, an American company, was the only viable option. This decision was driven by two factors:

- Previous experience with EFVM's BEL locomotive: This implies that Progress Rail had successfully provided a charger for a similar locomotive in the past, demonstrating their expertise and compatibility with the technology.
- Lack of readily available alternatives: The statement suggests that other suppliers were unable to provide a charger capable of handling the specific energy requirements and control needs of the new locomotive.

Disrupting the rail market requires not only innovative technology but also a collaborative approach. The project highlights both aspects, showcasing the development of a revolutionary "agnostic" charger that could adapt to different locomotives from various manufacturers, what behind happened:

- Acquisition of the Charger: Due to the lack of readily available alternatives and their proven success with similar projects, Progress Rail was chosen to supply the charger.

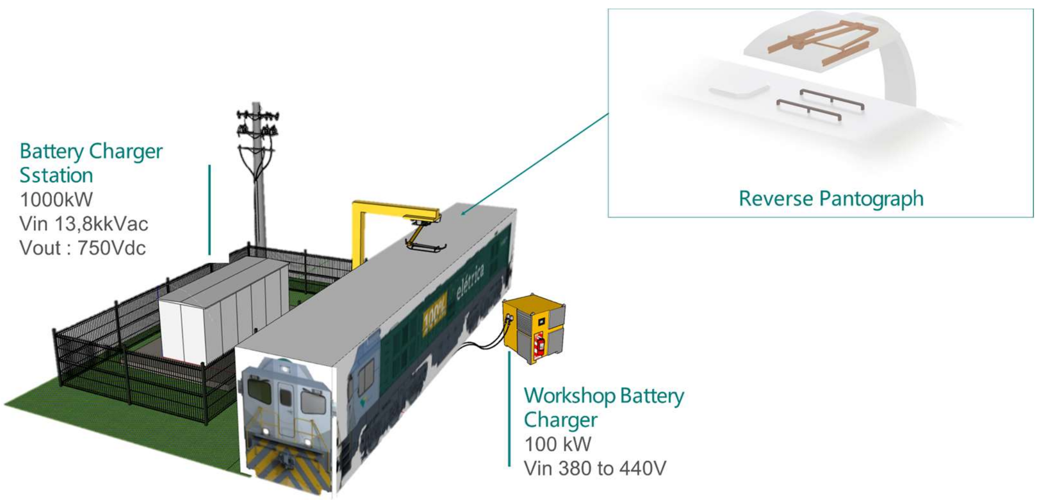
- Technological Integration: Collaboration went beyond simply acquiring the charger. The project embraced integration of technology from different suppliers, even competitors, to achieve the common goal of charger compatibility across diverse locomotives.
- Safety, Security and Operation Protocol: Recognizing the importance of safety and security, a dedicated integration protocol was developed. This ensures clear and secure communication between the locomotive and charger, protecting both operators and the system itself from potential cyber threats.

The project necessitated a forward-thinking approach, recognizing the importance of charger compatibility across various locomotives to achieve a common goal. This mindset aimed at addressing future needs and fostering adaptability within the evolving landscape of rail technologies. The goals on it was basically to:

- Increase competition and innovation in the field.
- Reduce costs and simplify maintenance.
- Enhance interoperability between different rail networks and different locomotive suppliers.
- Accelerate the adoption of new technologies and protocols across the industry.

This case study demonstrates how disruptive technology and collaboration can work together to drive progress in the rail industry. The agnostic charger concept paves the way for a more efficient, sustainable, and interconnected future for rail transportation. In Figure 2.6 the illustration of BEL, high power main charger with reversal pantograph and the low power workshop battery charger.

Figure 2.6 - Illustration with the BEL and its chargers



Source: Conceptual drawing based on author's archive

Both the workshop battery charger and the main charger prioritize operator safety by utilizing a fully automated process. This allows operators to control the charging remotely or directly from the cab, minimizing their exposure to potential hazards. A specifically designed communication protocol over a cryptofied Wi-Fi enabled secure and seamless interconnection between the locomotive and its dual battery chargers systems.

Though intended for maintenance with its low power, the workshop charger necessitates lengthy locomotive charging times. In contrast, the main charger swiftly restores full capacity (from 20% to 80%) in under an hour, minimizing operational disruptions.

2.3.5 Lessons Learned from Vale EFC's BEL

The locomotive battery charging project provided a valuable learning experience, shedding light on the intricate interplay between innovation and reality:

- Infrastructure planning is crucial: Securing high-capacity power near the yard, even if interruptible, proves necessary for efficient charging. This underscores the importance of collaborative infrastructure planning alongside technology implementation.
- Supplier integration takes effort: Integrating systems from competing suppliers demands significant effort and clear communication channels. Early collaboration and proactive conflict resolution are key to overcoming competitive barriers.
- Cultural shifts require patience: Introducing complex new technology involves navigating entrenched company cultures. Building trust and addressing concerns through transparent communication and shared ownership is crucial for successful adoption.
- Testing needs shared resources: Effective product testing necessitates cooperation between departments, even when priorities clash. Collaborative resource allocation and clear goal alignment are essential to overcome these challenges and ensure successful testing.

In essence, the project emphasized the value of holistic planning, open communication, and collaborative spirit when bringing groundbreaking technology into existing systems. By addressing these lessons, future endeavors can navigate the complexities of innovation with greater agility and success.

2.4 Vale Rail Decarbonization: Future Steps

Building upon the initial success of battery-powered switchyard locomotives in EFC and EFVM, Vale embarked on a comprehensive analysis and benchmarking process. Involving renowned researchers, engineers, manufacturers, and consulting firms, this endeavor aimed to identify and evaluate potential solutions for achieving carbon-free rail operations. This exploration yielded a diverse range of both unique and hybrid alternatives, including:

- Rail Electrification: This established solution involves the installation of overhead catenary wires to power locomotives directly, eliminating the need for onboard fuel.
- Heavy-haul Battery-powered Locomotives: These locomotives would be used as "helpers" to assist existing diesel locomotives on steep gradients, reducing overall fuel consumption and emissions.
- Hybrid Diesel-Electric Locomotives with Battery Packs: This hybrid approach combines a traditional diesel engine with a battery pack, enabling the locomotive to operate in electric mode in certain situations, minimizing emissions and fuel consumption.
- Battery Tender Car Concept: Specialized battery-powered car designed to be charged either by an overhead catenary system or from diesel-electric locomotive dynamic braking system. The purpose is to later utilize this charged car to supply power to a diesel engine or, potentially, to a heavy-haul Battery Electric Locomotive (BEL) in the future.
- Alternatives Fuels: Explore fuel alternatives such as hydrogen or ammonia to replace diesel on rail operations.
- Hybrid Train Configuration with Diesel Locomotives Boosted by BEL: Investigate options for enhancing trains by integrating Battery Electric Locomotives (BEL) and diesel locomotives. This configuration is augmented by dedicated trip optimization strategies to recover energy efficiently through dynamic braking.

Due to the inherent complexity and inflexibility of rail operations, combined with the varying levels of technological maturity, investment balance, and carbon life cycle across different solutions, Vale employed a Marginal Abatement Cost Curve (MACC) to assess and prioritize its decarbonization initiatives. This comprehensive tool allows Vale to:

- Evaluate the cost-effectiveness of each solution, considering upfront investment, operational costs, and long-term carbon reduction potential.
- Compare various technologies on a consistent basis, ensuring a balanced approach to investing in the most impactful solutions.
- Prioritize investments based on their potential to achieve significant emissions reductions while considering financial viability.
- Develop a strategic roadmap for transitioning to a carbon-free future for its rail operations, ensuring a phased and optimized approach.

By leveraging the MACC, Vale can navigate the complexities of rail decarbonization and make informed decisions about which solutions to prioritize in order to achieve its environmental goals in the most efficient and cost-effective manner.

Recognizing the multifaceted nature of decarbonizing rail operations, Vale acknowledges that a single, singular solution will not suffice. To pave the way for a cleaner future, a strategic mix of technological solutions is inevitable. Each technology, with its unique strengths and weaknesses, will be carefully considered to address specific opportunities and challenges within the network.

To build upon this discussion, the next section will briefly explore two additional solutions recently announced by Vale as part of their broader decarbonization strategy.

