Decarbonisation of Heavy-Duty Road Transport in Europe

A Market Segmentation Analysis

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Abstract

The heavy-duty road transport sector is critical to European trade and socio-economic development, moving millions of tons of goods within and to neighboring countries, and this depends on fleets of diesel trucks. The path to decarbonization in Europe will require joint efforts from multiple stakeholders and significant investments in technological development, infrastructure and fuel production. This study assesses the available drivetrains to meet the European Union's carbon reduction targets, and provides insight into the future market segmentation from the perspective of the transport companies. It quantifies selection criteria by setting a mixed-integer linear programming problem to optimize the total cost of ownership of transport, while complying with carbon reduction targets set by the European Union, and discusses underlying factors that may play a significant role. The results show that there will be significant segmentation and diversification in drivetrain technology in the short to medium term, including zero-emission, low-emission and conventional fossil technologies, as economics and carbon reduction targets play a major role in determining the composition of future truck fleets. Ultimately, fossil-based vehicles could be entirely phased out in favor of zero-emission trucks, where the market share is split between battery electric and fuel cell electric vehicles. Key factors influencing this segmentation are the price of fuel, availability of bio-based fuels and the role of emission regulation, in particular the scope and severity of future carbon reduction targets. Furthermore, underlying implications may also have important consequences, including customer perspective towards new technologies, renewable energy intermittency, security of supply, critical material supply chains, and the significant infrastructure upgrade and development costs. The degree to which these issues will affect the future transport market is unknown.

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1. Introduction

Decarbonization of Heavy Duty Road Transport

Commercial truck road transport is the backbone of European trade and commerce. With over 6.4 million units in the European Union (EU) and responsible for moving almost 80% of all the freight transported over land (European Automobile Manufacturers' Association, 2023), trucks play a pivotal role in long haul, regional and urban deliveries. Other modes of transport are also dependent on trucks on a daily basis, as they connect critical supply chain components such as inland waterways, shipping, air and rail transport hubs to major distribution depots. Furthermore, truck versatility, responsiveness and low cost make them suitable for a variety of services, from inner city deliveries of daily necessities, such as supermarket goods or public services, to cross-border trade of bulky machinery or raw materials for industry. The European medium and heavy-duty commercial truck market size is estimated at USD $38.97 billion (~ €35.7 billion) in 2024 and projected to reach USD $52.86 billion (~ €48.4 billion) in potential earnings by 2030, with the largest share being comprised of heavy-duty vehicles of 3.5 metric tons or more (Mordor Intelligence, 2023). For perspective, this translates to a demand of 257.7 million metric tons of diesel consumed in 2022 (Statista, 2022).

Europe’s economic reliance on heavy-duty trucks comes, nonetheless, at the cost of a high economic, social and environmental impact. The sector is responsible for 28% of the total carbon emissions related to road transport in Europe, even when it accounts for only 2% of all the vehicle registrations (Transport & Environment, 2023). With the EU aiming at reaching climate neutrality by 2050, the replacement of fossil-based internal combustion engine (ICE) vehicles with low and zero-emission vehicles (ZEV) has become a focal point in the European Commission’s (EC) agenda to fight climate change. This does not, however, come without major technical, operational, infrastructure and economic hurdles, calling for a multi-sectoral and multi-national approach to displace the incumbent diesel-fueled vehicles, which accounted for 95.5% of new EU truck registrations in the first quarter of 2024 (ACEA, 2024). Evidently, the market maintains a strong inclination towards diesel drivetrains given the degree of maturity in its technology, low fuel costs and a high level of operational flexibility granted by a continental network of refueling stations. Without a strong regulatory push for sector-wide decarbonization, low and zero-emission drivetrains would succumb to their fossil-based opponents, mainly for economic reasons. It is up to governments, manufacturers, energy and fuel providers to create a suitable environment for new technologies to thrive, and put Europe back on track to fulfill its pledge to the 2015 Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC).

Market Segmentation in a Decarbonized Heavy-Duty Sector

Shell aims at reducing the carbon footprint of its own activities, as well as the activities of its customers. Part of this involves gaining insight on the future of a decarbonized heavy-duty transport sector, and that insight begins with foreseeing that there will be a clear segmentation of the market as a result of emerging alternative drivetrains and fuel. This implies knowing when and which investments need to be made to reach decarbonization goals, while ensuring minimal impact to the daily operation of transport companies and their fleets. What will determine this segmentation is yet unknown, but it will include factors linked to technology availability, fuel infrastructure and cost, customer preferences and the regulatory landscape.

There are several vehicle drivetrain technologies to achieve decarbonization in the short, medium and long-term:

1. Battery Electric Vehicle (BEV). The degree of decarbonization depends on the origin of the power used for recharging, where a high renewable energy penetration offers the highest degree of carbon reductions.
2. Hydrogen used in fuel cell electric vehicles (FCEV) or hydrogen Internal Combustion Engine (H_2- ICE) vehicles. The degree of decarbonization depends on how the hydrogen is produced; the highest emission reductions are provided by green hydrogen from electrolysis with renewable electricity, and blue hydrogen from steam methane reforming (SMR) with carbon capture and storage technology (CCS). Other forms of hydrogen, such as grey from SMR, do not offer benefits for decarbonisation.
3. Liquified Natural Gas (LNG). Compared to fossil diesel, LNG has less carbon emissions[1] but not to the extent that BEVs, FCEVs or H_2-ICE technologies do.
4. HVO (biodiesel) from crops, oil or municipal waste and Bio-LNG, from animal manure. These are considered low-emission fuels, as the carbon released during their combustion process was previously absorbed from the atmosphere a relative short time before and not extracted from the ground (as is the case with fossil fuels).

[1] A reduction of 21.1% and 19.3% in carbon emissions from Tank-to-Wheel and Well-to-Wheel, respectively (Prussi, Yugo, De Prada, & Edwards, 2020). Methane slip can contribute to up to 8.5% of the total greenhouse gas emissions from LNG (Assefa Hagos & Ahlgren, 2018), given that methane has a global warming potential 27-30 times more potent than carbon dioxide (EPA, 2024).

Each technology comes with notable advantages and disadvantages, including underlying factors that will require careful consideration. Table 1 presents a non-exhaustive comparison of the technologies available for heavy-duty road drivetrains.

Vehicle Type	Strengths	Technical Challenges	Economic Challenges	Consumer Perception	Kg of CO_2e per kWh - tailpipe emissions (GOV.UK, 2023)
Diesel & LNG	Lowest vehicle cost	Low thermal energy efficiency and high carbon, NOx, particulate matter (PM) emissions and noise pollution	Rising prices of fuel and high maintenance and road toll costs	Need to find a sustainable alternative	Diesel: 0.29 LNG: 0.2
	No infrastructure investment required				
	Long range and high payload				
	Fast refuelling				
	Large market with widely available parts/vehicles				
BEV	Zero-emission vehicle	Resource availability	Cost and affordability	Range anxiety	Electricity: 0
	Lower refuelling and maintenance costs than ICE vehicles	Low charging speeds and possible high impact to the electric grid	Expensive components due to presence of rare earth materials in certain battery designs.	Power cuts/availability of energy in rural areas requires more planning for extensive or international travel	
	Less infrastructure investments than hydrogen vehicles	Range penalty		Varying electricity prices and subsidies between countries	
	High efficiency	Need for expensive grid development and expansion activities			
FCEV & H_2 - ICE	Zero-emission vehicle	High costs across entire value chain	Expensive technology, fuel and supporting infrastructure.	Safety concerns	Green Hydrogen: 0
	Higher energy efficiency than ICE technologies	Handling and storage challenges		Range anxiety due to lack of infrastructure	
	Faster refuelling than BEVs	Refuelling infrastructure is still very limited			
	High specific energy	Safety concerns when refuelling			
	Lesser payload loss than BEVs when operating long ranges	FCEVs require high degrees of H_2 purity			
	Possible to store for long time periods with low losses	Uncertainty of supply			
HVO & Bio-LNG	Compatibility with most current infrastructure	NOx, particulate matter (PM) and noise pollution	Price can vary drastically depending on feedstock availability	Consumers may have to accept a premium price (at least during initial stages) for long-term environmental benefit	HVO: 0 Bio-LNG: 0
	Drop-in-fuel	Limited feedstock availability. Some feedstocks may directly compete for water and land resources with the agricultural industry	Need for expensive specialized equipment & input materials		
	Possible to blend with diesel to reduce emissions in short-term	Production is energy intensive and costly			

	Long range and high payload	Some blends may pose incompatibility issues with current vehicle components			

Table 1 - overview of heavy-duty vehicle technologies.

There is no clear winner to replace diesel trucks, and it is unknown what other challenges may arise from scaling up operations. Transport companies have a responsibility to their customers in keeping a standard in their logistic services, so it will be down to other stakeholders to be able to provide a suitable environment for alternative technologies to mature.

Research Question and Objective

This study aims at obtaining insights behind the segmentation of the future heavy-duty road transport market, with the key objective of decarbonization of this sector. This segmentation refers to which vehicle drivetrains (and to what extent) will cover the future demand, as well as how these are distributed across different range and weight classifications, and this is done by combining two key approaches.

The first is reviewing information on the various technology options available for decarbonization, which include a mix of electric and internal combustion engine vehicles. This includes insights on vehicle costs, fuel prices and efficiency, range and weight limits; all of which are relevant for transport companies when choosing in which types of vehicles to invest in.

The second approach involves assessing the role that the external environment, such as stakeholders and environmental regulations, may have in displacing the incumbent diesel vehicles and in creating a future demand for new low and zero-emission vehicles. This is done by considering the carbon reduction targets set by the EU and the impact additional underlying factors may have on the price and availability of alternative fuels. This is important for energy companies and financial institutions to identify which investment opportunities are critical for sector decarbonization, which are linked to technology development, and insights on the size of each market segment to anticipate the need for fuel and supporting infrastructure, as well as critical issues across the energy value chain. Finally, this approach tests the effectiveness of current decarbonization policies by setting a maximum amount of emissions that can be produced every year, in line with EU reduction targets.

An optimization problem is used to minimize the total cost of ownership (TCO) of transport, while meeting the minimum demand and range requirements for transport companies. In addition, the cost of technology, fuel prices and carbon reduction targets are key factors in determining the size of each segment. The results include the market evolution from 2023-2040 under different scenarios, as well as the evolution for different range-weight segments.

The following research question is formulated:

What are the key factors that will influence the future segmentation of the heavy-duty road transport market, based on the available drivetrain technology, transport total cost of ownership and European regulation?

