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Energy Assessment of Alternative Propulsion Technologies for Long-Haul Heavy Goods Vehicles

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Executive Summary

Heavy-duty vehicles used in long-distance freight transport pose a major challenge to the EU's road transport decarbonization goals due to their high greenhouse gas emissions. Transitioning to sustainable alternative propulsion systems is essential, and to ensure seamless operations, the development of refueling and recharging infrastructure must occur in parallel. This paper assesses the energy performance of alternative propulsion technologies in heavy-duty vehicles in the Lisbon to Mangualde route, aligned with the Portugal–France Atlantic corridor, and outlines the refueling infrastructure needed for deploying battery-electric and hydrogen fuel cell trucks. Findings indicate that battery-electric heavy-duty vehicles consume 53% less energy, while fuel cell-equipped vehicles reduce energy consumption by 14% compared to conventional diesel semitrailer trucks. For effective operation along the proposed route, a minimum of eight charging stations and four hydrogen refueling stations will be required along the Atlantic corridor.

Keywords: Fuel Cell Electric Vehicles, Electric Vehicles, Modelling & Simulation, Energy Management, Smart Grid Integration and Grid Management.

1 Introduction

Reducing emissions from fossil fuel combustion, including CO_2, is a critical challenge for mitigating global warming and improving public health. The transportation sector is a significant contributor to greenhouse gas (GHG) emissions, with heavy-duty vehicles (HDVs) accounting for 25% of the road sector's emissions in the EU, despite representing only 2% of vehicles on European roads [1]. Long-distance trucks are a notable source, producing between 50% and 65% of HDV emissions. Emissions have continued to rise, increasing by almost 25% between 1990 and 2016, and are projected to grow by an additional 10% by 2030 without intervention [2], [3].po

The use of heavy-duty fuel cell electric truck (FCET) and heavy-duty battery-electric trucks (BET) has become more accepted recently as the two most viable options to lessen the carbon footprint of road freight transportation [4]. As they don't need fossil fuels to move, these alternatives have the huge benefit of not producing greenhouse gases on a tank-to-wheel level (TTW). The largest obstacle to the use of these technologies in HDVs, despite significant advancements, is the electrification of long-distance trucks [5], which are classified as N class heavy vehicles. Additionally, it is crucial to build multiple refueling stations to construct an efficient and strong road network for long-distance HDV circulation. Expansion of the electricity and hydrogen (H_2) refueling network throughout the trans-European transport network (TEN-T) will require funding and incentives for this sort of transportation to be a feasible choice. The industry identifies as the primary barriers to a more proactive energy transition the absence of public refueling facilities and the initial cost of trucks (a consequence of the small quantity of this type of vehicles) [6]. A more effective and financially sustainable decarbonization of this sector depends on cooperation between governments, truck manufacturers, and operators of the refueling infrastructure.

HDVs are a major contributor to GHG emissions and particulate matter in the transport sector. Despite their environmental impact, HDVs remain heavily reliant on diesel internal combustion engines (ICE), with 96.6% of new registrations in 2022 using diesel—a slight increase from 2021 [7]. This dependence makes decarbonization particularly challenging, requiring substantial policy and investment efforts [8].

BETs offer a promising alternative, eliminating tailpipe emissions through the use of electric motors powered by lithium-based batteries known for their stability, efficiency, and lifespan [9], [10]. However, their adoption in the HDV segment remains limited, representing only 0.6% of new vehicle registrations in the EU by 2022, despite a 32.8% rise in electric vehicle sales [8]. Key barriers include limited range (typically under 400 km per charge) [11], high vehicle and infrastructure costs, long charging times, and underdeveloped charging networks for long-haul freight. FCETs have emerged as another viable solution, combining the benefits of electric propulsion with longer driving ranges. Powered by hydrogen, FCETs emit only water vapor and can travel 600–1000 km on a single tank, depending on storage conditions [12], with refueling times of 5–10 minutes [13]. However, their market penetration is hindered by high costs, early-stage technology development, and a lack of hydrogen refueling infrastructure—only 178 stations exist across Europe, with few suitable for heavy-duty refueling [14].