2.4.1 Hybrid Train Consist - BEL Booster + Diesel Electric Locomotive

The typical train on Vale's EFC line comprises 330 wagons, powered by a locomotive configuration determined by the required tractive effort. Options include three 5,800 HP AC locomotives (Evolution series from Wabtec) or four 4,300 HP DC locomotives (SD70 from Progress Rail / Wabtec), with mixed configurations also possible. To support these options, Vale maintains a diverse fleet of locomotives:

Line Operations:

- 98 AC locomotives, 5,800 HP, Evolution series (Wabtec)
- 55 DC locomotives, 4,300 HP, SD70 (Progress Rail)
- 112 DC locomotives, 4,400 HP, SD80 (Wabtec)
- 7 AC locomotives, 5,300 HP, SD80 (Progress Rail)

Switching and Services:

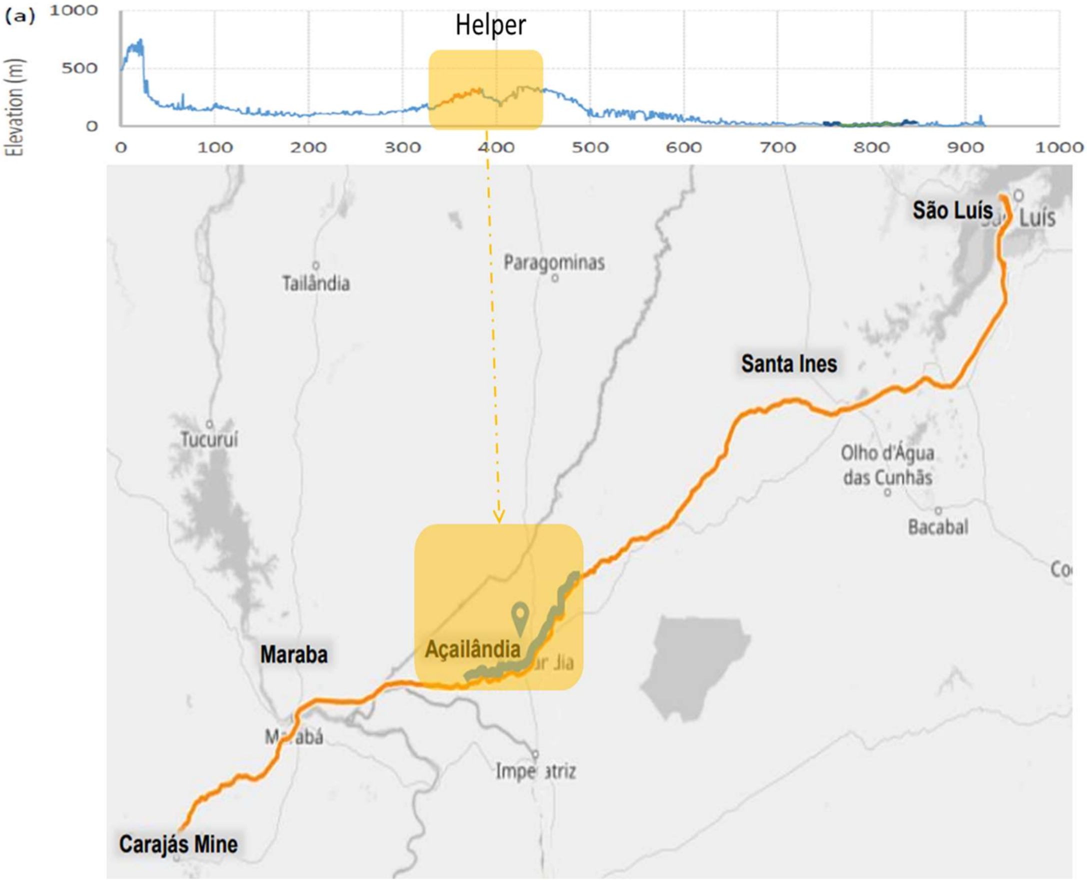
- 24 DC locomotives, 3,600 HP, C36 (Wabtec)
- 4 DC locomotives, 4,000 HP, C40 (Wabtec)
- 1 AC Battery Electric, 2400kW (CRRC)

As alternative, due the EFC altimetric rail profile, that can be viewed in the Figure 2.7, Vale announced a partnership with Wabtec Corporation to advance the decarbonization of the company's rail operations. The deal includes an order for three of Wabtec's FLXdrive[1] battery locomotives (Wabtec Corporation, 2023).

The Figure 2.7 provides a visual representation of the altimetric profile of the EFC rail from the mine to the port. The most challenging segment is concentrated in the Acailandia region, where the train, loaded with approximately 35,000 tons of iron across its 330 wagons, faces a nearly 140 km stretch of steep ascent.

[1] For customers in North America, South America, Central Asia, and Australia – Wabtec has a suite of battery-powered, heavy-haul mainline and switcher locomotives. These products are suitable for operation in multi- or single-unit consists providing reliable and safe zero-emission rail solutions. *Source: https://www.wabteccorp.com/FLXdrive-Battery-Electric-Locomotive?inline*

Figure 2.7 - Illustration with EFC Rail and its altimetric profile



Source: Drawing based on author's archive

In this specific rail segment, the train necessitates extra traction effort to smoothly overcome the challenge. This supplementary traction effort is supplied by two additional locomotives, typically four Dash9 units with 4400 hp each. These locomotives are dynamically coupled at the tail of the train, engaging just before the steep ascent. The coupling is facilitated by a modern control system that offers the conductor information and distance measurements through an optical laser system.

At EFC, a fleet of 22 Dash9 locomotives is exclusively dedicated to providing the extra traction needed in this segment. Operating in pairs, these locomotives collectively consume up to 25 million liters of diesel per year.

The FLXdrives will replace the two diesel Dash9 locomotives, known as “dynamic helpers,” that are used to pull the train uphill today. In this scenario, once delivered, the goal of the FLXdrives locomotives will be to join the diesel locomotives, forming Brazil’s first hybrid consist pulling the train. This move holds the expectation to retire the Helper locomotives in the future, thereby eliminating a significant amount of diesel consumption and reducing GHG emissions. The Figure 2.8 presents a brief specification published by the manufacturer.

Figure 2.8 - FLXdrive Locomotive Specification, Wabtec

FLXdrive Locomotive Specifications	FLXdrive Heavy-Haul
Applicable Regions	North America, South America, Australia
# of Axles	6
Wheel Arrangement	CoCo
# of Operator Cabs	1
Max Battery Capacity (MWh)	8.5
Max Traction Power (MW)	3.2
STE (klbf / kN)	200 / 890
Weight (klbs / tons)	432 / 196
Electric Supply	–

Source: (Wabtec Corporation, 2023)

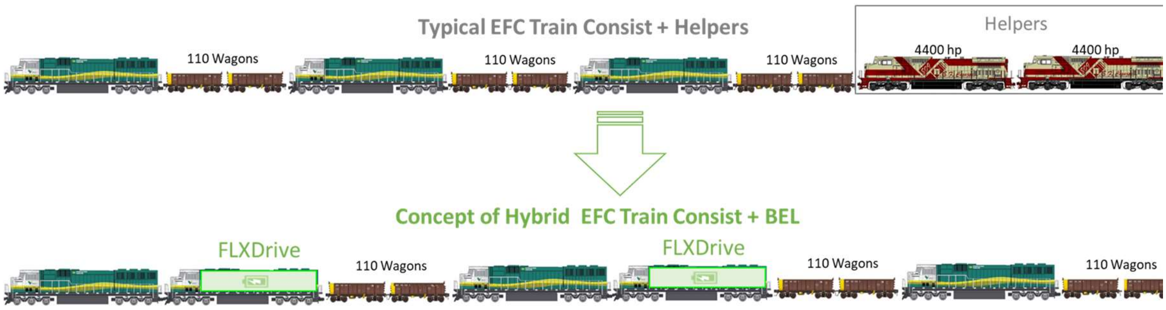
To achieve this reduction of diesel consumption and GHG emission, an advanced energy management system will be necessary. This system should optimize the trip by controlling the energy required by the train while simultaneously maximizing energy recovery to charge the batteries of the FLXdrives along the route as the train brakes.

As mentioned by manufacturer:

> “It's what we call regenerative energy produced by dynamic braking.In the downhill sections, The FLXdrive locomotives are estimated to save 25 million liters of diesel per year, considering the consumption of all the railway's trains that use the dynamic helper. This savings would reduce carbon emissions by approximately 63,000 tons, the equivalent emissions of around 14,000 passenger cars per year” (Wabtec Corporation, 2023).

The following figure illustrates the concept of a hybrid train consist, wherein conventional helpers could be replaced by the inclusion of Battery Electric Locomotives to recover wasted brake energy. This stored energy can then be used as needed throughout the journey, showcasing a more efficient and environmentally friendly approach.

Figure 2.9 - Hybrid train consist with the inclusion of BEL in place of Helpers



Source: Conceptual sketch from autor

Vale and the manufacturer plan to have the BELs available for testing up to 2026, where they will be evaluated for technical and operational feasibility validating the performance and effectiveness of the green locomotives in various operational scenarios.

2.4.2 Rail Green Ammonia Project

Brazil, brimming with untapped potential in renewable energy, particularly solar and wind, is actively exploring its potential to fuel the future. One promising avenue lies in converting this renewable energy into green ammonia, primarily through the Haber-Bosch process. While ammonia is crucial for agriculture, especially in Brazil, its potential as a clean alternative fuel for transportation is gaining momentum.

Ammonia has long been considered as a candidate vector for power generation, and has specifically gained significant interest recently. Though it is not free of drawbacks, ammonia has been identified as a promising potential alternative fuel for future power generation (Herbinet *et al.*, 2023).

In this way, Vale and Wabtec will also collaborate on a study of the use of ammonia as a clean alternative fuel, which does not emit CO_2. The study will initially validate performance, emissions reductions and feasibility within a lab environment and will last for two years (Wabtec Corporation, 2023).

Ammonia is expected to offer an expanded range compared with other carbon-free fuels. It also has a high-octane rating and users will benefit from a large-scale distribution infrastructure (Smith, 2023).

This collaborative venture between Vale and Wabtec signifies a groundbreaking project set to disrupt the market. Beyond the development of a locomotive engine powered by ammonia, it catalyzes the imperative need for a comprehensive infrastructure overhaul. This initiative extends its influence even further, acting as a catalyst for regulatory and policy adjustments necessary to accommodate the novel dynamics of ammonia as a clean alternative fuel.