This question is important because it addresses the issue of decarbonization for one of the key sectors of the economy and from a holistic viewpoint. The technical aspects of several drivetrain technologies are considered within a market analysis, where the goal is to minimize costs while being able to meet a growing demand and reducing carbon emissions in accordance with regulation. It builds on the hypothesis that there will be market segmentation in the transition to a decarbonized heavy-duty sector, and assesses the impact that fuel prices and the regulatory landscape may have on the size of each segment.

The rest of this document includes a Literature Review of available technologies, fuels and market outlook, followed by a section on Methodology where key considerations and formulation of the optimization problem is presented. This is followed by the Results & Analysis and Discussion sections, which present the results for different price and regulation scenarios, detail the cause for such segmentation and discuss key underlying factors that may arise in the coming years. Finally, the Conclusions & Recommendations section summarizes the key findings and point out what some key stakeholders need to consider to achieve decarbonization in the heavy-duty road transport sector.

2. Literature Review

Technology Overview

The general scientific consensus for the future of heavy-duty vehicles (HDVs) is that battery and fuel-cell electric drivetrains, or zero-emission vehicles (ZEVs), will eventually dominate the market, where most favor one technology over the other, and also attention is given to other alternative fuels, such as liquefied natural gas (LNG) or internal combustion engine (ICE) vehicles operating with biofuels. However, most of the published literature compares these drivetrains strictly from a technical perspective, rather than considering the market as a whole system where technologies may act as complimentary to one another. Common approaches include a qualitative analysis of the key implications of each technology, including advantages, limitations and possible policy scenarios, and draw comparisons based on modelling the total cost of ownership (TCO) of transport. More recently, there have been some contributions to modelling the composition of future vehicle fleets. This section discusses the alternative technology options in the context of heavy-duty vehicles and considers insights on the future market segmentation from previous studies.

Focal to decarbonization in road transport are ZEVs, which offer zero tailpipe or Tank-to-Wheel (TtW) carbon emissions. This, however, may not be the case for Well-to-Wheel emissions (WtW), which must consider in Well-to-Tank (WtT) emissions, and still are usually quite high due to, for example, a large share of electricity being generated from fossil fuel sources worldwide (Cunanan, et al., 2021). Figure 1 illustrates the scope of WtT and TtW emissions, and their addition results in WtW emissions. As per the example given, the electricity source for ZEV fuel can be generated from sustainable energy or fossil fuels.

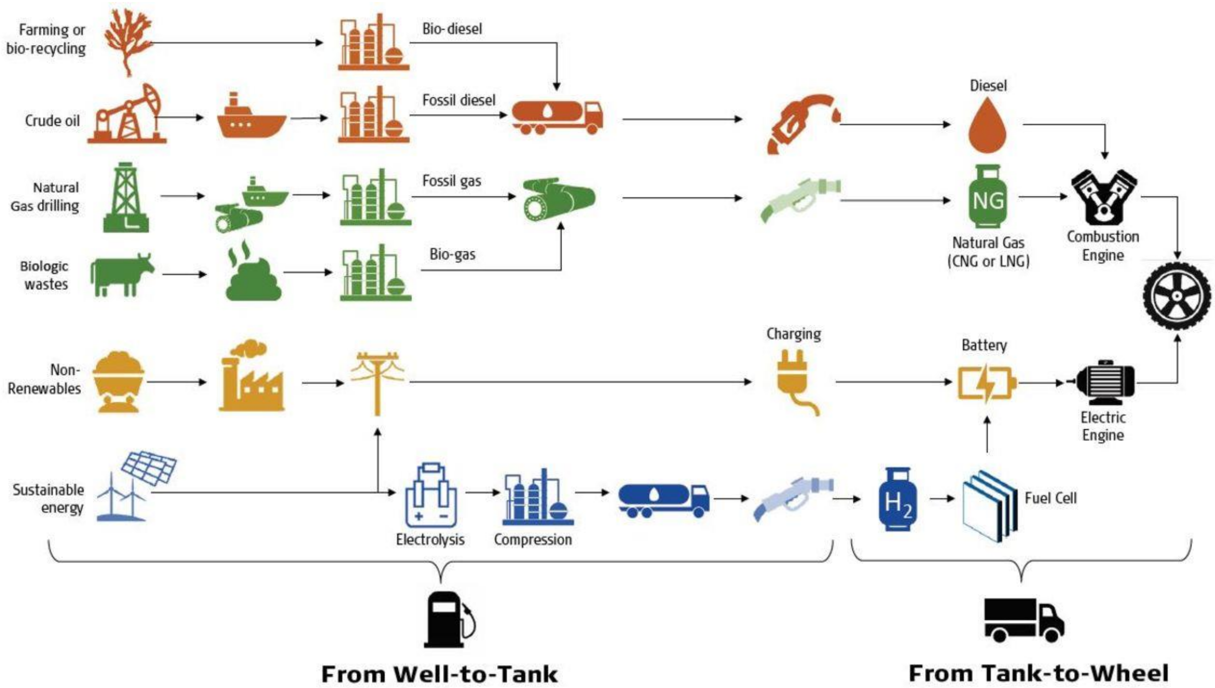


Figure 1 - Comparison of Well-to-Tank and Tank-to-Wheel emissions (Dinex, 2020).

The ZEVs considered in this study are battery electric vehicles (BEVs) and fuel-cell electric vehicles (FCEVs), which operate by converting chemical energy into electrical energy with electrochemical cells. The electricity in BEVs is usually stored in onboard lithium-ion (Li-ion) batteries, which offer impressive energy densities, high efficiencies and long lifespans when compared to other battery chemistries (Ralls, et al, 2023). There have arisen concerns regarding the supply chain sustainability and future availability of key materials (Slattery, Dunn, & Kendall, 2021) required for manufacturing Li-ion batteries. Most notably, cobalt, nickel and graphite are considered critical or near critical materials and have negative social, economic and environmental impacts, including toxic exposure to communities close to sites of industrial and artisanal mining operations in, for example, the Democratic Republic of Congo, where more than half of the world's cobalt mining takes place (Banza et al, 2018).

In the context of heavy-duty vehicles, BEVs offer zero tailpipe emissions, the highest efficiency of any vehicle drivetrain technology, lower maintenance costs when compared to ICE vehicles (Pelletier, Laporte, & Laporte, 2014) and regenerative braking, which recharges the vehicle's battery, reduces heat energy emission and increases the service life of discs and drum brakes (Vasiljevic, Aleksandrovic, Glisovic, & Maslac, 2022). The downsides of BEVs are the limited ranges that are caused by increased weight of the battery. Longer ranges require heavier batteries; an 800 km range, as claimed by Tesla's ~40 ton capacity truck (Tesla, 2024), would require at least 1,000 kWh of energy or equivalent to a 5.5 ton battery (Cunanan, et al., 2021), causing concerns related to the capacity requirements for trucks. The EU has proposed to allow for a 4,000 kg increase in the maximum permissible gross vehicle weight of HDVs to allocate this increment in weight (European Parliamentary Research Service, 2024), but other issues may arise with regards to the faster deterioration of roads and infrastructure, such as bridges, as well as other truck components (Znidaric, 2015). Improvements in battery technology, especially in terms of energy density, would help alleviate this 'range anxiety' and allow BEV users to drive for a longer distance without having to stop to recharge or sacrifice payload capacity (Henry, Luz, & Kayode, 2024). There is also the issue of very high costs for BEV technologies, with most estimates in literature ranging from USD $200,000 to $800,000 (~€180,000 – €730,000) in initial investment, including the battery pack accounting for roughly 60% of the total cost of the vehicle (Sharpe & Basma, 2022). These are, however, expected to decrease as battery technology develops and an increased demand for ZEVs helps to achieve economies of scale.

Lastly, current charging technology is still limited, and charging a 1,000 kWh battery could take at almost three hours, assuming a 350 kW fast-charger is used. Using more powerful chargers in the megawatt scale incurs much higher costs (Hildermeier & Jahn, 2024), can increase battery degradation thus impacting its lifetime and efficiency (Miao, 2023) and can cause severe stresses to the grid, with one study showing that as little as 11% of HDVs charging simultaneously can compromise grid reliability (El Helou et al, 2022). This becomes an even greater threat if a high degree of renewable energy penetration is considered due to their intermittent nature and availability throughout day and night cycles.

On the other hand, FCEVs are also driven by an electric motor, but this is powered by a hydrogen fuel cell. A fuel cell is an electrochemical device that converts the chemical energy stored in the hydrogen molecule, by making it react with atmospheric oxygen, to produce electricity and heat. In principle, it operates like a battery, but does not require recharging like a battery as long as the fuel, hydrogen, is supplied (Williams, 2011). Polymer electrolyte fuel cells (PEMFC) are the most commonly used in mobile applications due to their low temperature, which offers short starting and stopping times, and high energy density (Monaharan, et al., 2019). In terms of critical materials needed for PEMFC manufacturing, platinum is the noble metal of choice to act as a catalyst, as its activity, selectivity and poisoning resistance make it the best material available for such applications (Holton & Stevenson, 2013). There are, however, arisen concerns about meeting the future demand for platinum, as it is mainly produced in countries with a certain degree of political instability, and would require effective exploitation strategies for the medium and long-term, which could have an impact on the deployment of FCEVs (Reverdiau, et al., 2021). Similarly to batteries, the extraction process of such materials is cost and energy intensive, with high environmental and social impact (Aguilar & Groß, 2022).

In the context of heavy-duty transport, hydrogen fueled vehicles offer zero tailpipe emissions, similarly to BEVs, but with longer ranges and shorter refueling times, comparable to that of conventional ICE drivetrains. In short, the range of the vehicle is proportional to the amount of hydrogen that can be carried onboard. Typically, heavy-duty FCEVs have significantly greater ranges than BEVs, reaching up to 800 km without refueling (Pardhi, et al., 2022), and are less expensive, with estimates of $200,000 - $600,000 (~€180,000 – €550,000) per unit (Sharpe & Basma, 2022). Although FCEVs are also not immune to the negative effects of the additional weight from the drivetrain and hydrogen storage unit, increasing the storage capacity onboard can be deemed negligible compared to the overall weight of the vehicle (Aguilar & Groß, 2022).

As an alternative to FCEVs, there has been recent progress in developing internal combustion engine hydrogen vehicles (H_2 ICEs), which would also help mitigate carbon emissions and are less expensive (Balu & Karunamurthy, 2022). These share many of the characteristics that make diesel powertrains attractive, including lower upfront costs, increased flexibility and robustness, are tolerant to contaminants present in the hydrogen fuel and have no added payload constraints, other than the need for a hydrogen storage tank (U.S. Department of Energy, 2023). The major drawbacks are the lower fuel efficiencies compared to FCEVs at typical operating loads, making H_2 ICEs more suited for vehicles with high power requirements, such as concrete, mining and construction trucks, in addition to the presence of NO_x emissions (Heid, Martens, & Orthofer, 2021).