The HDV sector is diverse, with varying vehicle types tailored for specific uses, complicating energy efficiency comparisons. To address this, the European Commission implemented the Vehicle Energy Consumption Calculation Tool (VECTO) in 2019 as a mandatory standard for CO_2 certification in HDVs. Under regulation (EU) 2017/2400, HDVs are categorized by axle, chassis, and weight configurations. For long-haul applications, the most representative vehicle type is the VECTO 5 truck, which includes two axles, a semi-trailer body, and a 40-ton maximum permitted gross weight [15].

This paper assesses the energy consumption of conventional HDVs on long-haul routes and compares it with BET and FCET alternatives [4], which are gaining traction in the heavy goods sector. Using AVL Cruise M software by AVL List GmbH [16], the study evaluates these propulsion technologies' energy performance and identifies the required infrastructure to support their operation. The ultimate objective is to advance the decarbonization of long-haul freight transportation by outlining the energy and infrastructure needs for a more sustainable HDV sector along key routes in the EU.

2 Data and methods

The methodology for this study is presented in Figure 1. It begins with gathering key data about the route and road topology, along with the speed profiles for the HDVs under examination. The chosen route, from Lisbon to Mangualde, Portugal, represents a typical segment of long-haul journeys in the Iberian market. Key details like the elevation gain, road types, and rest points are incorporated, with the route extending over national roads to minimize toll costs. Using Microsoft Excel, this initial data is processed and organized. AVL Cruise M software [16] is then employed to create models for three distinct HDV types—battery-electric, fuel-cell electric, and traditional internal combustion engine trucks—integrating each vehicle's specific physical attributes and propulsion configurations.

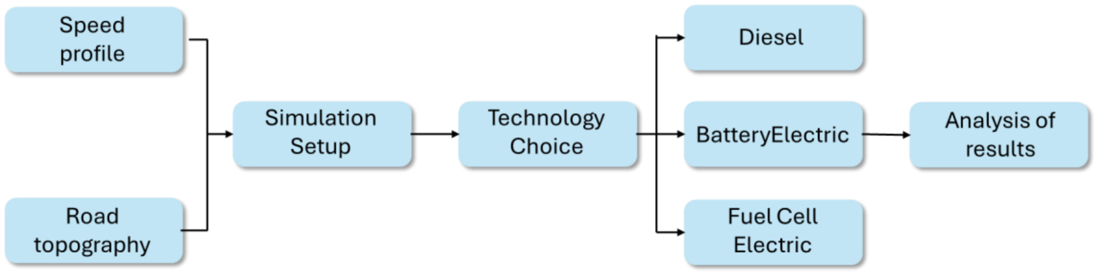

Figure 1: Methodology layout

In the AVL Cruise M simulation environment, a modular approach allows for detailed configuration of each HDV's propulsion system, as illustrated in Figure 2. Each vehicle model incorporates consistent external variables, ensuring comparability, while their propulsion systems differ according to their unique transmission setups: the battery-electric truck connects directly to the drive shaft, the fuel-cell truck employs an automated transmission, and the diesel truck uses a manual gearbox. AVL Cruise M’s extensive library of components enables accurate modeling by combining the hydraulic, mechanical, electrical, and thermal systems necessary for each type of propulsion. These simulations help analyze factors such as energy flow, fuel consumption, and emissions, giving a comprehensive picture of the performance across vehicle types.