The two-year study, focusing on performance validation and emissions reduction in a controlled lab environment, lays the groundwork for a future where ammonia could revolutionize carbon-free transportation. Smith's insights from 2023 shed light on a transformation that goes beyond a singular locomotive engine — it aspires to reshape the very fabric of the transportation ecosystem.

It is important to highlight the challenges about the introduction of an alternative fuel: Considering the For Battery Electric Locomotives (BEL), designed to augment the train's power, it has the potential for recharging during the trip. In this case, it is expected that operation itself will not be impacted by charging. However, for ammonia-powered locomotives, the refueling process will begin at established stations.

At EFC, for the current Diesel Locomotives, the fueling process unfolds in two scenarios: the main refueling happens at TFPM (Terminal Ferroviário Porto Madeira), and a secondary, complementary refueling takes place at Terminal Ferroviário Marabá, situated roughly 738 km away from TFPM.

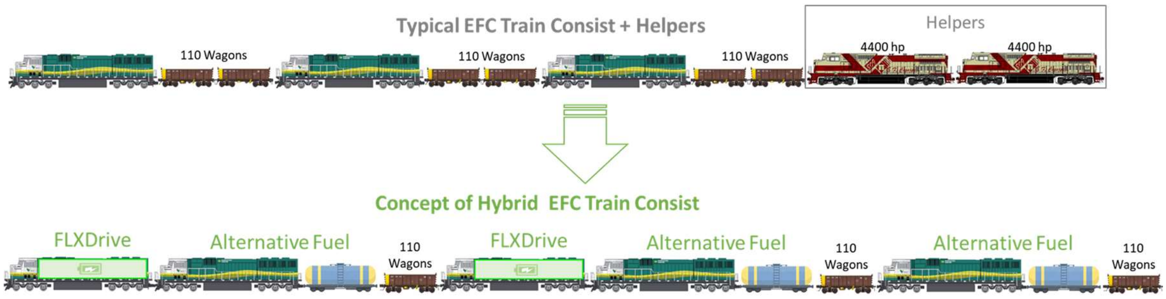
In TFPM, where the primary fuel station is situated, the process involves the following steps:

1. The train consist arrives at TFPM from the mine.
2. The 330 wagons are divided into three slots of 110 wagons each.
3. The locomotives transport these slots to different car dumpers.
4. While the slots are being emptied, the consist locomotives proceed to the Posto de Inspeção e Abastecimento (PIAL) for a maintenance inspection concurrent with refueling.
5. Considering a typical AC train consist, composed of three ES58ACi locomotives, each locomotive is fueled with up to 24,000 liters of diesel.
6. Within the same time window, as the wagons are emptied and locomotives are fueled, the train is reassembled for a new journey.

After the train departs TFPM en route to the mine for iron loading, the locomotives receive additional fuel at Marabá to ensure they have sufficient fuel for the return journey.

In the transition to a scenario where a mix of ammonia-powered trains, diesel engines and BEL possibly in a hybrid configuration, is envisioned, the ammonia locomotive's refueling process should align with the established fueling locations for diesel engines.

Figure 2.10 Hybrid train consist with the inclusion of BEL and Alternative Fuel



Source: Conceptual sketch from autor

However, considering the significant energy density difference between diesel (42.5 MJ/kg) and ammonia (18.6 MJ/kg), the ammonia locomotive might require a larger fuel reservoir or more frequent refueling along the trip. This characteristic adds complexity to finding a balance to avoid operational disruptions, such as frequent stops or the need for large additional fuel tanks in the consist.

As mentioned in (Herbinet *et al.*, 2023), ammonia is an important energy vector, and it is foreseen that it will play an important role in the future energy economy. While there remain many challenges before large scale deployment of ammonia as a significant energy vector, various works of safe utilization of ammonia as a fuel already underway could significantly advance its feasibility.

This necessitates additional considerations regarding safety protocols, fuel handling procedures, personnel training, and emergency evacuation plans, all tailored to the unique properties of ammonia. Moreover, there's a need to evaluate how the introduction of an alternative fuel will impact the overall operation and maintenance activities.

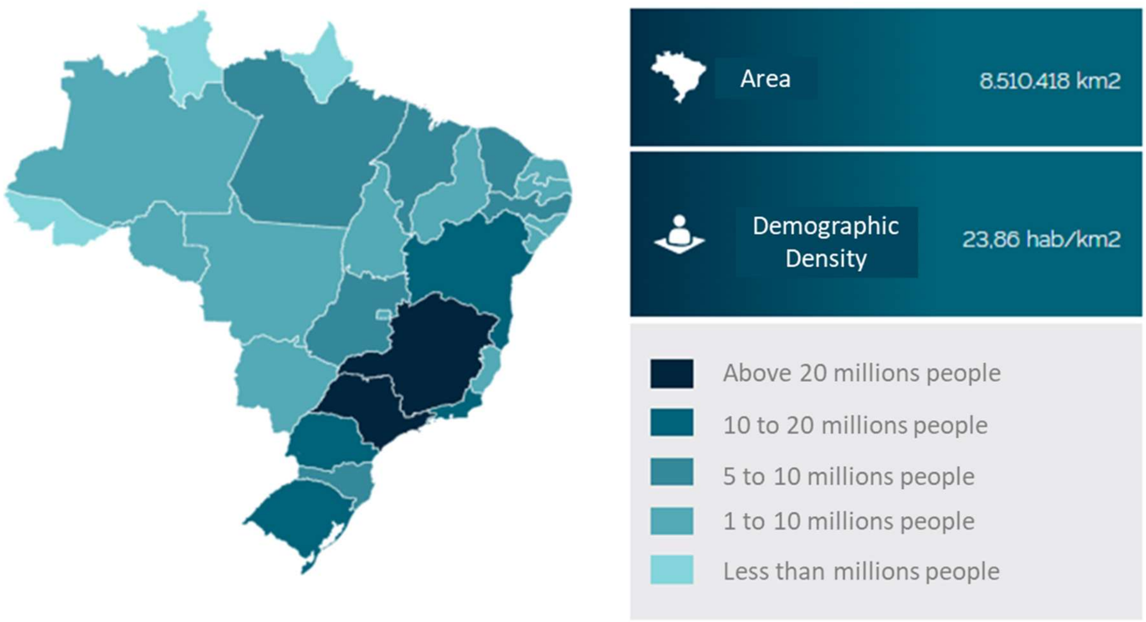
3 CHALLENGES IN DECARBONIZATION IN PASSENGER TRANSPORTATION

Within the scope of Brazil's rail decarbonization initiative, this section turns its focus to the challenges inherent in decarbonizing passenger transportation. Recognizing the distinctive aspects of this sector is essential for crafting strategies that align with the specific needs and expectations of passengers.

3.1 Exploration of challenges specific to decarbonizing passenger transportation in Brazil

Brazil is characterized by its large continental dimensions, with its about 203 millions citizens spreaded through 5570 cities. Nevertheless, according to the data from the Census of the Brazilian Institute of Geography and Statistics (IBGE) released in 2023, slightly more than 5% of Brazilian cities account for more than half of the country's population. In total, 115.6 million people, or 56.95% of the population, live in just 319 cities. Currently, Brazil has more than 5,500 municipalities, 41 of which have more than 500,000 inhabitants. This range concentrates 58.8 million people. Another 278 cities have between 100,000 and 500,000 inhabitants. Combined, they have a population of 56.7 million people.

Figure 3.1 - Brazilian Population Demographic Density



Source: (IBGE, 2023)

In this context, the urban mobility in Brazil is a challenge and the metro-rail transportation system in Brazil is available only in 15 cities: Belo Horizonte, Brasília, Cariri, Fortaleza, João Pessoa, Maceió, Natal, Porto Alegre, Recife, Rio de Janeiro, Salvador, Santos, São Paulo, Sobral, and Teresina. According to data from the balance of the metro-rail sector, released by the National Association of Passenger Rail Transport Companies (ANPTrilhos), in the year 2022, 7.8 million passengers were transported per day, representing 4% of the travel demand in Brazil (ANTP, 2018). In total, there are 1.129,4 km of operational commercial lines with 47 routes and 629 stations. The sector employs 38.200 employees, with 29.700 being permanent staff and 8.500 being outsourced (ANPTrilhos, 2022).

The Brazilian metro-rail transportation consists of 15 operators and 21 systems, operated in four modalities: Metro, Urban Trains, Monorails, and Light Rail Transit (VLTs), classified as small, medium, and large scale. Systems transporting less than 10 million passengers per year are considered small scale. Medium and large-scale systems are represented by subways and urban trains, accounting for 81% of passengers transported in the Brazilian metro-rail system (ANTP, 2018).

Figure 3.2 - Metro-rail transportation system in Brazil

Source: (ANPTrilhos, 2022)

Mega-cities like São Paulo face a transportation dilemma: how to build a mass rail system that eases congestion without further burdening dense, bustling urban landscapes. Underground metros offer a solution, but their astronomical costs often act as a deterrent. Surface railways, while more affordable, struggle to find space amidst the urban sprawl.