The storage method of onboard hydrogen is also essential, with the present choice in technology being compressed gas tanks, up to 700 bar for HDVs. Obtaining such pressures is, however, cost and energy intensive, and pressure vessels are subject to strict safety regulations and the need for high strength materials (Rivard, Trudeau, & Zaghib, 2019), but some original equipment manufacturers claim that these can result in refueling times as low as 20 minutes (Nikola Corporation, 2024). An alternative for onboard storage is cryogenic liquid hydrogen (LH_2), which would lower the pressure needed for storage and increase storage density, leading to higher gravimetric and volumetric capacity (Ahluwalia, et al., 2023). Some drawbacks of using LH_2 are the very high costs, in terms of energy and equipment, needed to reach temperatures of 20 K (-253 ^oC) at atmospheric pressure for hydrogen to become a liquid, as well as high boiloff rates (Rivard, Trudeau, & Zaghib, 2019). The latter is of particular concern for HDVs given that road traffic and, in particular, border customs can result in unpredictable waiting times (up to days) and lead to a considerable percentage of LH_2 boil off. More recently, attention has been given to hydrogen storage in chemical hydrides, including metal and non-metal hydrides, amongst other adsorption materials that can offer very high gravimetric and volumetric energy densities, while operating at low temperatures and pressures (Durbin & Malardier-Jugroot, 2013). There is still much need for research and development of these technologies, as they still suffer from performance and regeneration related issues, as well as relatively high material costs, which currently makes them less viable for road transport applications (von Colbe, et al., 2019).

One major challenge to successfully deploy a large scale hydrogen mobility operation rests in being able to produce enough low-emission hydrogen via electrolysis. This is the process where electricity splits the water molecule into hydrogen and oxygen in a device called an electrolyser. If this electricity comes from renewable sources, the hydrogen obtained is known as 'green hydrogen', and it is considered to be the most promising method for large scale and distributed generation (Squadrito, Maggio, & Nicita, 2023). This is yet far from becoming a reality, as currently only 1% of the hydrogen produced worldwide comes from renewable sources (International Renewable Energy Agency (IRENA), 2021). Furthermore, there is the issue of competition with other industries for this resource, most notably, the ammonia and petrochemical industries, which account for 93% of the global hydrogen demand, leaving the rest to be shared between the methanol, metallurgical, mobility, electronic and food industries (Ajanovic, Sayer, & Haas, 2024). The potential for green hydrogen production is particularly limited in Europe due to a low renewable energy generation potential, calling for the need to import hydrogen from countries like Morocco, Chile and Australia to meet the future demand (The Oxford Institute for Energy Studies, 2024).

Lastly, is the matter of developing an extensive hydrogen refueling infrastructure, which remains a major bottleneck for the development of hydrogen-based vehicles. Hydrogen refueling stations (HRS), including transport and distribution infrastructure, is still very limited, as these represent quite notable differences from their traditional diesel or electric charging stations (Genovese & Fragiacomo, 2023). As of 2023, there were a total of 178 HRS in Europe, all servicing compressed hydrogen (350 or 700 bar), and over half of them located in Germany (European Hydrogen Observatory, 2023). There are two methods for hydrogen refueling, the first being to produce, purify and compress hydrogen onsite, mitigating the need for transportation to the refueling station, but subject to the technical capacity limits. The second method is through offsite, large-scale production and transportation of hydrogen via a pipeline network or through trailers (Apostolou & Xydis, 2019). There is also the need for added safety equipment in HRS, including regulated dispensing, leak detection, flow measurement, emergency shutdowns and appropriate management and storage, as hydrogen is highly combustible and can undergo explosive reactions (Genovese, Blekhman, & Fragiacomo, 2024). Very high capital expenditures for the necessary production, distribution and supporting infrastructure remain a key bottleneck in developing a large scale HRS operation, with at-the-pump prices covering a large range of EUR 10-20 per kg (H2.LIVE, 2024). Although the general trend in forecasts is that green hydrogen production costs will undergo a decline in the coming decade, with some estimates as low as EUR 4.4 per kg in 2030 (Frieden & Leker, 2024), there is also the added cost of compression, transportation and supporting infrastructure at HRS stations. Cost estimates are quite variable due to underlying factors such as production and compression technology maturity, energy costs and the need to create a demand for widespread adoption for hydrogen in mobility.

As previously mentioned, there is much discussion that ZEVs are to dominate the future of the heavy-duty market. There exist, however, the possibility of covering part of the market with a mix of ICE vehicles powered by alternative fuels, notably LNG, bio-LNG and hydrotreated vegetable oil (HVO), more commonly known as biodiesel. LNG road vehicles have the benefit of slightly reduced CO_2 emissions from operation and cost affordability from an investment perspective (Smajla, Sedlar, Drljaca, & Jukic, 2019). Issues, however, become apparent when assessing the WtW emissions of LNG, which are high and do not provide a solution for deep decarbonization (Rodriguez, 2020) and would only help to mitigate a portion of the environmental impact in the short-term.

In the case of low-emission, bio-based fuels, such as bio-LNG and HVO, which are produced by transforming large quantities of biomass from waste, manure, vegetable oils and animal fats into usable fuel with the advantage of low WtW emissions, even more so than green hydrogen or electricity from the current grid (JEC, 2021). Although the value chain and processes required may be regarded as energy and cost-intensive (Joint Research Centre, 2022), three major drawbacks pose a great threat to the future of biofuel availability. Firstly, the feedstock supply is limited and can vary significantly between regions, causing serious fluctuations in price (Sandaka & Kumar, 2023). Second, there may be fierce competition for resources during the production phase of crop-based HVO, such as competition with the food industry for land and water (Fradj, Jayet, & Aghajanzadeh-Darzi, 2016), as well as competition to obtain the finished product with other harder-to-decarbonize transport sectors, such as aviation or the maritime industries (European Court of Auditors, 2023). Lastly are the caps imposed by the EC on the final energy consumption in the transport sector from biofuels, in an effort to limit overexploitation and enable fair competition between the various uses of biomass (European Court of Auditors, 2023). The combination of one or more of the factors mentioned pose a serious threat for the large-scale adoption of alternative low-emission fuels, but they do present themselves as viable options to reach short-term decarbonization goals.

Heavy-Duty Future Market Outlook

There is much debate on which technology will dominate the future of heavy-duty road transport, where most of the insights come from analyzing the TCO while achieving deep decarbonization. The International Council on Clean Transportation (ICCT) published a white paper in 2023 to analyze two decarbonization pathways for the European market. The first scenario considered the previous EU CO_2 regulation and contemplated an emission reduction of 30% by 2030, and the second full decarbonization by 2040. An optimization problem was set to minimize compliance costs based on carbon emissions and technology specific constraints, with diesel, liquefied natural gas (LNG), battery electric (BEV) and fuel-cell hydrogen (FCEV) as drivetrains to consider. The results for the scenario proposed by the ICCT suggest that BEVs are expected to dominate new vehicular registrations leading up to 2040, while hydrogen fuel-cell trucks left to play a secondary role (Basma & Rodriguez, 2023). This idea is further elaborated in another study also by Basma & Rodriguez (2023), where the lowest TCO is achieved by battery electric trucks of all sizes.

Similarly, Shirizadeh et al. (2024) presented an optimization study to model the decarbonization of road transport coupled to the development of the European energy system, and concluded that BEVs represent the majority of the market for all segments. This, however, is subject to a very high degree of electrification and battery manufacturing, and proved to be very sensitive to policy interventions in favor of clean hydrogen production, which resulted in a heavy uptake of FCEVs for long-haul operations. Similar results are discussed by Aryanpur & Rogan (2024), who propose a cost-reduction model that also considers a preference for more efficient vehicles. In their results, BEVs are dominant in all weight categories in a base scenario, but lose part of their market share to FCEVs if other intangible costs of BEVs are considered. These additional costs have to do with limited cargo capacity and longer downtimes for recharging, a direct penalty of having a large battery, and is particularly noticeable in larger trucks.

A separate study by Xue et al (2022) assessed the systematic decarbonization of China's heavy-duty sector and concluded that the deployment of only one type of drivetrain would be insufficient. This would need to be achieved by improving the efficiency of internal combustion technologies and introducing diesel-electric hybrid drivetrains for the short-term, and a broader mix (including FCEVs and BEVs) for the longer-term. Additionally, Guandalini & Campanari (2018) investigated the energy consumption of different ZEV drivetrains and concluded that BEVs are more suited for smaller ranges, in particular for urban logistics with centralized recharging, due to the increased loss in payload (up to 30% loss for a driveable distance of 250km) and energy consumption related to the sizing of the battery. Longer distances should hence be covered by FCEVs or another technology, such as ICEs fed with biofuels. Other works by Boschat et al (2022) and Hunter (2018) in reports by Zenon Research/Kearney and the National Renewable Energy Laboratory (NREL), respectively, support the idea that the future market will have to be covered by a combination of technologies.

The degree to which any technology penetrates the market is highly reliant on a combination of factors directly related to transport TCO, such as the upfront costs of zero-emission trucks (Sharpe & Basma, 2022) or the availability and cost of fuel (Sandaka & Kumar, 2023) and factors related to regulation and policy landscape (Seemungal et al, 2021) such as incentive mechanisms (ie. purchase subsidies for ZEVs). This makes any results in this topic highly dependent on the inputs and initial assumptions, but it can be said that all studies have been able to conclude that there will be segmentation of the market, as no one technology is able to cover the entire demand, and the different drivetrains should not be regarded as antagonistic.

It is important to consider that the only way to reach deep decarbonization is to shift the focus from a TtW emission quantification, which can produce misleading results (Prussi, Laveneziana, Testa, & Chiaramonti, 2022) to a WtW focus, as the general view is that the transport and power sectors will become increasingly integrated, and overall emissions will thus depend on the electricity carbon intensity (Gustaffson et al, 2021). Keller et al (2019) suggests that deep decarbonization can only be achieved in the long-term through a higher renewable energy penetration, in which electrolysers and hydrogen storage play a critical role in grid balancing, but this uptake will have to be gradual with substantial financial requirements (Parviziomran & Berggvist, 2023). Furthermore, the increase in demand of ZEVs will result in the need to alter supply chains, leading to structural shifts in employment from traditional vehicle manufactruing towards battery and fuel cell production, fuel supply and refueling/recharging infrastructure (Tamba, et al., 2022) (Ko & Shin, 2023).