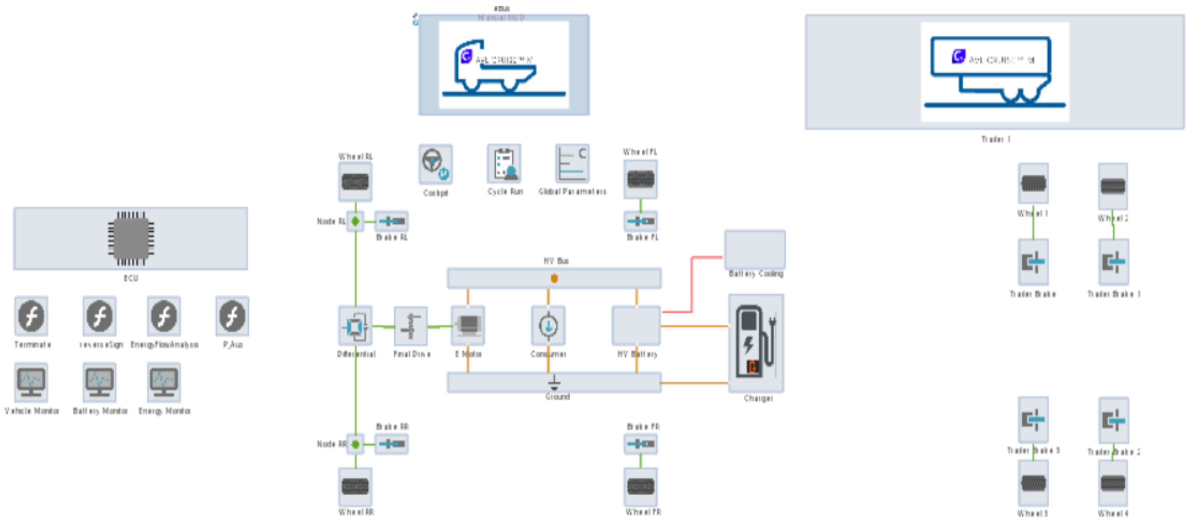

Figure 2: AVL Cruise M layout for the simulation of battery-electric truck

Finally, energy consumption for each vehicle model is calculated, factoring in various scenarios for each propulsion type. The energy usage is determined by assessing the hydrogen consumption in fuel-cell models, battery energy usage in electric trucks, and diesel fuel consumption in traditional models.

Additionally, route-specific parameters, including topographical variations captured using Google Earth and Google Maps, create a realistic representation of the Lisbon-Mangualde route's slope changes, adding depth to the simulation (see

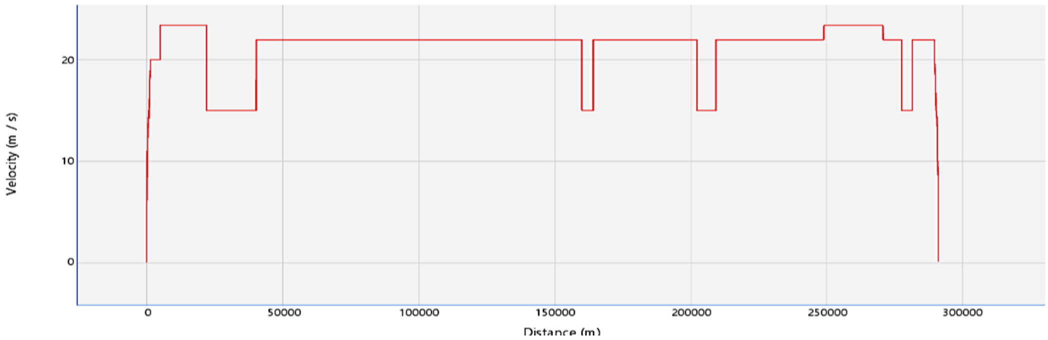

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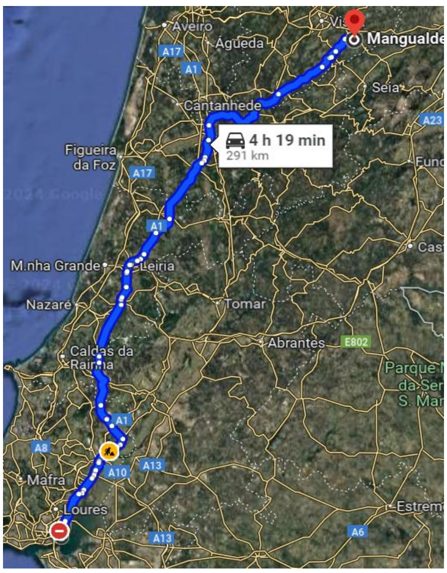
Figure 3). The reverse trip was also included in the simulation with the same procedure.