Light rail systems, like Rio de Janeiro's VLT, are making significant strides in urban mobility, especially for shorter urban journeys. However, their impact on commuter habits and addressing mass transportation needs might be more effective when integrated with a comprehensive network that includes underground and surface systems, forming a powerful triumvirate of transportation options.

For major cities, energy isn't the main barrier. Both systems can be powered by electricity, a great advantage of Brazil's electricity that is derived from clean sources[2], where these modes of transport hold the potential to be environmentally friendly. However, the challenge lies in optimizing their interplay to create a seamless mass transit network that effectively reduces car dependence. This means carefully considering factors like cost, space utilization, and connectivity to design a system that serves the specific needs of each megacity. While large Brazilian cities hold the potential for expansive, clean rail networks, a significant portion of the Brazilian population lacks any railway connections within and between cities and states.

3.2 CO_2 Emissions in Railway Systems

Emissions in railway systems encompass various stages. As highlighted by Andrade, Leal Junior, and Bittencourt (2013), 'CO_2 emissions in railway systems occur in various phases of their life cycle.' While non-operational phases focus on the construction and maintenance of infrastructure and vehicles, operational phases refer to the daily operation of these systems. This study specifically focuses on the operational emissions of these systems, as they have a direct and immediate impact on the environment.

When concentrating on operational emissions, it becomes evident that the consumption of electrical energy for train propulsion is a pivotal factor in these emissions. Matters such as the energy source used and the energy efficiency of trains are essential to understand and reduce such emissions. Strategies aimed at enhancing transportation system efficiency, such as seeking cleaner energy sources and implementing more efficient technologies, can play a significant role in reducing operational emissions.

Furthermore, considering the role of railway systems in the context of sustainable urban mobility underscores that these modes can play a fundamental role in reducing total emissions in urban environments. Therefore, understanding operational emissions not only provides crucial information about the environmental sustainability of these systems but also can influence urban policies and strategies aimed at reducing carbon emissions in cities and metropolitan regions.

3.3 Comparison with other transportation modes

The metro railway systems, when analyzed individually, are significant consumers of electrical energy. However, when comparing their consumption

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[2] According to the Ministry of Mines and Energy, in 2023, 85% of the electricity produced in Brazil came from renewable sources, and the plan is to reach 87% by 2030.

against their transportation capacity, it becomes evident that they are the mode of transportation with the lowest CO_2 emissions when compared to buses and cars.

According to Andrade (2016), an example of high energy consumption is observed in the London and New York metros, which consume 1TWh and 3.4TWh respectively. In Brazil, for instance, the São Paulo Metro consumed 561,341 MWh in 2012. The Table 3.1 presents the electricity consumption of some of the world's metro systems.

Table 3.1 - Annual Electricity Consumption of Metro Systems

Metro	Electricity Consumption	Source
New York	3.4 TWh	MTA (2008)
Hong Kong	1.4 TWh	MTR (2013)
London	1.0 TWh	LU (2009)
São Paulo	0.6 TWh	METRÔ SÃO PAULO (2014b)
Porto	0.5 TWh	METRÔ PORTO (2011)

Source: Adapted from Andrade, C.E.S. Thesis, Graduate Program in Transportation Engineering, COPPE, Federal University of Rio de Janeiro, 2016

To compare CO_2 emissions from the metro railway sector with other modes, it is important to adopt a single indicator. In this context, according to Andrade (2016), the measure grams of CO_2 per passenger-kilometer (gCO_2/PKM) is commonly used in evaluating the transportation system's efficiency in terms of CO_2 emissions. This indicator considers the total CO_2 produced per total passengers transported, multiplied by the average distance traveled during trips. Table 3.2 displays the outcomes of the indicator for several metros that have released their results.

The consumption data presented refers exclusively to direct emissions, which denote the energy used for train traction. Not included in these figures is the consumption designated for other purposes, such as station lighting and administrative areas. This distinction is crucial for understanding that the highlighted values represent only a portion of the total energy consumption of metro railway systems.

Table 3.2 - CO_2 Emissions from Train Traction Energy in Metro Systems

Metro	Annual Traction Energy (MWh)	Annual Emissions Produced (tCO_2)	tCO_2/MWh	Emissions (gCO_2/PKM)	Base Year
London	820,000	507,662	0.62	63	2008
Lisbon	57,102	28,304	0.50	33	2010
Rio de Janeiro	146,668	14,085	0.10	7	2013
São Paulo	437,500	42,000	0.10	6	2013

Source: Adapted from Andrade, C.E.S. Doctoral Thesis, Graduate Program in Transportation Engineering, COPPE, Federal University of Rio de Janeiro, 2016

When comparing the gCO_2/PKM emissions between the railway system and the road transport mode, the greater efficiency of the rail-based system in terms of emissions becomes evident. It is observed that all the analyzed systems have lower emissions than cars and buses. To enable comparison, Table 3.3 presents the CO_2 emissions for buses, automobiles, and metro systems in each of the locations.

Table 3.3 - Emissions in gCO_2/PKM for metros, cars, and buses

Location	Metros	Cars	Buses	Source (Metros)	Source (Cars and Buses)
London	58	170	80	LU (2009)	TFL (2010)
Lisbon	33	180	85	Metro Lisboa (2011)	AGENEAL (2005)
São Paulo	6	110	64	Metro São Paulo (2014)	Metro São Paulo (2014)
Rio de Janeiro	7	-	-	Metro Rio (2014)	Metro São Paulo (2014)

Source: Adapted from Andrade, C.E.S. Doctoral Thesis, Graduate Program in Transportation Engineering, COPPE, Federal University of Rio de Janeiro, 2016

3.4 Energy efficiency in Brazilian Metro Systems

As observed in Table 3.3, the efficiency of Brazil's rail transit systems is higher than that of the other listed countries. A contributing factor to this disparity lies in the energy generation sources powering these systems. Brazil predominantly relies on renewable energy sources for its electricity generation, primarily hydroelectric power. According to the Electric System Monitoring Bulletin in the Ministry of Mines and Energy, hydroelectric sources were responsible for 63.2% of Brazil's electricity generation in November 2019. This marks a distinct contrast to several other countries, particularly in Europe, where reliance on fossil fuels for energy generation persists.

Although its weight varies from country to country, in 2017, oil and its derivatives accounted for 41% of final consumption in the EU, followed by natural gas (22%). The use of clean energies, considering the transformation of water, sun, and wind into electricity, represented 21% of consumption.

Brazil's extensive utilization of hydroelectric power in its energy matrix significantly influences the emission rates of its metro systems. Hydroelectricity, constituting a substantial portion of Brazil's energy production, contributes to reduced carbon emissions as it is considered a cleaner and renewable energy source. In contrast, many European countries still rely heavily on thermal power plants, utilizing a mix of coal, oil, and gas, which tend to have higher carbon footprints due to their reliance on fossil fuels.

The reliance on renewable energy sources in Brazil's energy mix has rendered its metro systems comparatively more environmentally friendly. This dependence on cleaner energy contributes to the lower CO_2 emissions per passenger-kilometer (gCO_2/PKM) observed in Brazilian metros. These systems benefit from a more sustainable approach, effectively reducing their environmental impact compared to counterparts operating on fossil fuel-dependent grids.

The contrast in energy generation sources between Brazilian metros and those in Europe underscores the significance of energy mix in determining the environmental impact of transportation systems. The emphasis on renewable energy in Brazil's electricity generation lays a foundation for its metro systems to operate with lower carbon footprints, offering an example of how strategic energy planning can lead to more environmentally sustainable urban transport solutions.

The data highlighting the greater efficiency of Brazilian metro systems due to the country's reliance on renewable energy sources not only underscores the importance of energy mix but also serves as a testament to Brazil's commitment towards a greener and more sustainable future in its urban transportation systems.

3.5 Initiatives of Brazilian Metros Systems

The São Paulo subway system has an extension that includes 91 stations and covers a little over 100 kilometers of lines. In the year 2019, it recorded the transportation of more than 1 billion passengers, consuming a total of 473 GWh during the operation of the system (Reis, 2020). Given this scenario, the search for energy efficiency initiatives not only represents a significant reduction in operational costs but also assumes extreme importance for the reduction of emissions. In this context, according to the article "Energy Efficiency in Metrô-SP: Strategies to reduce energy consumption in trains through energy efficiency actions" (Reis, 2020), the company took a series of actions to reduce energy consumption:

1) Shutdown of the air conditioning and ventilation system of trains parked in yards

When trains are parked in yards at the end of the commercial operation, the air conditioning and ventilation systems are turned off. Table 3.4 presents the annualized results of the initiative.

Table 3.4 - Potential savings on the 3 lines through the shutdown of the air conditioning and ventilation system

Results	Line 1	Line 2	Line 3	Total
Annual Energy Savings (GWh/year)	1	8,2	1,4	10,6
Annual Avoided CO_2 Emissions (tCO_2)	76	618	106	800

Source: Adapted from Reis, W. Energy Efficiency in São Paulo Metro: Strategies to reduce train energy consumption through energy efficiency actions, presented at the 26th Week of Metro Railway Technology, 7th Metro Railway Technology and Development Award.

2) Shutdown of trains parked in yards

On weekends and holidays, it is not necessary for the entire fleet to remain connected to the power grid, available for operation. It is possible to operate with only the necessary fleet plus some reserves for each line. In this way, the other trains can be shut down in parking yards after the end of commercial operation on Friday (or the day before a holiday).