The need to address short and medium-term decarbonization, coupled with the limiting factors for ZEV uptake as discussed, opens the door for bio-based or drop-in fuels to come into the mix, offering increased flexibility and technology maturity for an immediate impact on emission reduction (Prussi, et al., 2020). There are, however, major constraints for bio-based fuels, such as the availability of feedstock supply and, depending on the nature of the feedstock, having to compete for land and water resources with the food industry (Verger, Azimov, & Adeniyi, 2022). Furthermore, a significant portion of biobased fuel demand will be reserved for harder-to-abate transport sectors, such as the aviation and marine industries, posing a major constraint on the amount available for road transport (Pelkmans, 2017). It is clear that biobased fuels have a role to play to achieve short-medium term decarbonization goals, but to what extent is still unknown.

Finally, the segmentation studies presented above create a systematic optimization problem, where the transport sector is aligned and dependent on the development of the power sector. In practice, this approach is generally true and useful to provide policy insights from a governmental perspective, allowing officials to identify and target certain areas that will have a holistic impact on the system. The study presented in this work differs in that it sets out from solely the transport companies' perspective, which will be the adopters of new heavy-duty vehicle technology. Its objective is to determine the market segmentation from a consumer point of view, under a set of rules and conditions put forth by the other relevant stakeholders.

3. Methodology

The methodology includes a qualitative and a quantitative phase, where the former aims at acquiring a deeper understanding of the whole system, the affected parties and other external factors that should be included when conducting the analysis in the quantitative phase. The qualitative phase consists of collecting information on the various stakeholder groups involved, as well as their key requirements within the scope of decarbonizing heavy duty road transport. With such requirements in mind, key selection criteria and potential bottlenecks are identified across the technical value chain. These key factors are proposed as objective functions for the quantitative analysis, where possible problem formulations and solution approaches are evaluated, including optimization, Game Theory and Agent Based Modelling. In the end, a Mixed-Integer Linear Programming (MILP) optimization problem in Python is selected as the method of choice. The following sections discuss in more detail the information collected, the mathematical problem formulation and the rationale behind choosing optimization to solve it.

Stakeholder Analysis

The first step is to identify the key stakeholders, and relevant influencing factors, in the context of heavy-duty road transport. Survey results conducted by Ragon & Rodriguez (2*022),* and published in a report by the ICCT, showed that infrastructure and vehicle availability, range, TCO and losses in payload were amongst the key perceived barriers for the adoption of ZEVs in existing fleets. The mixed nature of such factors further implies the need for collaboration across multiple sectors and a strategic rollout of new technologies. The first step is to map the most relevant stakeholders (Figure 2) , followed by a breakdown of their roles and summary of their interests (Figure 3).

In the context of the heavy-duty road transport industry, the following primary stakeholders include:

- Transportation companies and their customers, who share similar interests
- Original equipment manufacturers (OEMs) – Automakers
- Energy and fuel providers
- Grid operators
- Governments and authorities
- Financial institutions

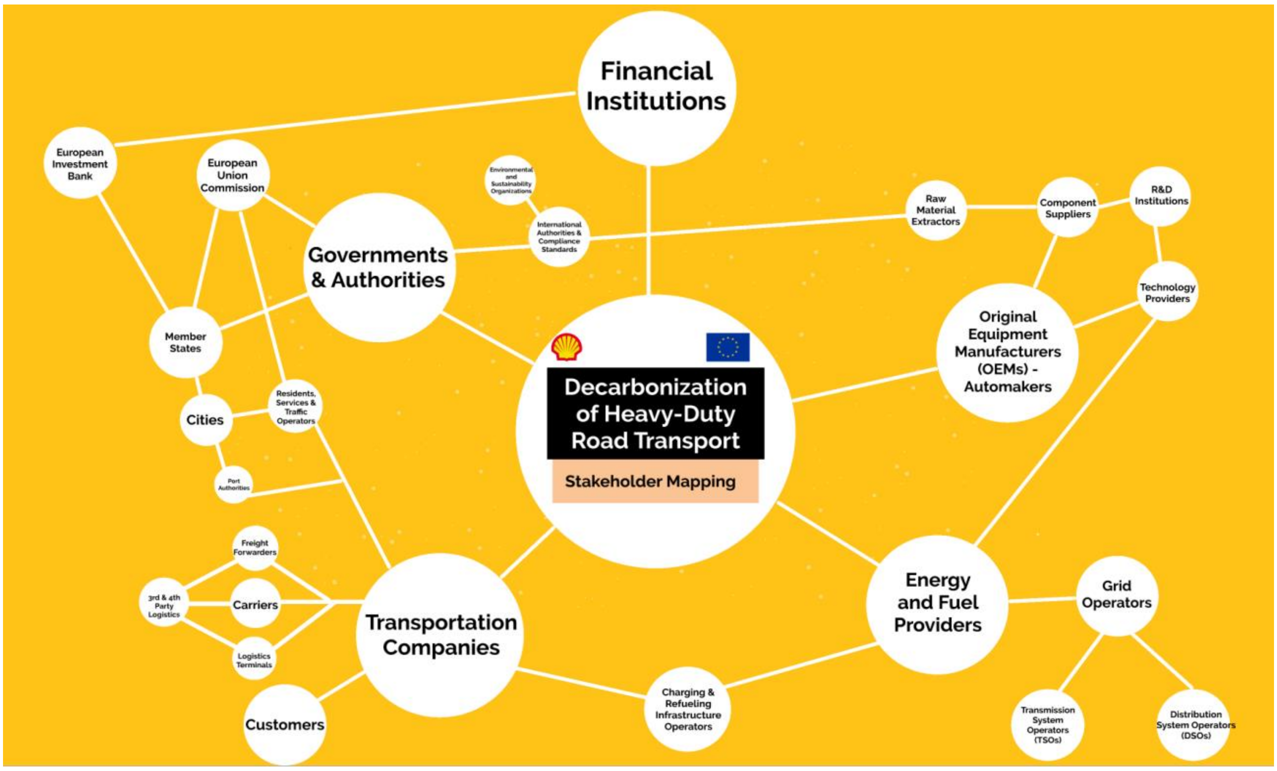


Figure 2 - Stakeholder overview and their most relevant interaction network.

Widespread adoption of zero or low-emission heavy duty vehicles will rest with the Transportation companies (TCs) and their inner circles, including carriers and/or truck operators, freight forwarders, 3rd and 4th party logistic service providers and logistic terminals. These are the key players responsible for providing a freight transport service that is efficient and cost-effective, and to ultimately create a demand for these new drivetrains. On the other hand, the customers are those organizations that hire such services to move their goods; these can be manufacturers, freight forwarders, import and export providers, amongst others. To comply with sustainable practices, TCs are tasked in incorporating ZEVs in their existing fleets, gradually transitioning away from diesel engines, and establishing green procurement and subcontracting practices. It is key, however, this be achieved without disrupting the core of their logistic services and maintaining a similar level of transport flexibility to retain a good relationship with customers (Yu, Cadeaux, & Song, 2016).

TCs and their customers may have to consider that future operations will be subjected to renewable fuel and energy availability. In particular, unplanned movements or expedited shipments will become more expensive during peak energy demand periods. Transparency and planning will be key to mitigate these external impacts, and Yu, Cadeaux & Song (2016) further emphasize that good performance under uncertain environments leads to very positive results for customer relationships and momentum building.

OEMs, or automakers, are responsible for maintaining a constant supply of trucks by securing raw material chains and incorporating state-of-the-art components in their products, such as updating battery and fuel cell technology. It is critical, however, to establish a suitable environment and degree of security to support the investments on behalf of the OEMs in the development and rolling out of these new vehicles, and to justify the purchase of new vehicles on behalf of the TCs.

The creation of this healthy environment rests on the remainder of the primary stakeholders: governments and authorities, energy and fuel providers, and financial institutions. Governments must enforce emission regulation and best practice policies on all parties, as well as promote incentives in the form of purchase subsidies and increase carbon taxes. From an economic perspective, governments need to create the necessary schemes for external financial institutions, in the form of banks or funds, to invest in such projects. Two examples are the recent rollout of new EU Green Deal or the Inflation Reduction Act (IRA) in the United States; two policy schemes that promote investment in energy and climate projects. From a technical feasibility perspective, energy and fuel providers are tasked with deploying the necessary charging and refueling infrastructure, securing fuel supply and to promote research and development (R&D) into scaling up production of new technologies. There must be close cooperation between energy providers and grid operators to mitigate the impact on the grid, as well as to adapt to changes in supply and demand profiles. As evident, the creation of this environment is very complex and will require extensive collaboration between the mentioned (and other) stakeholder groups.

Primary Stakeholder	Interests
Governments & Authorities	• Compliance with decarbonization standards • Transparency and accountability. • Promote competition and a fair playing field. • Build consumer awareness around benefits of low carbon HDVs.
Original Equipment Manufacturers	• Low investment costs and securing demand. • Secure supply chains for materials and technology to increase output and technology availability.
Transportation Companies & Customers	• Low costs and risks. • No range anxiety and low cost refueling. • Minimize dwell time and impact to payload. • Establish long-term contracts with fuel providers and operators. • Keep a high degree of flexibility with operations and avoid bottlenecks.
Energy Providers	• High demand for fuel to justify high CAPEX costs. • Secure a reliable supply of raw materials for energy projects. • Profit responsibility with shareholders.
Financial Institutions	• Investment security. • Long-term returns.
Grid Operators	• Minimize impact on grid. • Promote best practices for intermittent grid utilization.

Figure 3 - Primary stakeholder interests in the context of a decarbonized heavy-duty transport market.

Key Factors in Decision Making

The stakeholder identification phase consisted of identifying and analyzing their respective roles in the system. From this it was possible to select certain important factors, most of which can be quantified and formulated into objective functions, inputs, variables or constraints. These include:

- <u>Range or drivable distance without having to refuel or recharge</u>. This is proportionate to the size of the battery or tank for the case of hydrogen and other fuels. Reducing range anxiety for truck operators is key in promoting ZEV vehicle uptake.
- <u>Payload and total truck weight</u>. This is important when considering that gross vehicle weights are limited under regulation, and increasing truck weight comes at the expense of payload capacity.
- <u>Total cost of ownership (TCO)</u>. This factor was identified as a key determinant factor for heavy-duty vehicle uptake. TCO is a function of a vehicle's capital and operational expenditures, and will be discussed in more detail in the following section.
- <u>Recharging and refueling infrastructure availability</u>. This is especially important for tractors with a limited range due to the nature of their drivetrains, as limited or a lack of infrastructure availability would result in unreachable locations.
- <u>Emissions and emission regulation</u>. At the core of reaching decarbonization is to reach regulatory compliance with European emission targets. The severity of such targets will have

a great impact on how quickly, and to what extent, low and zero emission technologies penetrate the European market, and this has been considered as a Carbon Budget in this study.

- Operational flexibility. The nature of road transport operations may be variable, requiring TCs to be able to meet quick changes in customer demand and meet expectations. Such flexibility can be impacted when there is lower fuel availability, as can be the case during moments of grid congestion, renewable intermittency, safety issues or supply chain disruptions.