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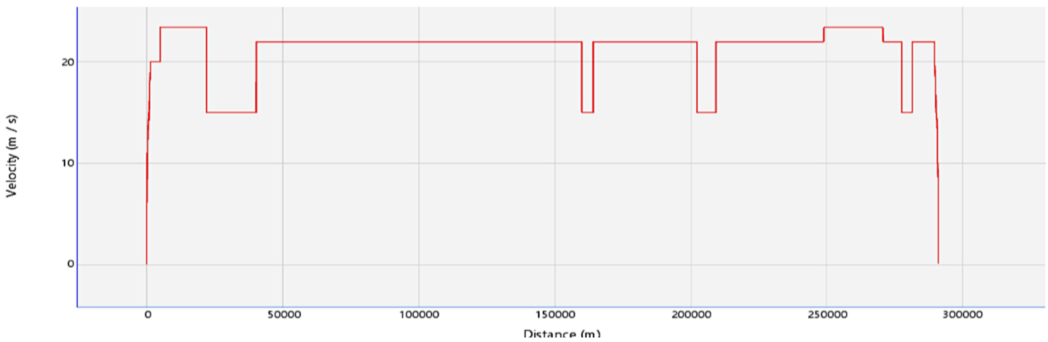

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Figure 3: a) representation of the Lisbon-Mangualde route (source: Google Maps) and b) drive cycle for the route

A method similar to VECTO's certification process for long-distance vehicle performance monitoring was adopted due to the lack of second-by-second real velocity data for the route. Target speeds were assigned based on road type: 50 km/h for urban sections, 80 km/h for national roads, and 85 km/h for freeways, forming the speed profile shown in Figure 3. To reflect topographical variation, real altitude data were used. Key peaks and valleys were identified using Google Earth, with distances measured via Google Maps, resulting in a topography profile, that captures detailed elevation dynamics. By incorporating these altitude variations and the established velocity profile, the study delivers a robust analysis of energy requirements for each propulsion system along both directions of the route.

3 Results and discussion

To ensure the accuracy of the vehicle models, simulations were conducted to validate the three propulsion system models used, with energy consumption results compared to values published in the literature. Figure 4 presents the energy consumption of each technology in MJ/ton-km, based on the VECTO reference load of 19 tons. When compared to literature findings of a recent comprehensive study on various vehicle types [17], the differences in energy consumption across the three models are relatively minor. The largest deviation was observed in the BETs, with a discrepancy of approximately 4.7%. These differences can be attributed to several factors. First, some input parameters in AVL Cruise M differ slightly from those used in the reference models. Although the same velocity profile was applied, the topography used in our validation cycle varied, which affected overall consumption. In all three cases, the energy consumption in our simulations was lower than the reference values, suggesting that the AVL-derived cycle featured less demanding gradients. Additionally, differences in engine maps and gear-shifting strategies between our simulations and the reference data further contributed to the observed discrepancies. Overall, the close agreement between simulated and reference values supports the robustness and reliability of the models developed using AVL Cruise M.

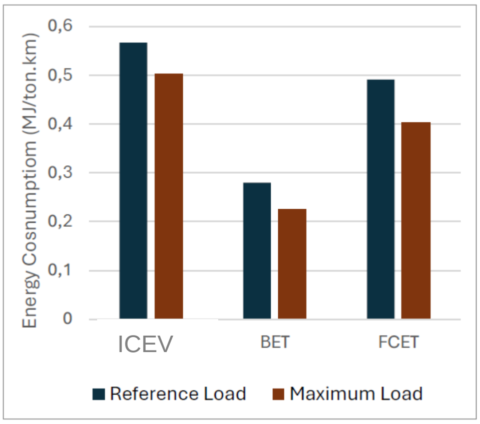


Figure 4: Energy consumption for the VECTO validation cycle

The second-by-second velocity profiles obtained for the Lisbon–Mangualde route, using the reference load and each propulsion technology, are shown in Figure 5. The graph illustrates that, although the target speed was kept constant across the different route sections, the interaction between the velocity profile and the terrain resulted in acceleration and deceleration peaks that are characteristic of real-world long-haul travel. This pattern was consistent across all three case studies, with the simulated vehicles completing the journey in approximately 4 hours and 25 minutes. This travel time aligns closely with estimates derived from Google Maps, supporting the realism of the modeled scenarios.