In this context, it was also recommended to shut down trains from older fleets (E and H) that have less efficient traction systems than the trains from newer fleets (METRÔ-SP, 2016). Table 3.5 below presents the annualized results of the initiative.

Table 3.5 - Potential Savings on 3 Lines by Shutting Down Trains

Results	Saturdays	Sundays and Holidays	Total
Annual Energy Savings (GWh/year)	0,7	1,9	2,6
Annual Avoided CO_2 Emissions (tCO_2)	54	141	195

Source: Adapted from Reis, W. Energy Efficiency in São Paulo Metro: Strategies to reduce train energy consumption through energy efficiency actions, presented at the 26th Week of Metro Railway Technology, 7th Metro Railway Technology and Development Award.

3) Retrofit of the main lighting in fleet h trains

According to Reis (2020), the trains of fleet H have main lighting composed of T5 fluorescent lamps. This is the only fleet where there has been no retrofit of lighting, with the replacement by LED.

In this initiative, it was recommended to replace the lighting bulbs of the trains in this fleet with LED bulbs. To make this possible, a change in the train lighting power supply system would be necessary, transitioning from 72Vdc to 220Vac. Therefore, for this initiative, an investment in the train compositions would be required. Table 3.6 below presents the expected return from the initiative, as well as the expected return on investment time.

Tabela 3.6 - Expected Results with the Fleet H Train Lighting Retrofit Initiative

Annual Energy Savings (GWh/year)	**0,327**
Payback (months)	10
Annual Avoided CO_2 Emissions (tCO_2)	24,6

Source: Adapted from Reis, W. Energy Efficiency in São Paulo Metro: Strategies to reduce train energy consumption through energy efficiency actions, presented at the 26th Week of Metro Railway Technology, 7th Metro Railway Technology and Development Award.

In addition to the initiatives presented, a myriad of other sustainability-driven measures has been undertaken, not only within the São Paulo metro but also across various operators of metro and passenger rail systems nationwide. The primary objective of the highlighted examples was to underscore actions that, despite requiring relatively modest investments, hold the potential for substantial returns in curtailing CO_2 emissions. This collective effort contributes significantly to the ongoing decarbonization initiatives within the operational framework of metro and rail systems throughout the country.

The trio of proposals delineated in the text stands out as compelling illustrations of this overarching strategy. These specific initiatives, designed with a focus on energy efficiency, not only bear the potential to save a noteworthy 13.5 GWh/year of energy but also exemplify a forward-looking approach. This quantum of energy is sufficiently substantial to meet the annual power needs of more than 3 thousand households, underscoring the impactful and sustainable nature of these interventions. Furthermore, the associated reduction in carbon emissions surpasses a significant milestone, eclipsing over a thousand tons of CO_2 annually, contributing measurably to the broader goals of environmental conservation and sustainable urban mobility.

3.6 Integration between modes of transport as strategy to decarbonization

The integration of different modes of transport, transport systems, transport policies, and transport technologies as a strategy to provide a more efficient, sustainable, and accessible transport network. Lah, Fulton and Arioli (2019) provide a comprehensive overview of decarbonization strategies for land transport, with a special focus on the role of urban mobility. The article explores decarbonization scenarios in medium-sized cities in emerging economies, highlighting the importance of sustainable and integrated urban mobility measures. Additionally, the study underscores the relevance of cities as centers of co-benefits for the transition to a low-carbon economy, addressing the interaction between local and national policy actions and institutions.

According to Lah, Fulton and Arioli (2019), transportation emissions can be reduced through three main strategies:

a. Integration of transport systems: coordination of various transport systems, including public transport, car-sharing, and cycling, can result in a more interconnected and accessible transport network.

b. Enhancing the efficiency of the modes: incorporation of transport technologies, such as electric vehicles, traffic management systems, and transport apps, can facilitate a smarter and more efficient transport network.

c. Integration of transport policies and reducing the total volume of travel and transport activities: The harmonization of transport policies, such as land use policies, parking policies, and fuel pricing policies, can contribute to a more sustainable and efficient transport network.

The study conducted by Wimbadi *et al.* (2021) presents important implications for policymakers and urban planners seeking to promote sustainable public transport systems in cities. The authors emphasize the need for an integrated approach, where innovative solutions are organized in an integrated manner to support low carbon mobility transitions.

The main implications for policymakers and urban planners aiming to promote sustainable public transport systems in cities are:

Tabela 3.7 - Strategies to promote sustainable public transport systems in cities

STRATEGY	OBJECTIVE
Integrated Approach	Policymakers and urban planners should adopt an integrated approach to maximize the potential outcomes of urban experimentation in reducing CO_2 emissions and realizing other benefits. This involves arranging innovative solutions in an integrated manner to support low carbon mobility transitions.
Strategic Planning	Urban experimentation serves as a critical platform to select and consolidate novel ASI-public transport measures supported by strategic planning to address long-term climate change targets in cities. Therefore, policymakers and planners should consider incorporating climate change targets into plans to support low carbon mobility.
Agenda-Setting and Long-Term Targets	Future urban transport experimentation for climate change should not be limited to testing and adopting technological innovations but should also involve agenda-setting to set long-term targets/pathways, including participatory backcasting approaches.
Global and Local Context	Policymakers and planners should recognize that low carbon mobility transitions are a spatially-constituted process, and urban experimentation plays a pivotal role in selecting and assembling novel measures at the local level.
Role Modeling and Knowledge Sharing	The experiences of cities in implementing urban public transport experiments, particularly in the rollout of Low Emission Vehicle technologies, can serve as role models for other cities. Policymakers and planners should facilitate knowledge sharing and learning from successful urban experimentation initiatives.

Source: Adapted from Wimbadi, R. W., et al. (2021). Urban experiments with public transport for low carbon mobility transitions in cities - A systematic literature review (1990–2020).

Considering these implications, policymakers and urban planners can leverage urban experimentation to drive the development of sustainable public transport systems and contribute to low carbon mobility transitions in cities.

3.7 Initiatives of regular passenger train operated by the concessionaire VALE

As part of Brazilian railway concessions, the governor proposes obligating concessionaires, under certain conditions, to implement public rail passenger transportation systems for communities residing near the tracks. This initiative aims to improve accessibility and foster economic development in these often marginalized areas. Currently, there are two regular passenger train lines in the Brazilian concessioned railway network. These trains are operated by the concessionaire VALE S.A. on the Vitória a Minas Railway - EFVM and the Carajás Railway - EFC, as a result of obligations contained in the respective concession contracts (ANTT, 2023).

In 2022, EFC transported 320,200 passengers, while EFVM served 429,000 passengers during the same period. EFC operates in 23 municipalities in Maranhão and four in southeastern Pará. In contrast, EFVM connects 30 stations, bridging the municipalities of Belo Horizonte in Minas Gerais and Vitória in Espírito Santo. VALE plans to increase the offer of passenger rail transportation on both lines. On EFC, the offer is expected to be doubled, from one pair of trains per day to two pairs per day, as of December 2026. On EFVM, the offer is expected to remain at one pair of trains per day, but with the inclusion of a new passenger car (ANTT, 2023).

Figure 3.3 - Vale’s Railways

Source: Conceptual drawing based on author's archive

These railways, originally conceived for transporting iron ore, lack crucial infrastructure for passenger service. Notably, they operate entirely on diesel fuel, and the prospect of electrification faces significant challenges. Two major hurdles stand out: the astronomical cost of electrifying such vast stretches of track and the uncertain availability of sufficient electric energy across the entire network. Converting diesel locomotives and installing overhead catenary systems would require colossal investments, straining both concessionaires and potentially public funds. Furthermore, guaranteeing a stable and adequate supply of electricity along the railways' extensive routes raises concerns about infrastructure limitations and potential strain on local grids capacity. These aspects make it difficult to realize net-zero emissions considering electricity as a power source for heavy haul and passenger transportation in these railways.

Nevertheless, exclusively having a focus on passengers, despite these obstacles, addressing the transportation needs of communities surrounding these railways remains a crucial consideration. Exploring alternative solutions, such as modernizing diesel engine technology or implementing hybrid options, might offer more feasible pathways towards improved regional accessibility.

Vale's passenger trains, typically hauled by powerful 4300hp diesel-electric locomotives, rely on just one locomotive per train formation on both the Estrada de Ferro Carajás (EFC) and the Estrada de Ferro Vitória a Minas (EFVM). While the EFC typically uses SD70 DC locomotives from Progress Rail, the EFVM often employs C44 DC locomotives from Wabtec.

Despite these passenger trains utilizing diesel in its locomotives and generator cars, these trains inherently exhibit significant emission reductions when compared to alternative modes of transportation catering to the same passenger volume. Even in front of several challengers, and even considered the train already efficient in terms of emission, the passenger train for EFC and EFVM could be ideal candidates for transitioning toward even cleaner solutions, such as partial electrification or hybrid technology. However, these alternatives must be carefully considered and implemented to avoid conflicting with the primary business core. Concerns about charging infrastructure (in the case of battery electric locomotives) and the availability of alternative fuels can impact the logistics system, potentially deprioritizing the adoption of new technologies.