Total Cost of Ownership (TCO) of Transport

The total cost of ownership (TCO) for transport can be defined as the sum of vehicle operational expenditures (OPEX) and capital expenditures (CAPEX) over its lifetime. Rout, Li, Dupont, & Wadud (2022) make a very detailed breakdown of all the components of vehicle TCO, most of which were considered in this study. Vehicle CAPEX is influenced by the total cost of the vehicle acquisition, including the powertrain, glider and other overhead costs. From this, we can subtract any resale value for the entire vehicle or each individual component at the end of its lifetime. Any other form of grant or incentives can also be subtracted from the total acquisition cost. In general, the total vehicle acquisition cost is expected to decrease with time as the industry benefits from economies of scale, the technology reaches maturation and grant and incentive schemes are more widely available. Many vehicle OEMs do not publish the cost of particular vehicle or vehicle components but, for perspective, the current price of a battery or fuel-cell electric truck can be several times higher (5 or more) than that of a diesel vehicle (Sharpe & Basma, 2022). For this thesis, vehicle CAPEX has been simplified to cover the acquisition cost minus a fixed resale percentage that considers resale value, in line with component depreciation and internal insight.

On the other hand, vehicle OPEX considers the variable costs that come with vehicle use, with the main components being fuel price, vehicle maintenance and insurance costs. These can be further broken down into other subcategories but, for simplicity, a fixed value has been taken for maintenance and insurance costs, leaving fuel cost as a variable that changes depending on the drivetrain and the year. Assumptions in fuel cost over time will be further discussed in the Formulation of the Heavy-Duty Transport Optimization Problem section, as in some cases they are highly dependent on a variety of factors and externalities.

Operational Flexibility

As mentioned in the Stakeholder Analysis, transport companies must maintain a degree of operational flexibility to increase customer satisfaction. There are many types of flexibility within supply chain operations, but the most relevant is transport flexibility, which falls into logistics flexibility, enabling a firm to satisfy demand as it occurs and is important to effectively respond to customer needs. Improving such flexibility has a direct impact on the firms performance, has a positive impact on perceived benefit and customer satisfaction, and can have a cumulative effect. Perceived physical capabilities are also a strong indicator for the transport company's future performance, meaning that it is important to get a good head start and exploit a competitive market position (Zhang, Vonderembse, & Lim, 2005). On a tactical level, flexibility in transportation includes the ability to change the mode, route or carrier, the transport capacity or frequency and the ability to conduct express delivery (Fink & Benz, 2019). Additional studies by Vujanovic, Momcilovic, Bojovic, & Papic (2012), Chen & Kasikitwiwat (2011) and Kulovic (2004) were reviewed to find ways to quantify this flexibiity, but the data required for a quantitative assessment are not publicly available, as it relates directly to a transport companies performance on a per customer basis. Consequently, this has been excluded from the methodology and is considered a limitation. However, given the fact that this study deals with a market and region-wide approach, individual logistic operations have little significance on the broader scale, but it is important to emphasize that customer perception can have an impact during the early stages of technology adoption.

Choice of Method

A quantitative methodology is used to consider the decision making criteria mentioned in the previous section. Three different methods were assessed: optimization, Game Theory (GT) and Agent Based Modelling (ABM). A short description is included below and more information can be found in Appendix 1:

1. Optimization – selects the most optimum solution for given objective function, subject to a series of inputs, variables and both equality and inequality constraints. An example of an objective function can be to minimize costs, and a solution is feasible if all the constraints are met.
2. GT – oversees and understands how the strategic actions of two or more rational 'players' affect the outcome of a given situation, where a player's actions has a direct impact on the decision-making of another.
3. ABM – simulates a system comprising of different 'agents', each with its own behavior and attributes, that interact with other agents and the environment, which is used to provide information to an agent of his relative role with respect to other agents. Key elements include that each agent expresses different attributes and behaviors, and it is possible to define the nature of agent relationships.

A literature survey was carried out understand the formulation and applicability of each method. For optimization, this included reviewing the works of Chiandussi et al. (2012), which compares various optimization methodologies in engineering, highlighting the strengths and weaknesses of different approaches. Gunantara (2018) further expands on this by discussing the applicability of multi-objective optimization across various fields, emphasizing on its ability to tackle complex problems with conflicting factors.

For GT, the works of Laidoui et al. (2023) and Zhao et al. (2012) describe the multi-perspective, strategic selection process for tackling environmental risk and carbon emissions reduction, highlighting its ability to environmental challenges. Furthermore, Lokeshgupta and Sivasubramani (2018) illustrate a practical approach to optimize energy usage while integrating renewable energy sources.

For ABM, the works of Bonabeau (2002) and Garcia (2005) discuss the potential of this technique to be applied in new product development and research, emphasizing how the different dynamics of the system and its agents can have great influence on the outcome. This provides for a very comprehensive approach to addressing complex issues with multiple influencing factors. Furthermore, Macal & North (2010) provide a tutorial on how to effectively setup a simulation.

Ultimately, GT was rejected on the basis that it would yield predictable results and has a limited interpretation of reality, given that it assumes all player decisions are based on rational choices. ABM provides a very high degree of complexity due to the fact that it simulates the actions of individual 'agents' through time, but this liberty may result in a variety of outcomes that may be difficult to interpret or replicate. It was rejected for this reason, and creating a complex model would take a significant amount of time, while simplifying it too much could yield predictable results. This leaves optimization as the method of choice, as it is a very powerful tool capable of solving multi-criteria problems. It is also quite straightforward to translate the decision-making insight obtained from the stakeholder analysis into mathematical equations. For example, the influence of governments and regulation can be translated into a Carbon Budget constraint, where the total emissions from the sector cannot exceed the limit set by the EU's reduction targets. In the next section the formulation, model and assumptions are further discussed.

Formulation of the Heavy-Duty Transport Optimization Problem

The first stages of setting an optimization problem include setting equations that predict the response of physical process, including an objective function, decision variables, boundaries and constraints. This is followed by the selection of an optimization technique, including the modelling and solving via computational numerical methods (Rangaiah, Feng, & Hoadley, 2020). During this stage of the study, an internal Shell TCO tool was used, which was designed to provide small transport companies with a short-term roadmap to decarbonize their fleets. This template was adapted to fit the scope of this study, *Segmentation Path*, which considers a long-term approach, more range and weight segments, and a demand and fuel consumption profile for the Western European market. Amongst the key factors in decision making, the *Total Cost of Ownership (TCO) of Transport* was selected as the objective function to minimize, as it is quantifiable and has a heavy influence on which technologies will be preferred from a transport companies' perspective. The tool was created in Pyomo, a Python-based, open-source optimization modeling language, and the solver used is GNU Linear Programming Kit (GLPK). This results in a Mixed Integer Linear Programming (MILP) problem, subject to a series of equality and inequality constraints.

Sets, Parameters, Objective Function & Constraints

This section presents the mathematical formulation of the optimization problem used in *Segmentation Path*. At the end of the optimization, the tool delivers a file that with the total amount of fuel purchased, kilometers produced, and the number of active, bought and retired vehicles. All of this information is provided per drivetrain, year and range and weight category. The emissions are quantified as carbon dioxide equivalents (CO_2e), and the input can be in TtW or WtW, depending on the particular scenario to be tested. The carbon budget is adjusted based on the current EU carbon reduction targets.

Sets

The sets represent the truck characteristics, where each truck falls into a category for drivetrains, weight and range.

1. Set of drivetrains available

   D *= {Diesel, BEV, FCEV, H_2 ICE, LNG, HVO, Bio-LNG}*

2. Set of fuels available

   F *= {LNG, HVO, H_2 (FCEV), H_2 (ICE), Electricity, Diesel, Bio-LNG}*

3. Drivetrain and fuel combination, where each drivetrain can only use the fuel it has been assigned.

   Diesel = {Diesel}

   LNG= {LNG}

   Bio-LNG= {Bio-LNG}

   BEV= {Electricity}

   HVO= {HVO}

   FCEV= {H_2 (FC)}

   H_2 ICE = {H_2 (ICE)}

4. Set of years to be considered

   $\boldsymbol{Y} = \{Y \in \mathbb{Z}: 2023 \leq y \leq 2040\}$

5. Set of weight categories for total gross vehicle weight (tons)

   $\boldsymbol{W} = \{w_1, w_2, w_3, w_4, w_5\}$, *where…*

   $w_1 \in [0,10)$

   $w_2 \in [10,20)$

   $w_3 \in [20,30)$

   $w_4 \in [30,40)$

   $w_5 : \geq 40$

6. Set of range categories for maximum distance a truck can cover without having to recharge or refuel (kilometres)

   $\boldsymbol{R} = \{r_1, r_2, r_3, r_4, r_5, r_6\}$, *where...*

   $r_1 \in [0,50)$

   $r_2 \in [50,150)$

   $r_3 \in [150,300)$

   $r_4 \in [300,500)$

   $r_5 \in [500,800)$

   $r_6 : \geq 800$

Parameters

The parameters are inputs for the model, and are determined based on the truck characteristics.

d – demand in kilometers, representative of the Western European demand. This varies based on the year, weight and range category.

i – investment cost of a vehicle, this varies with type of vehicle and the year it is bought.

p – vehicle resell percentage as a fraction of i.

m – maintenance cost of a vehicle per km.

η – fuel consumption in different years in megajoule per kilometre (MJ/km)

c – carbon emissions per unit of fuel type in kilograms of carbon dioxide equivalent (CO_2e) per megajoule (MJ) of fuel. Can be TtW or WtW, depending on the particular scenario to test.

f – cost of fuel in different years (EUR per megajoule of fuel).

C – Carbon Budget per year. Maximum emissions in kilograms of CO_2e per year, for the entire region.

K – maximum distance a vehicle can travel in a year (kilometres).

u – maximum distance a vehicle can travel without recharging or refuelling (kilometres).

t – lifetime of a vehicle (years).

M – maximum cumulative number of vehicle investments.

Variables and Objective Function

The variables to consider are presented below. These are pre-determined for each year and are not parameters given that they are not subject to any technological constraints or external factors, rather assigned values at the start of the optimization.

v– Total vehicles per year

y - Active vehicles per year

x- Bought vehicles per year

z - Retired vehicles per year

k - Produced kilometres per year

b - Bought fuel per year

The objective is to minimize the transport TCO (Equation 1), as a function of the different variables and subject to a series of constraints.

$minimize\ \boldsymbol{TCO}(x)$

$$TCO(x) = \sum_{Y=2023}^{2040} \frac{\left(x_y i(1-p)\right)}{t} + b_y + mk_y$$

Equation 1

subject to…

$$g_j(x) \leq lim, \ \ j = 1, \dots, n,$$
$$h_i(x) = 0, \ \ i = 1, \dots, n,$$

where...