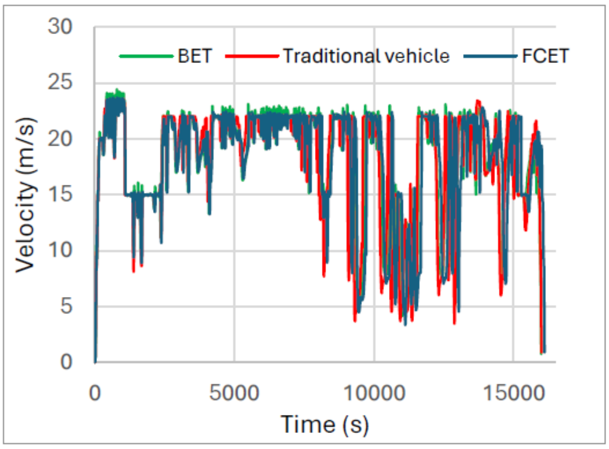
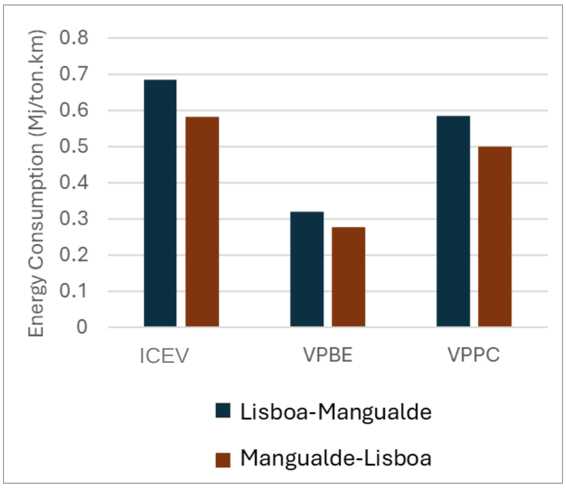


Figure 5: Speed profile obtained for the VECTO reference load

The study validated the energy consumption of each propulsion system using simulations, confirming that BETs use significantly less energy per unit load than traditional diesel vehicles, with a reduction of 50.6%. As presented in Figure 6, FCETs also show improved energy efficiency, consuming 12.7% less than diesel HDVs. BETs perform particularly well even on uphill gradients, while FCETs provide a feasible alternative for longer routes, given their ability to cover greater distances on a single refuel. In scenarios with maximum load, diesel trucks show a 19% reduction in energy consumption per unit of transported cargo relative to the reference load, whereas BETs and FCETs show smaller decreases, consistent with their lower weight capacities.



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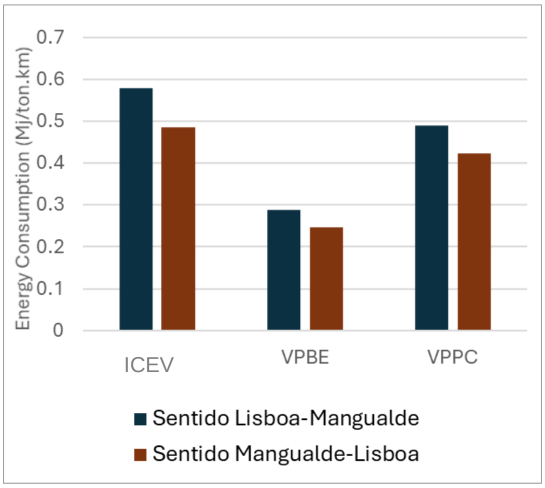

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Figure 6: (a) Energy consumption for the route, in both ways; (b) Specific energy consumption for maximum load.