With a substantial number of passengers transported annually by both railways, the adoption of cleaner solutions for passenger trains becomes a potent avenue to heighten environmental awareness among users. Making a conscious choice in favor of an environmentally friendly rail alternative holds significant potential in contributing to emission reduction, underscoring the pivotal role of sustainable transportation choices.

4 REGULATION AND LEGISLATION FOR NEW ENERGY SOURCE ADOPTION IN BRAZIL

This section delves into the labyrinthine realm of regulations and legislation shaping the adoption of alternatives in the energy transition in Brazil's rail sector. We will dissect it based on three key aspects: compliance, incentives, and barriers, uncovering both the green shoots of progress and the tangled weeds hindering further advancement.

4.1 Review of current regulations and legislation related to decarbonization in the Brazilian rail sector

In Brazil, regulatory agencies are relatively recent, having been established after the 1990s in response to the need to carry out privatization processes following the opening of the Brazilian market. These agencies were created to regulate and oversee concessions, privatizations, and permissions granted to private institutions to explore specific sectors of the economy. In simple terms, "Concession" refers to the temporary transfer of public assets to private companies to manage and exploit these assets. "Privatization" involves the definitive sale of a public asset to a private company for management, while "Permission" is an instrument in which the government authorizes a private company to carry out an activity of predominant public interest, with the possibility of unilaterally revoking this permission.

The Federal Constitution of 1988 established the foundations for the reorganization of the State's role in the Brazilian economy, allowing the private sector to participate in sectors previously exclusively operated by the State, such as energy, telecommunications, and transportation. During the 1990s, faced with the government's inability to invest in railways, a decision was made to privatize a significant portion of the national railway network. This included the privatization of Vale S.A. in 1997, following an integrated model comprising mine, railway, and port operations, aiming for operational efficiency and competitiveness in the sector.

After the privatizations and railway concessions in the 1990s, the need arose to create an agency to control, manage, and regulate this sector. In 2001, the government created the National Council for Integration of Transport Policy, the National Land Transportation Agency (ANTT), the National Waterway Transportation Agency, and the National Department of Infrastructure of Transportation.

The ANTT aims to implement policies formulated by the National Council for Integration of Transport Policy and the Ministry of Transportation, regulate and supervise activities related to the provision of services and the exploration of transport infrastructure, ensuring efficiency, safety, comfort, regularity, punctuality, and moderation in freight and tariffs. The responsibilities of the ANTT include regulating railway and road transportation, formulating norms and regulations, overseeing service provision, authorizing projects and investments, among other duties.

Comparatively with regulatory agencies around the world, the regulatory process in Brazil is recent and in development. The country has agencies like ANATEL (1997) and ANTT (2001), while other nations established their agencies much earlier, highlighting the need for maturation and the complexity of formulating long-term policies in the country. In 2015, faced with the need for investments in the national railway network, the government initiated studies to anticipate renewals of railway concessions. This move aimed to modernize contracts, invest in security, carry out cross investments, and share infrastructure, contributing to the increase of direct and indirect jobs.

On December 23, 2021, Law No. 14.273/2021 was enacted, instituting the Legal Framework for Railway Transportation. This law seeks to simplify and streamline the procedure for the exploration of railway transportation services, attracting private investments and allowing self-regulation of the sector. This evolution in the regulation of the national railway sector is essential to meet the country's needs, especially in the context of a sometimes precarious road transport matrix, high CO_2 emissions, and significant logistic costs impacting the competitiveness of Brazilian products abroad.

The decarbonization of railways gained momentum in the face of advancing technologies, increased discussions on ESG-related topics, and the need for companies, especially those listed on stock exchanges, to take on the responsibility of being key players in such a relevant issue for society. However, the regulation of sectors to meet companies demands and national and international emission reduction agreements has not kept pace with the planned actions. This has necessitated additional government action to approve projects and laws aligned with these new premises. The Brazilian market is marked by a sluggishness in the approval of measures, laws, and regulations by responsible agencies, resulting in overlaps of projects and, in some cases, drastic changes to their initial requests.

According to Ungaretti *et al.* (2023), on the publication ESG: A Pocket Guide to the Main Regulations in Brazil by Xp Expert, the main projects and laws in Brazil can be divided into high-emission reduction and efficiency gain, chain value management as the main risk, and a growing institutionalization of governance. This text will mainly address the first topic, highlighting the main regulations for Brazil to achieve the goals set in the 2015 Paris Agreement.

To meet these demands, initiatives related to waste management, sanitation, biodiversity, renewable energy, regulated carbon credit markets, biofuels, and clean technologies are discussed. Two topics take center stage in renewable energy opportunities: the modernization of the electrical sector, addressed by Proposal of Law 414/2021, which aims to expand and open the energy market in Brazil, allowing consumers to negotiate with various suppliers, including opting for more sustainable sources; and the Legal Framework for Green Hydrogen, with ongoing projects in the Chamber of Deputies and the Senate.

The Proposal of Law in progress (PL 2308/2023 and PL 5816/2023) on Green Hydrogen are expected to intensify discussions in 2024. While the Chamber's project mainly addresses the taxonomy for low-carbon emission hydrogen, the Senate's includes topics such as Renewable Hydrogen and Green Hydrogen. Both emphasize the role of the National Petroleum Agency (ANP) and the National Electricity Regulatory Agency (ANEEL) in production authorization, with the possibility of causing delays in approvals. The projects seek to establish policies to incentivize the production and use of Green Hydrogen, with the Senate's project linking this incentive to the existing Special Incentive Regime for Infrastructure Development (REIDI), excluding biogas and biomethane producers. The Chamber's project creates the Special Regime of Incentives for Low Carbon Emission Hydrogen Production (Rehidro), including biogas and biomethane producers, but does not clearly detail the fiscal benefits.

A point of attention is the certification of Green Hydrogen, with PL 2308 proposing the creation of the Brazilian Hydrogen Certification System (SBCH2) to regulate the sector, accounting for greenhouse gas emissions in the production chain. Regarding the carbon market, PL 5816 foresees measures to support the development of projects related to carbon asset generation in the context of low-carbon hydrogen production. However, PL 2308 does not address this market.

In December 2023, the Legal Framework for Green Hydrogen (PL 2308) was approved by the Chamber of Deputies, heading for approval by the Federal Senate and subsequently by the President, thereby becoming law. However, the absence of fiscal incentives in the approved text may hinder the achievement of emission reduction goals and weaken the production market. To mitigate this impact, some Brazilian states have reduced state taxes to attract investments.

4.1.1 Compliance and Emission Standards

Contrary to emissions from road vehicles, whose limits are regulated by the PROCONVE (National Program for Air Pollution Control by Motor Vehicles) through Resolutions of the National Environment Council (CONAMA), there is no specific regulation for railway emissions in Brazil. Thus, average emission factors for locomotives in operation in Brazil are not available.

In the realm of emission inventory, it wasn't until 2012 that ANTT (National Land Transport Agency) initiated comprehensive efforts with the 1st National Inventory of Atmospheric Emissions from Freight Rail Transport. Prior to this, the railway subsector, particularly in freight transport, lacked a specific study. This study aimed to provide a simultaneous understanding of both air pollutant emissions and Greenhouse Gas emissions for the entire subsector. It also delved into the specific contributions of individual railway transport concessionaires.

Basically, this inventory marked the initial understanding of the sector, encompassing not only GHG but also the estimation of emissions of CO_2, CH_4, N_2O, CO, NMVOC, NOx, and particulate matter (MP) from 2002 to 2010. In summary, this 1st National Inventory of Atmospheric Emissions from Freight Rail Transport allowed:

- Enhance institutional capacity at the federal level to encourage the proper application of methodologies for estimating emissions in the subsector.
- Deepen knowledge about the emissions profile of concessionaires for both air pollutants and GHG.
- Organize, provide transparency, and ensure full access to information generated in the sectoral regulation sphere.
- Reflect the results in the pursuit of environmental improvements in freight transport in the country.

- Contribute to the development of the Sectoral Plan for Transport and Urban Mobility for Mitigating Climate Change (PSTM).

Brazil's ambitions for a cleaner rail sector face a crucial hurdle: the inadequacy of current emission standards for new energy sources. Examining existing regulations through the lens of government mandates, industry initiatives, and international comparisons reveals a stark gap between aspiration and action, where:

- National Climate Change Policy - PNMC (Ministry of Environmental, 2023): While ambitious in its overall goals, the PNMC lacks specific emission standards for the rail sector, offering limited guidance for incentivizing cleaner technologies.

- CONAMA Resolution 416/2014 (CONAMA, 2009): This road vehicle standard, though not directly applicable to railways, serves as a rudimentary benchmark. However, its focus on conventional fuels fails to address the unique emissions profiles of newer options like hydrogen locomotives or biofuels.

- National Urban Mobility Policy - PNMS (Federal Law No. 12.587/2012): Like the PNMC, the PNMS falls short of concrete emission targets for rail, instead emphasizing broad sustainability principles. This vagueness hinders the development of effective compliance mechanisms.

Nevertheless, industry initiatives are shedding light on a transformative potential that could significantly support and elevate the rail sector. This industry, marked by its commitment to sustainability and decarbonization, emerges as a focal point where the integration of new technologies and substantial research and development (R&D) investments is not just beneficial but increasingly imperative.