Y – years for which TCO is optimized

x- Bought vehicles per year for all drivetrains

i – Vehicle investment cost

p – Vehicle resell as a fraction of i

t – lifetime of a vehicle (years)

b – bought fuel per year

m – maintenance cost per km

k – total kilometres produced per year

g_j – are a series of inequality constraints (ie. maximum carbon budget, maximum vehicle range)

h_i – are a series of equality constraints (ie. meeting demand for each year, fuel use)

n – total number of constraints

Furthermore, all relationships are linear and some decision variables can only take integer values (ie. number of trucks can only be an integer), which yields a mixed integer linear optimization problem (MILP).

Constraints

1. Supply and demand matching constraint: where all the demand *(d)* for every range (*R)*, weight (*W)* and year *(Y)*, is matched by the produced kilometres (*k),* where the optimization determines which drivetrains *(D)* will be operated.

$$d_{R,W,D,Y} = k_{R,W,D,Y}$$

Where...

$\boldsymbol{R} = \{r_1, r_2, r_3, r_4, r_5, r_6\}$

$\boldsymbol{W} = \{w_1, w_2, w_3, w_4, w_5\}$

$\boldsymbol{D} = \{Diesel, BEV, FCEV, H_2\ ICE, LNG, HVO, Bio\text{-}LNG\}$

$\boldsymbol{Y} = \{Y \in \mathbb{Z}: 2023 \leq y \leq 2040\}$

2. Match weight bucket to kilometre production: limits vehicles of weight w_n to only produce kilometres for their assigned weight class (ie. the demand for 20-30 ton vehicles can only be allocated to vehicles within that same weight bucket. This prevents larger or smaller vehicles from covering the demand of other weight categories).

$$\boldsymbol{W_1} = \{w_1\} \quad \text{for } w_1 \in [0,10)$$

$$\boldsymbol{W_2} = \{w_2\} \quad \text{for } w_2 \in [10,20)$$

$$\boldsymbol{W_3} = \{w_3\} \quad \text{for } w_3 \in [20,30)$$

$$\boldsymbol{W_4} = \{w_4\} \quad \text{for } w_4 \in [30,40)$$

$$\boldsymbol{W_5} = \{w_5\} \quad \text{for } w_5 : \geq 40$$

3. Vehicle balance constraint: total vehicles (*v*) is equal to the number of active vehicles from the year before (A_{Y-1}), plus bought vehicles (*x*) minus retired vehicles (*z*), for each drivetrain (D) in the set.

$$v_D = A_{Y-1} + x_D - z_D \quad \text{for } Y \in \mathbb{Z}: 2023 \leq y \leq 2040$$

4. Vehicle acquisition year constraint: a vehicle (*x*) can only be bought for the year (*Y*) defined in the input.
5. Vehicle retirement constraint: bought vehicles (*x*) retire after completing their lifetime (*L*) and retired vehicles (*z*) can no longer be used.
6. Daily distance limit constraint: this means that a vehicle of drivetrain *D* can only drive a maximum number of kilometres per day (u) without having to recharge or refuel. This depends on which type of drivetrain the vehicle is and of the year (*Y*) it was acquired in. As technology improves, the more kilometres can be driven on a single charge or tank.

$$u_{D,Y} \leq \text{lim\_}u$$

7. Yearly distance limits per vehicle: all active vehicles (*y*) can only produce a maximum amount of km (K) in a year (*Y*). This is the sum of al kilometres driven by one vehicle throughout the year, which cannot exceed an inputted limit.

$$K_{v,Y} \leq \text{lim\_}K$$

8. Vehicle fuel combination constraint: produced km (*k*) can only be true for the correct fuel (*F*) and drivetrain (*D*) combinations, as defined in the sets. For example, a BEV vehicle can only use electricity as fuel.

9. Fuel balance constraint: all bought fuel (*b*) matches the requirements to execute all produced km (*k*) per year (Y), considering fuel consumption (η) per drivetrain (*D*) per year, as defined in the sets. This means that for more efficient vehicles, their fuel consumption will be lower to produce the same amount of kilometres.

$$b_{Y,D} = \eta_{Y,D} k_{Y,D}$$

10. Carbon limit constraint: amount of CO_2 (η , *p*, *c*) emitted in one year (*Y*) does not exceed the maximum limit (*C*).

$$\eta_Y p_Y c_Y \leq C_Y$$

11. Maximum vehicle investment constraint: the maximum number of vehicle investments (*M)* for all years (*Y)* cannot exceed the inputted limit.

$$\sum_{Y=2023}^{2040} M \leq lim\_M$$

12. Planned investments constraint: the maximum number of bought vehicles (*v*) for each year (*Y)* cannot exceed an inputted limit.

$$v_Y \leq \lim \_v$$

Tools & Inputs

The *Segmentation Path* tool is a Python code that uses an open-source mixed integer programming solver called *GLPK.* To run the optimization model, an input Excel template needs to be filled out with the Sets, Parameters, Objective Function & Constraints presented in the previous section, and then uploaded to an internal Shell server.

The inputs for the costs relating to vehicle CAPEX and OPEX, and efficiency parameters until 2030 were obtained from an internal Shell database. Since this study considers a long-term approach until 2040, assumptions and estimates on future vehicle and fuel prices were made with data found in a report by Basma & Rodriguez (2023) for the International Council on Clean Transportation (ICCT); these are summarized below.

The Western European heavy-duty transport sector considers the following countries: The Netherlands, Belgium, Spain, France and Germany.

Vehicle Cost & Range Assumptions

- A flat 10% residual value is assumed for all vehicles for all years.

Battery Electric Vehicle (BEV)

- Vehicle and fuel costs and range estimates for 2023-2030 are internal.

- The ICCT vehicle cost estimate for 2040 was taken as a reference for the future. The last internal value available for 2030 and the ICCT 2040 estimates were used to linearly interpolate for the years in between, followed by a linear extrapolation until 2040.
- The internal data only considers 40 ton trucks, so the cost of smaller trucks was adjusted with the ICCT values as a scaling reference:
  - Trucks in the <10 ton category were characterized as *Urban Delivery* trucks, 10-20 and 20-30 ton weight segments were considered as 4-Regional Delivery trucks.
  - 30-40 ton weight segments was considered as a 5-LH (500km) trucks.
- Range estimates until 2040 consider periodic increases following the same evolutionary trend as internal data for 2023-2030. The maximum range for all BEV trucks is less than 800 kilometers.
- The vehicle acquisition cost decreases linearly with time at the same rate for all trucks.

Fuel Cell Electric Vehicle (FCEV)

- Vehicle and fuel costs from 2023-2030 are internal.
- Same vehicle cost approach as BEV to estimate costs after 2030.
- Range estimated based on tank size (ie. amount of hydrogen onboard), with periodic increases of 300 km in range every 7 years, as per the data provided by internal experts.
- For trucks under 30 tons, the initial hydrogen tank sizes from the ICCT report were used and scaled up for the 30-40 and 40+ ton segments. In summary:
  - <10 ton and 10-20 ton trucks have a tank size of 16 kg of hydrogen in 2023, enough to yield 213 km.
  - 20-30 ton trucks have a tank size of 45 kg of hydrogen in 2023, enough to yield 600 km.
  - 30-40 ton and 40 ton trucks have a tank size of 60 kg of hydrogen in 2023, enough to yield 800 km.

Hydrogen Internal Combustion Engine (H_2 ICE) Vehicle

- No internal data was available for vehicle cost, so the inputs were taken from the ICCT report and scaled for the respective weight segments similarly as with BEVs.

- Vehicle ranges are internal and lower than for FCEVs under the assumption that fuel cells have a higher efficiency than hydrogen ICEs for road transport applications. In summary:
    - <10 ton and 10-20 ton trucks have a tank size of 16 kg of hydrogen in 2023, enough to yield 185 km.
    - 20-30 trucks have tank size of 45 kg of hydrogen in 2023, enough to yield 525 km.
    - 30-40 and larger trucks have a tank size of 60 kg of hydrogen in 2023, enough to yield 700 km.

Diesel & HVO Internal Combustion Engine Trucks

- Vehicle and fuel costs from 2023-2030 are internal
- Same vehicle cost approach as BEVs and using data from the ICCT report to estimate the cost from 2030-2040.
- Vehicle ranges are equal for all weight categories and assumed at 5,000 km for a 1,500 liter tank.

Bio and Fossil Liquefied Natural Gas (LNG) Truck

- Bio-LNG/LNG vehicle costs were assumed to be 10% more expensive than diesel and HVO drivetrains for all years and all vehicle weights.
- Vehicle range is equal for all weight segments and assumed at 1,600 km.

Fuel Consumption per Kilometer Assumptions

- Fuel consumption (in megajoules per kilometer) for 40 ton trucks was acquired internally for 2023-2030, and then interpolated until 2040 using ICCT reported values.
    - H_2-ICE assumed to be spark ignition engines and have a lower efficiency than fuel cells.
    - Diesel, HVO and LNG efficiencies assumed for compression ignition (CI) drivetrains.
    - BEV and FCEV vehicles are able to benefit from regenerative braking, which was assumed at 15% in fuel savings (Lakshmi, Kanwar, Sandhyaa, & Laksmhi Priiya, 2017).
- Different vehicle sizes have different fuel consumptions. Hence, the internal consumption data for a 40 ton truck was adjusted based on results by Delgado, Rodriguez & Muncrief (2017), which models the changes in roll and air resistance with respect to different vehicle weights, sizes and driving cycles. Such changes result in a variable instantaneous power-at-the-wheels profile, which is translated to the amount of fuel consumed per kilometer driven. Key considerations include:

- Smaller vehicles (<10 ton and some 10-20 ton) are used for urban delvieries (less than 150 kilometers), which have less weight and lower average speed, but consume more fuel due to frequent starts, stops and idle times. An 18-27% increase in consumption from the 40-ton truck baseline was assumed for these classes.
- Medium vehicles (which can fall under 10-20 and 20-30 tons) are used for regional delivery (less than 300 kilometers) and have steep changes in acceleration, resulting in moderate consumption. A 7% increase in consumption from the 40-ton baseline was assumed for these classes.
- Large vehicles (30 tons or larger) are used for long-haul (300+ kilometers) and have constant speed, resulting in the lowest consumption.

Fuel Cost Assumptions

All fuels costs are assumed to be independent of each other, including the price of electricity and green hydrogen. This decision to decouple both sectors is explained in section *The Future Energy System & Fuel Prices* of the Discussion.