From an emissions perspective, BETs have the lowest CO_2 emissions, producing 71.2% less than traditional diesel vehicles, whereas FCETs emit 38% more, primarily due to the reliance on gray hydrogen (see Figure 7). If green hydrogen (produced via renewable sources) were used, FCETs' carbon footprint could decrease by 92.8%. Future projections suggest that as renewable energy use increases, BETs could achieve an additional 31.65% reduction in emissions by 2030, yielding an 80.9% lower carbon footprint compared to conventional diesel HDVs.

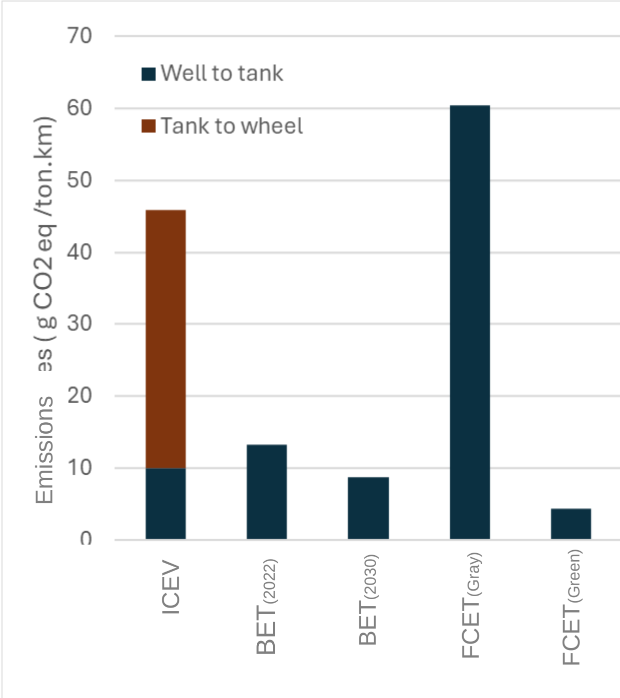

Figure 7: CO_2 emissions for each scenario

To support these alternative vehicles, infrastructure requirements along the Atlantic corridor were assessed. FCETs would need at least four hydrogen refueling stations along the Lisbon-Paris route, whereas BETs require at least seven high-capacity charging stations (800 kW) to allow full charging during drivers' mandatory breaks (see Figure 8). These stations are positioned at strategic intervals, including Lisbon, Mangualde, and key cities in Spain and France, ensuring continuous operation of long-haul BETs and FCETs along this route, aligning with AFIR regulations and ensuring practical viability for sustainable HDV operations.

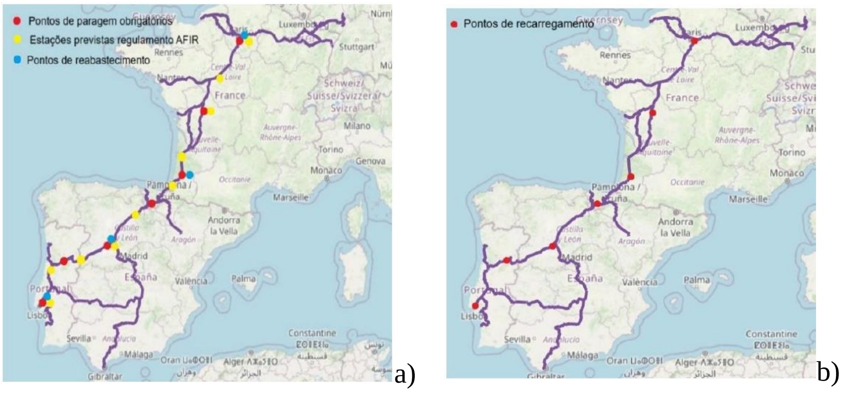

Figure 8: a) Necessary and planned hydrogen recharging stations along the Atlantic Corridor and b) BET charging stations required along the Atlantic Corridor

As a result, this study provides a comparative analysis of energy consumption and CO_2 emissions for battery-electric (BET), fuel cell electric (FCET), and diesel HDVs on a key segment of the Atlantic Corridor. Key contributions include showing that BETs and FCETs are more energy-efficient than diesel HDVs, with BETs using up to 53% less energy and FCETs around 15% less, especially on routes with elevation changes. It also highlights the significant emissions reduction potential of FCETs if green hydrogen is adopted, positioning them as a low-emission alternative. Additionally, the research identifies the need for a robust refueling infrastructure along long-haul routes, proposing specific locations for hydrogen and charging stations to support sustainable HDV operations across the Lisbon-Paris route.