The propulsion toward decarbonization has emerged as a compelling force, compelling the rail sector to adopt innovative solutions. In response to the urgent imperative to reduce carbon emissions and shift towards cleaner alternatives, the rail industry has positioned itself as a trailblazer in this transformative paradigm shift. Industry stakeholders acknowledge the pivotal role of substantial investments in research and development (R&D) to drive the creation of cutting-edge technologies. These technologies not only improve efficiency and sustainability but also enhance the overall environmental performance of rail transportation.

This active involvement by the rail industry holds broader significance, as it shapes the discourse that could potentially influence standards and guide local legislators in formulating future benchmarks. Such influence extends to proposing tailored emission standards for various modes of transportation, complete with specific targets, with a particular focus on the environmental impact of locomotives. It is essential to note, however, that while these industry recommendations are commendable, they have yet to be translated into concrete legislative measures, especially in Brazil. Bridging the gap between industry insights and legislative action remains a crucial stride toward realizing impactful change and ensuring that the entire sector adheres to environmentally responsible standards.

On the other hand, upon examining international comparisons, it is evident that various initiatives have already been implemented to establish standards to which the rail sector must adhere.

In Europe, the imposition of stringent emission standards, exemplified by Euro 6 for heavy, has spurred notable technological advancements and the widespread adoption of cleaner alternatives. In contrast, Brazil lags behind in this regard. The Euro Standards considered within the implementation Stage III/IV, regulations in terms of emissions to be applied for new railroad locomotives, that have to be in compliance with the limit emissions, inclusive the GHG.

In North America, the 1998 Federal off-road engine regulation was structured as a three-tiered progression, with each tier involving a phased-in approach based on horsepower (hp) ratings over several years. The implementation timeline for these tiers unfolded as follows: Tier 1 standards were phased in from 1996 to 2000, Tier 2 from 2001 to 2006, and Tier 3 from 2006 to 2008. Subsequently, Tier 4 standards were phased in from 2008 to 2015, and as of 2012, all diesel off-road vehicles, including locomotives, are required to comply with stringent emission regulations, including greenhouse gas (GHG) standards (World Health Organization - IARC Monographs, 2012).

The Environmental Protection Agency's (EPA) Tier 4 standards for locomotives stand as a noteworthy example, illustrating the feasibility of establishing ambitious targets for reducing emissions. This underscores the pivotal role of regulatory frameworks in propelling the rail industry toward environmentally responsible practices while concurrently fostering innovation on a global scale.

4.1.2 Alternative Fuel Types

In Brazil, there is not a significant restriction on the use of alternative fuels in railway operations. Biodiesel has been widely adopted in Brazilian locomotives, with testing initiated more than 20 years ago. According to Murta *et al.* (2022), the tests conducted with palm oil biodiesel in ore-carrying railway locomotives yielded positive results. The study describes a pioneering project in the use of palm oil biodiesel (B20) in railway ore transport locomotives. The tests were conducted on locomotives of Vale S.A., one of the world's largest mining companies, between January and December 2006.

The locomotives were subjected to tests under operating conditions on the Vitória Minas Railway (EFVM), with one locomotive fueled with petroleum diesel oil (control locomotive) and another fueled with 20% palm oil biodiesel (test locomotive). The locomotives were coupled with a jumper cable to ensure the same traction effort in both. The results of the tests were very positive, which led to a change in the company's fuel matrix. From 2007, the company started using B20 regularly in part of its fleet, demonstrating the good performance of palm oil biodiesel in railway ore transport locomotives.

Currently, locomotives in circulation in Brazil, according to the study on palm oil utilization, use a blend of approximately 20% biodiesel and 80% petroleum diesel (B20). The study estimates a reduction in emissions when using B20 in a Dash 9 locomotive on the EFVM railway, as presented in Table 4.1.

Table 4.1 - From the Palm Oil Utilization Study - Expected percentage reduction in pollutant emissions using B20 in a Dash 9 operating on the EFVM

Pollutant	Percentage Reduction (%)
CO_2	1,57
CO	-9,09
HC	-19,17
NO_2	-6,08
O_2	-0,05
SO_2	-23,42

Source: According to Murta, Freitas, and Murta (2022), the tests conducted with palm oil biodiesel in ore-carrying railway locomotives yielded positive results.

The government is actively working on updating the Social Biocompatible Seal, aiming to ensure that half of the purchased product for biodiesel production comes from family farming. The government's future expectation is to achieve a biodiesel blend of 25%, higher than the current practice, although it remains to be seen if family farming will be able to generate the necessary input for companies to use fuel with the social seal.

Hydrogen does not yet have a defined regulation, as mentioned earlier, allowing its use without restrictions. Tests with locomotives using biodiesel and natural gas, as well as 100% electric locomotives, are still being conducted. In Brazil, there is a lack of incentives for the use of cleaner energies, and this movement is primarily driven by existing concessionaires in their pursuit of cleaner operations.

4.1.3 Barriers and Incentives

For railways, the Legal Framework for Railways, instituted by Law N. 14.273 on December 23, 2021, aimed to organize and facilitate various processes related to the implementation of new railways, expansion of existing ones, and improvement in the use and sharing of infrastructure. The main improvements introduced by this legislation are related to the exploitation regime, transitioning from concession to authorization. The law establishes new rules for requesting the deactivation or deauthorization of unviable ventures, defines responsibilities and competencies of the regulatory agency, even allowing for self-regulation. Additionally, it introduces new participants in the private regime process, such as the investor-associate and the user investor.

The terms "investor-associate" and "user investor" are crucial to advancing the process, facilitating improvements and expansions in the railway network by private initiative. The investor-associate is someone who invests in the construction, improvement, adaptation, expansion, or operation of adjacent facilities, aiming to enable the provision or enhance the profitability of services associated with the railway. The user investor, on the other hand, is a legal entity that invests in increasing capacity, improvement, or operational adaptation of railway infrastructure, rolling stock, and ancillary facilities, aiming to enable the execution of railway services and related or associated services.

Article 19 of the law establishes the contract period, which can extend up to ninety-nine years, allowing for successive extensions as long as the authorized party expresses an interest in renewing and is operating the railway at minimum standards of operational safety, production, and quality.

In December 2022, Decree No. 11,245 was signed, creating the Railway Development Program and regulating points of the Railway Law, such as the expropriation of real estate and its reversal, in addition to establishing deadlines for obtaining licenses, installations, and operation. These guidelines created the necessary framework to provide security to investors and expand the railway sector in a less bureaucratic manner, initially meeting the needs of routes requiring a more robust transportation mode.

The government aims to facilitate the implementation of new railways and their expansions, primarily through two major Incentive Regimes: REIDI (Special Incentive Regime for Infrastructure Development) and REPORTO (Tax Regime for Incentive to Modernize and Expand Port Structure).

REIDI exempts companies from the collection of PIS/PASEP and COFINS contributions for the sale or importation of new machinery, devices, instruments, equipment, and construction materials for use or incorporation into infrastructure projects.

REPORTO benefits companies with exemptions from IPI and II, in addition to the same exemptions provided by REIDI. This regime allows the importation of machinery, equipment, spare parts, and other goods with the suspension of federal taxes when directly imported by beneficiaries and destined for their fixed assets for exclusive use in modernizing and expanding port facilities. While it is intended for the modernization and expansion of ports, REPORTO also applies to goods used in the execution of freight transport services on railways and to rails and other elements of railway tracks.

These measures create a conducive environment for investments and promote the development of the railway sector, contributing to a more efficient and sustainable expansion. By exempting companies from significant contributions, the government seeks to make the investment in railway projects more attractive, benefiting not only private initiatives but also contributing to regional and national economic development.

REPORTO, extending to the railway sector, is extremely relevant, considering the crucial role that railway transport plays in logistical efficiency, emissions reduction, and logistics cost reduction. Its extension to encompass goods used in railways, such as rails and elements of railway tracks, demonstrates an understanding of the importance of this mode in the freight transport landscape.

These incentive regimes create conditions for the railway sector to grow and modernize, expanding current volumes and meeting the growing demands for transport. They also aim to attract investors who, in conjunction with enacted laws and decrees, contribute to development through ease and security in investments.

An integrated policy of incentive regimes and robust laws is essential for the expansion of services and the pursuit of more efficient systems to become increasingly real.

4.2 Identification of regulatory gaps and proposals for adjustments

Building on the review, this section identifies regulatory gaps that may hinder the smooth integration of new energy sources into the Brazilian rail sector. By pinpointing these gaps, we aim to propose targeted adjustments and enhancements to the existing regulatory framework. This involves considerations of technological advancements, industry best practices, and alignment with broader sustainability goals. The ultimate goal is to contribute to a regulatory environment that actively supports and accelerates the adoption of new energy sources, fostering a conducive atmosphere for successful decarbonization initiatives in Brazil.

When we confront concession contracts in the face of technological and operational efficiency advancements, we observe a rigidity in the contracts that may hinder progress or more efficient operations.

Contracts signed in the 1990s scarcely delved into best practices for addressing ESG demands. The contract-linked goals were primarily associated with Railway Accidents and Transported Volume.

With the early extensions of concession contracts, there has been an evolution, allowing better monitoring by the regulatory agency. New contractual goals, such as Average Speed, Maximum Age of Locomotive Fleet, Railroad Saturation, and Serious Accidents, have been implemented. Additionally, an Investment Plan in infrastructure works for the communities around railways has been established, aiming to ease existing conflicts and enhance urban mobility, safety, and well-being in these communities.