- Electricity – internal prices are available until 2030, and then it is assumed that they follow the same trend until 2040. As an exception, the ICCT reported values were not taken into account for all scenarios as they show a very substantial cost drop, which does not correlate with internal insight. The following assumptions were made for the Base, Low and High price scenarios:
    - Base: prices follow an increasing trend until 2040 and consistent with the internal values from 2023-2030.
    - High: prices follow the same trend as the Base scenario but are 20% higher.
    - Low: prices follow the same trend as the Base scenario from 2023-2030, and then gradually decrease until reaching the 2040 price as reported by the ICCT.
- Hydrogen – internal prices are available until 2030. Upon consultation with internal subject matter experts, a ~50% and ~80% reduction from the initial price was assumed for 2035 and 2040, respectively. The following assumptions were made for the Base, High and Low price scenarios:
    - Base: price evolution set upon consultation with internal subject matter experts.
    - Low: prices are 20% lower than the Base scenario.
    - High: prices are 20% higher than the Base scenario.

- HVO – internal prices are available until 2030, and then it is assumed that they follow the same trend until 2040. As an exception, the ICCT reported values were not taken into account because it shows a very substantial cost drop and does not correlate with internal insight.
- LNG and diesel costs were taken from internal data and a 20% difference from 2030 to 2040 was assumed, consistent with their respective trend.

Fuel Emissions Assumptions

- All emissions factors for tank-to-wheel and well-to-wheel are internal and quantified in kilograms of CO_2e/MJ.

Vehicle & Fuel Availability

- The maximum vehicle uptake rate is the same for all drivetrains except for Bio-LNG and HVO, which can cover a maximum of 10-20% of the total demand given the limits on feedstock and fuel availability. There is unlimited fuel availability for all other drivetrains.
- The maximum uptake per year increases at a rate of 10% and there is accumulation, meaning that vehicles bought in previous years can be used at a later stage if they have not reached their maximum lifetime.

Carbon Emissions Estimates

- The year of reference for emission reduction was 2019, which is the year the EC adopted the current CO_2 emission standards for heavy-duty vehicles; a sector that is responsible for 6% of the total emissions in Europe (European Comission, 2024). These reduction targets were used to calculate the drop in Carbon Budget, with linear interpolation in between target dates.
- The carbon emissions for the Western European heavy-duty transport sector was estimated by taking its share of tractor stock, 38.6% of the total EU market as reported by Eurostat (European Union, 2024), and multiplied by the total amount of emissions of the EU heavy-duty transport sector.
- It is assumed that all emissions in the first year of the optimization, 2023, are from diesel vehicles.

Demand Estimates & Distribution

- It is assumed that all the initial demand is covered by diesel vehicles, as the share of zero-emission vehicles is orders of magnitude smaller (European Union, 2024).

- The initial demand in kilometers for Western Europe was estimated from the total 2019 CO_2 emissions by using internal emission factors.

$$Demand\ [km] = \frac{emissions[kgCO_2e]}{emission\ factor\ \left[\frac{kgCO_2e}{MJ}\right] * consumption\ [\frac{MJ}{km}]}$$

Equation 2

- The demand for the first year of the optimization, 2023, was estimated by applying a 2% compound annual growth rate (CAGR) to the demand for 2019.
- The demand for the different range-weight segments is allocated by using a combination of ICCT (Basma & Rodriguez, 2023) and North American Council for Freight Efficiency (NACFE, 2019) survey insight. In short, it is assumed that shorter ranges are mainly covered by small and medium-sized trucks, while longer ranges are covered by the heavier trucks. These assumptions were made given the lack of primary public data on truck operations.

Hydrogen-Electricity Price & Environmental Impact Scenarios

As discussed in the previous section, different scenarios are set to test the sensitivity of the optimization with respect to the price of green hydrogen-at-the-pump and grid electricity. A Base, High and Low price is determined for each category, yielding a total of 9 different pricing scenarios.

In addition, two Carbon Budget scenarios are set to quantify the environmental impact, with 2019 the baseline year for emission limits. The first scenario is in line with the current carbon reduction targets, and it involves a 45% reduction by 2030, 65% reduction by 2035, 90% reduction of tank-to-wheel (TtW) emissions by 2040. The second scenario tests the effect of a shift in the regulatory scope from TtW to well-to-wheel (WtW) emission quantification, under current reduction targets.

4. Results & Analysis

This section presents the optimization results, where the market share for each drivetrain is color coded and represented as the number of kilometers driven each year in a stacked column chart. The first section presents an illustrative perspective on the future market, as well as the impact of applying the biofuel availability and carbon budget constraints to the system. This is followed by the segmentation results for newly adopted EU heavy-duty carbon reduction targets, from both a TtW and WtW perspective, while varying the price of hydrogen and electricity. A sensitivity analysis to further discuss the effect of price variations on the market share of zero-emission technologies, BEVs and FCEVs, is also included for. The last section will cover the drivetrain distribution between the various distance and weight buckets.

A Perspective on Market Segmentation & the Influence of Bio-availability & Carbon Budget Constraints

It has been proposed in this report that the future of heavy-duty road transport will have to accommodate a variety of segments based on technology, weight and distance buckets. Figure 4, which has been included for illustrative purposes, displays the development of the cumulative kilometers of the heavy-duty sector until 2040. Most notably, each colored area represents a specific market segment, showing the complexity behind the problem and how the optimization tool is flexible in allocating the demand based on the lowest possible cost. It further emphasizes that the heavy-duty transport market is a growth market, as every year new demand needs to be allocated while considering carbon reduction targets, and provides evidence that an optimization formulation is suitable for producing results for very complex problems.

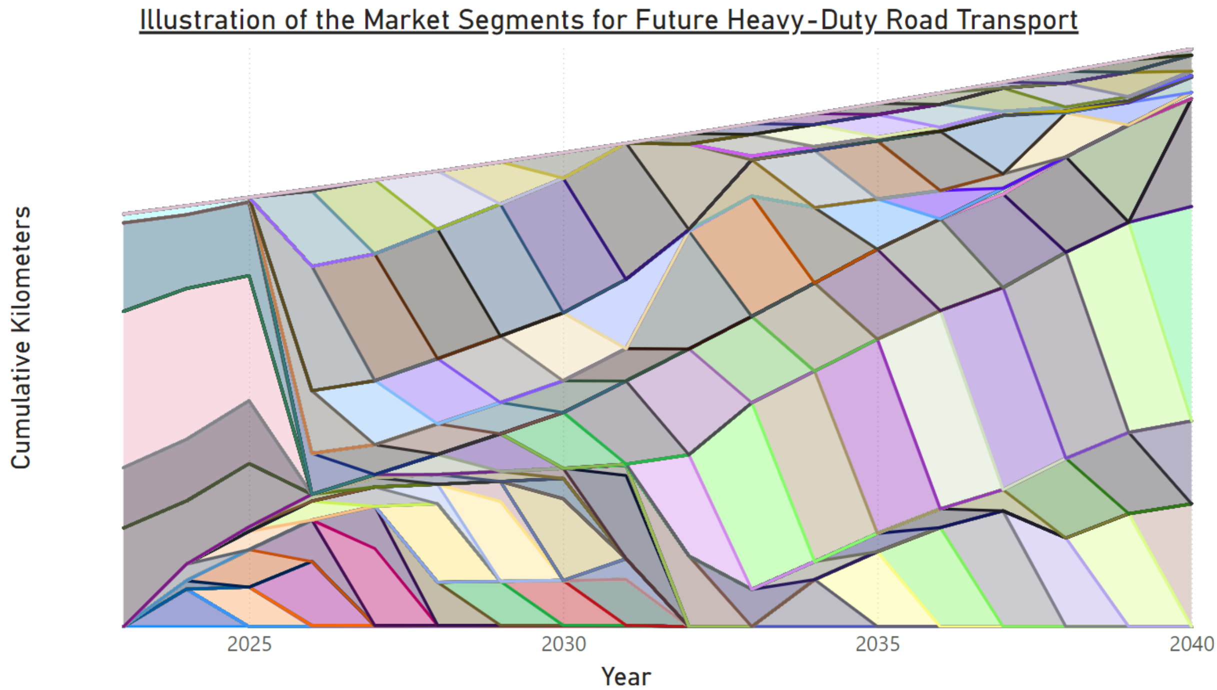


Figure 4 - Illustration of the results, where ach colour represents a market segments until 2040 and assuming a 2% CAGR.

Figure 5 shows a clearer representation of the results, where all the segments are filtered per drivetrain type. There are four key aspects to note from this figure: firstly, as stated above, the yearly increase in cumulative kilometers is representative of a growth market and emphasizes the need for a high rate of adoption of new drivetrain technologies to meet the existing and new demand. Second is the size of each drivetrain segment per year, which is represented by different colors including BEVs (orange), FCEVs (purple), diesel (navy blue), Bio-LNG (light blue), HVO (green) & LNG (yellow). H_2 – ICE vehicles (pink) do not have a presence. Third, the limited share of Bio-LNG and HVO vehicles is a direct result of the limited biofuel availability. Fourth, the influence of the carbon reduction targets can firstly be noticed in the decrease in share of diesel vehicles, and similarly at a later stage for LNG vehicles.

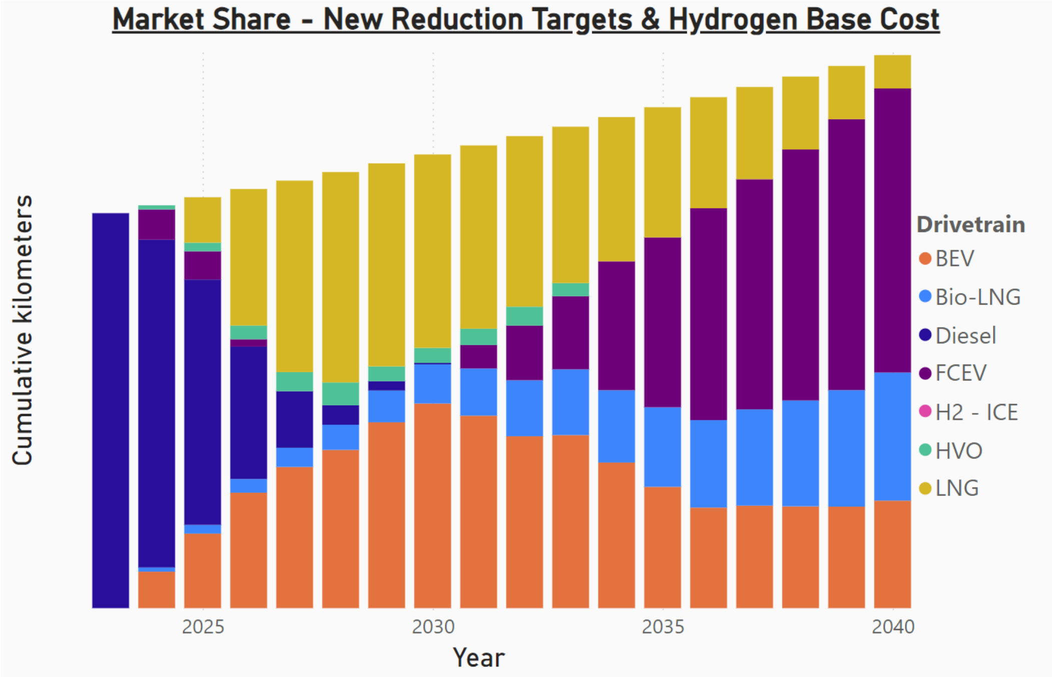


Figure 5 - Base hydrogen cost results under the newly approved EU reduction targets and considering TtW emissions.