4. Conclusions

This study evaluates the energy consumption and CO_2 emissions of three propulsion technologies—diesel, battery electric trucks and fuel cell electric trucks - on a long-haul route using AVL Cruise M software. The Lisbon–Mangualde corridor was selected due to its strategic position along the TEN-T Atlantic Corridor and its relevance to a leading Portuguese freight operator. Energy consumption and emissions were calculated based on trip simulations and converted using established primary energy factors. Infrastructure requirements were also assessed, identifying the minimum number and approximate locations of charging and refueling stations needed for BETs and FCETs to complete a Lisbon–Paris journey.

Results show BETs and FCETs are more energy-efficient than diesel trucks, particularly on gradient-heavy routes. For the Lisbon–Mangualde trip (and in the reverse direction), BETs consumed 53.1% less energy and FCETs 14.6% less than diesel. When carrying the maximum payload allowed per technology, energy efficiency per ton-km narrowed slightly: BETs improved by 50.3%, FCETs by 15.6%. CO_2 emissions analysis, from well-to-wheel, revealed FCETs as the least favorable option when using conventional hydrogen, emitting 71.2% more than BETs and 38% more than diesel trucks. However, under green hydrogen scenarios for 2030, FCETs become the cleanest option—cutting emissions by 92.8% compared to diesel and 50.7% compared to BETs.

Infrastructure estimates suggest three hydrogen refueling stops and six electric charging stations (approximately every 290 km) would be needed along the Lisbon–Paris route. While hydrogen tank sizes are expected to support this with minimal refueling, BETs will require charging technologies capable of full recharge within the mandated 45-minute break to maintain efficiency.

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Presenter Biography

	Miguel Reis is a M.Sc. student in Mechanical Engineering at Instituto Superior Técnico, Portugal. He developed his M.Sc. thesis work on the energy evaluation of alternative propulsion technologies in long-haul heavy goods vehicles.
	Miguel Campino received the M.Sc Degree in Mechanical Engineering (2021) from Instituto Superior de Engenharia de Lisboa. He is currently enrolled in the LARSyS PhD Programme focus on Sustainable Energy Systems. In his master thesis, developed in the area of transportation, Miguel focused on the propulsion management of a plug-in hybrid vehicle, developing a metric capable of bridge the gap between the test cycles under real conditions of use though forecasting methods. As a PhD student, Miguel is working to assess the real impacts of using light and heavy-duty vehicles with one or more propulsion sources at multiple levels.
	Patrícia Baptista received the Ph.D. in Sustainable Energy Systems (2011) from Instituto Superior Técnico, Portugal. She is currently a Principal Researcher at IN+ Center for Innovation, Technology and Policy Research. Her main research topics have been on the quantification of energy and environmental impacts of alternative transport options, on how to influence user behavior by using ICT to characterize driving behavior and policy design for more sustainable transports.
	Tiago Farias is an Associate Professor at Instituto Superior Técnico – Universidade de Lisboa and a researcher at IDMEC – Instituto de Engenharia Mecânica. His research and knowledge transfer activities cover energy and environment in transports, sustainable urban mobility and accessibility, alternative energies and vehicle technologies, and environmental footprint of mobility solutions. He was a former member of the board of several associations, namely: APVE (Portuguese Electric Vehicle Association), APVGN (Portuguese Natural Gas Vehicle Association), and president of AP2H2 (the Portuguese Hydrogen Association). As a manager, and among several roles, he was the executive president of CARRIS – the Lisbon Municipal Bus and Tram Operator.