In this context, we can note that forces contrary to the emissions reduction and sustainability process may arise. For instance, the Average Speed target, if not met, can result in penalties such as warnings or fines for the concessionaire. These penalties may occur even if the concessionaire is operating with sufficient capacity at speeds below those specified in the contract, regardless of how efficient the operation is in terms of fuel consumption and emissions.

The new contracts also stipulate materials for level crossings and enclosures, limiting the use of new technologies, renewable materials, or those with better efficiency and application. The need for "asphalt" on the surface of level crossings, for example, hinders the use of new technologies such as Polymeric sleepers, which, in many cases, may be more efficient for operation, safer for the community, and environmentally advantageous due to the use of recycled materials. Concerning Domain Fence Enclosures, their construction in "concrete block masonry" is mandatory, preventing the use of products with technologies that provide more efficient sealing and dampening of sound emissions.

On the other hand, the new Maximum Age of Locomotive Fleet target aims to update the equipment used in Brazil, bringing greater modernity to the sector with more efficient locomotives, lower consumption, and greater power.

It is worth noting, in Annex 9 of the contract for the Vitória to Minas Railroad, the construction of the FICO - Midwest Integration Railway in contrast to the early renewal of the contract through the creation of the cross-investment model. This contract imposes various obligations related to socio-environmental conditions, including, for example, the obligation to develop and approve the Indigenous Environmental Basic Plan (PBACI), fulfill obligations related to Environmental Compensation, and prepare the Participatory Socio-Environmental Diagnosis (DSAP) for impacted communities, among others. This evolution in the construction projects of new railways in Brazil demonstrates the importance given to environmental and socio-economic issues, aiming to mitigate interferences and be prompt and fair in expropriation processes.

5 CONCLUSIONS

In conclusion, the pursuit of decarbonization has presented significant challenges, but it has also propelled sectors like rail transport to embrace innovative and sustainable initiatives. Faced with the increasing need to reduce carbon emissions and promote more ecological practices in transportation, the railway industry has stood out by implementing solutions that aim not only for operational efficiency but also for the minimization of environmental impact. From investments in cleaner technologies to the adoption of smarter logistical strategies, railways have adapted to confront the challenges posed by decarbonization, thereby fostering a more sustainable and ecologically balanced future for transportation. These initiatives not only meet the growing demands for environmental responsibility but also underscore the importance of innovation and collaboration in the quest for effective solutions to the contemporary obstacles of the transportation sector.

The primary aim of this study has been to outline the challenges and opportunities associated with the transition of energy matrices in railway systems, with a specific focus on heavy haul and passenger transportation. The Carajás Railway has been examined as a case study, shedding light on its various initiatives aimed at embracing more sustainable energy sources. Through an emphasis on the initiatives and outcomes of its decarbonization pursuits, offering insights that extend to broader conversations about sustainable rail practices in Brazil.

When we consider the challenges of decarbonization in the context of the Brazilian rail systems, we discern an intricate interplay of geographical, infrastructural, and operational factors. The vast expanse of Brazil, combined with the intricate nature of the railway network spanning over 29,000 km, poses significant obstacles to the transition towards more sustainable practices.

The importance of the rail mode in linking production zones to export locations, especially for critical commodities like iron ore, soybeans, and corn, emphasizes its pivotal role in the nation's economic landscape. Overcoming these challenges requires innovative solutions, particularly given the unique characteristics of Brazilian rail transport. However, the journey towards decarbonization is complex, demanding thoughtful strategies to harmonize environmental sustainability with the inherent demands of efficient transportation in Brazil's diverse and expansive rail network. The exploration of alternative energy sources, such as biodiesel, signals the nation's dedication to mitigating environmental impacts and enhancing energy security. Brazil, through ongoing endeavors, aims to navigate the intricacies of decarbonizing its rail systems, contributing to the global initiative for a more sustainable and resilient transportation sector.

In 2020, Vale disclosed an investment plan ranging from US $4 to $6 billion with the aim of reducing its direct and indirect emissions by 33% by the year 2030. Currently, 10% of the total carbon emissions from Vale can be attributed to its rail network. This undertaking represents another significant move towards attaining the overarching goal of achieving net-zero carbon emissions by 2050, aligning seamlessly with the targets set by the Paris Agreement to restrict global warming to below 2°C by the century's end.

The company has committed to reducing emissions across Scopes 1, 2, and 3. For Scope 1, direct emissions from operational activities, measures include fuel substitution and energy efficiency programs. In Scope 2, focused on indirect emissions from purchased electricity, the goal is to source 100% renewable electricity in Brazil by 2025. Scope 3 encompasses all other indirect emissions in the value chain, and the company aims for a 15% reduction by 2035, covering purchased goods and services, capital goods, and transportation emissions.

In its pursuit of an energy transition, Vale has embarked on a journey to explore the potential of locomotive prototypes powered exclusively by batteries. This venture began with the establishment of partnerships with two distinct suppliers, signifying an ambitious effort to disrupt the market and usher in environmentally-friendly locomotives. As the company delves into this innovative realm, the commitment to sustainable practices becomes evident, showcasing a forward-looking approach to reduce environmental impact in the transportation sector. The exploration of battery-powered locomotives stands as a significant stride in Vale's broader mission toward a more sustainable and eco-friendly future.

Disrupting the rail market poses formidable challenges due to the substantial energy requirements and operational inflexibility inherent in the system. High energy needs, whether from electricity or diesel, present a complex task in achieving efficiency and environmental sustainability. The fixed nature of rail networks contributes to their lack of adaptability to unforeseen situations and new requirements. Established infrastructure creates inertia, impeding the implementation of substantial changes. Stringent safety regulations add complexity, particularly for novel technologies lacking a safety track record. Resistance from current industry players, both within companies and the broader sector, further complicates the introduction of innovations that could impact market share. Internal resistance may stem from employees unfamiliar with or perceiving new ideas as threats.

The process of selecting the optimal battery for a locomotive environment involved a careful and intricate evaluation of various factors, such as active material composition, energy density, power output, lifespan, cost, and safety. Achieving the desired performance and operational efficiency requires a delicate balance among these critical variables.

The project emphasized a forward-thinking approach, recognizing the significance of charger compatibility across diverse locomotives for a common goal. This approach aimed to address future needs and promote adaptability in the evolving rail technology landscape, with goals such as increasing competition, reducing costs, enhancing interoperability, and accelerating technology adoption. The case study illustrated how disruptive technology and collaboration can drive progress in the rail industry. The showcased agnostic charger concept, featuring BEL with a high-power main charger, a reversal pantograph, and a low-power workshop battery charger, points towards a more efficient, sustainable, and interconnected future for rail transportation.

The locomotive battery charging project provided valuable insights into the intricate interplay between innovation and reality. Key lessons include the crucial need for infrastructure planning to ensure efficient charging, the effort required for integrating systems from competing suppliers with clear communication channels, the patience necessary when introducing complex technology into entrenched company cultures, and the importance of shared resources for effective testing. These lessons underscore the significance of holistic planning, open communication, and a collaborative mindset when incorporating groundbreaking technology into existing systems. Addressing these insights will enable future endeavors to navigate the complexities of innovation with greater agility and success.

Metro railway systems, while individually significant consumers of electrical energy, exhibit the lowest CO_2 emissions per transportation capacity when compared to buses and cars. This efficiency is particularly evident in Brazil, where the extensive use of hydroelectric power in the energy matrix contributes to cleaner and renewable energy sources, resulting in reduced carbon emissions. In contrast, many European countries heavily rely on thermal power plants using fossil fuels like coal, oil, and gas, leading to higher carbon footprints. The comparison underscores the environmental advantages of metro systems in regions with access to cleaner energy sources.

The three outlined proposals analyzed in the text serve as compelling examples of the overarching strategy. These initiatives, emphasizing energy efficiency, not only have the potential to save a significant 13.5 GWh/year of energy but also demonstrate a forward-looking approach. This energy-saving quantum is substantial enough to fulfill the annual power needs of over 3 thousand households, highlighting the impactful and sustainable nature of these interventions. Additionally, the resultant reduction in carbon emissions surpasses a significant milestone, exceeding over a thousand tons of CO2 annually. This contribution notably aligns with broader goals of environmental conservation and sustainable urban mobility.

The text comprehensively addressed the current situation in Brazil regarding the regulation of decarbonization in railways. It emphasized the importance of policies geared towards energy efficiency and the adoption of more sustainable energy sources in the railway context. The discussion underscored the need for regulatory initiatives that promote the transition to cleaner energy matrices, aiming to reduce carbon emissions in Brazilian rail transportation. Additionally, possible measures and strategies to drive decarbonization were explored, reflecting a commitment to environmentally conscious practices aligned with global sustainability goals.

In conclusion, this work provided a comprehensive analysis of the complexities and advancements on the path to decarbonization in the railway sector. We explored specific challenges within the Brazilian context, highlighting notable initiatives such as Vale's investment in clean technologies. Furthermore, we discussed universal obstacles in the pursuit of more sustainable transportation. This study underscores the ongoing need for innovation and collaboration to shape a cleaner and more efficient global future for the railway industry.

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