The latter two aspects are of particular significance; Figure 6 shows the results under a speculative scenario in which there is unlimited access to bio-based fuels.

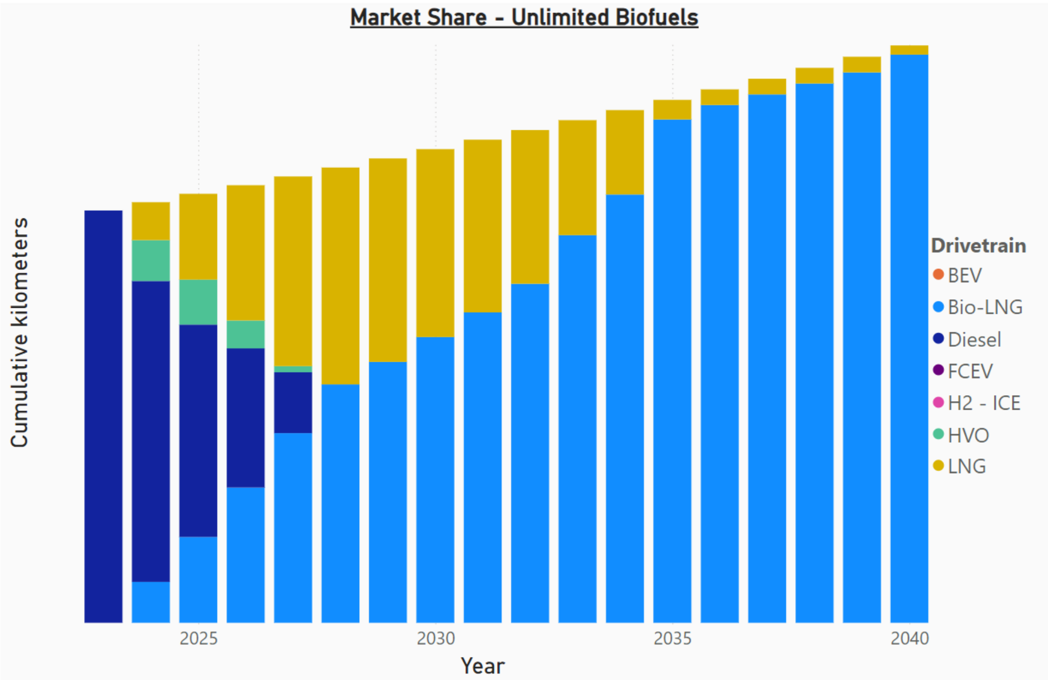


Figure 6 - Market share assuming unlimited bio-based fuel availability.

This approach is not realistic, as biofuels are only be able to cover from 10-20% of the total market share due to the feedstock and policy barriers discussed in Technology Overview, but it gives evidence to the potential these technologies have to contribute to a decarbonized sector.

Lastly, the influence of the Carbon Budget constraint is shown in Figure 7Figure 7, where fossil fuels dominate the market. Diesel vehicles are phased out by LNG vehicles based on cost, and Bio-LNG retains a very modest part of the market. Evidently, emission reduction targets are a key driver for zero- and low-emission technologies making an appearance as seen in Figure 5.

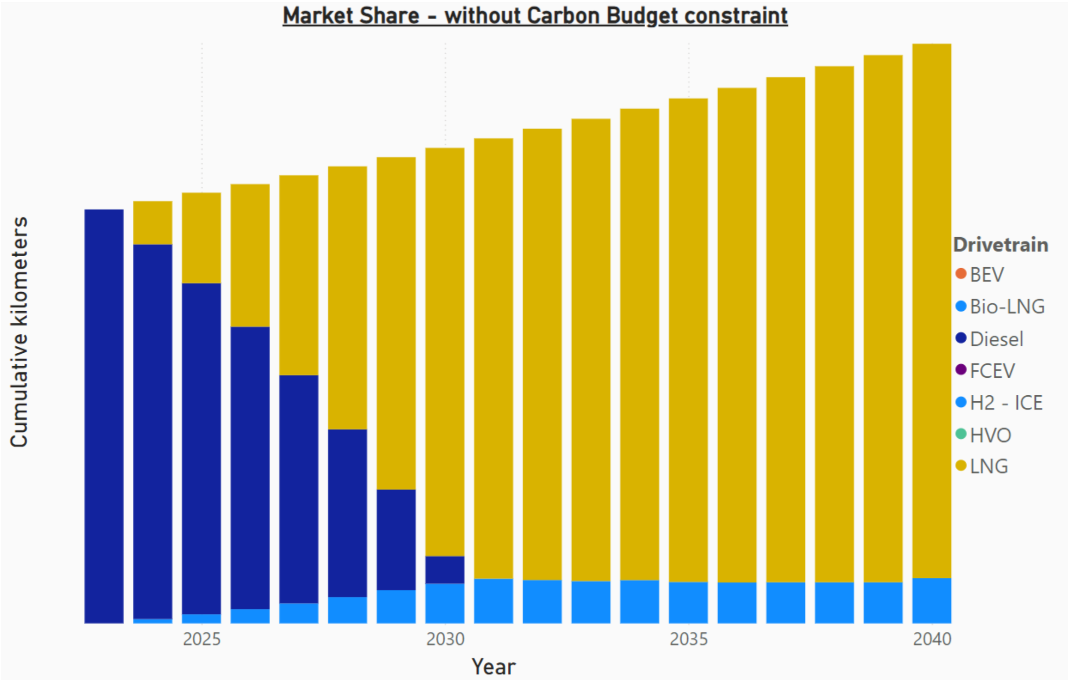


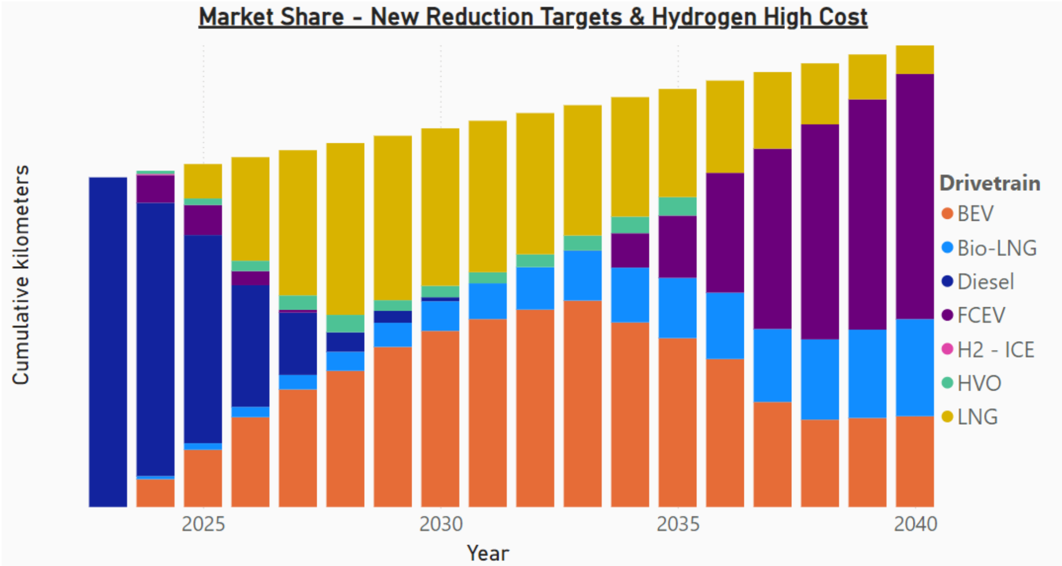
Figure 7 - Market share without a Carbon Budget constraint.

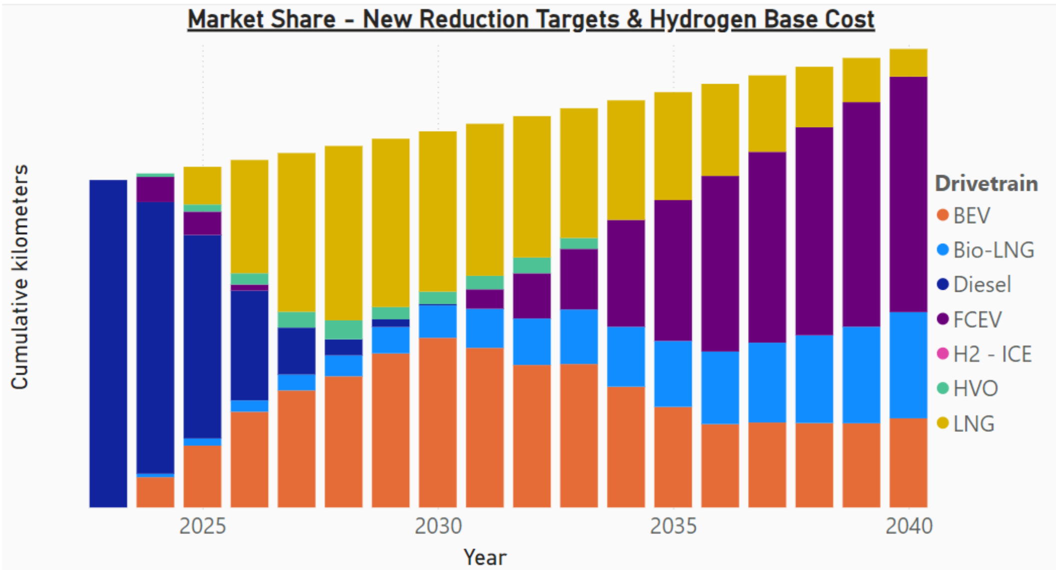
Results for Newly Agreed Carbon Reduction Targets

The EU has set the goal to decrease the carbon emissions from heavy-duty transport by 45% in 2030, 65% by 2035 , and 90% by 2040. This legislative standard was put into effect in May 2024 and will be subjected to review in 2027 (Mulholland, 2024).

Hydrogen Cost Scenarios

The results from the hydrogen Base, High and Low cost scenarios are presented in Figure 8 and consider an average price of electricity.





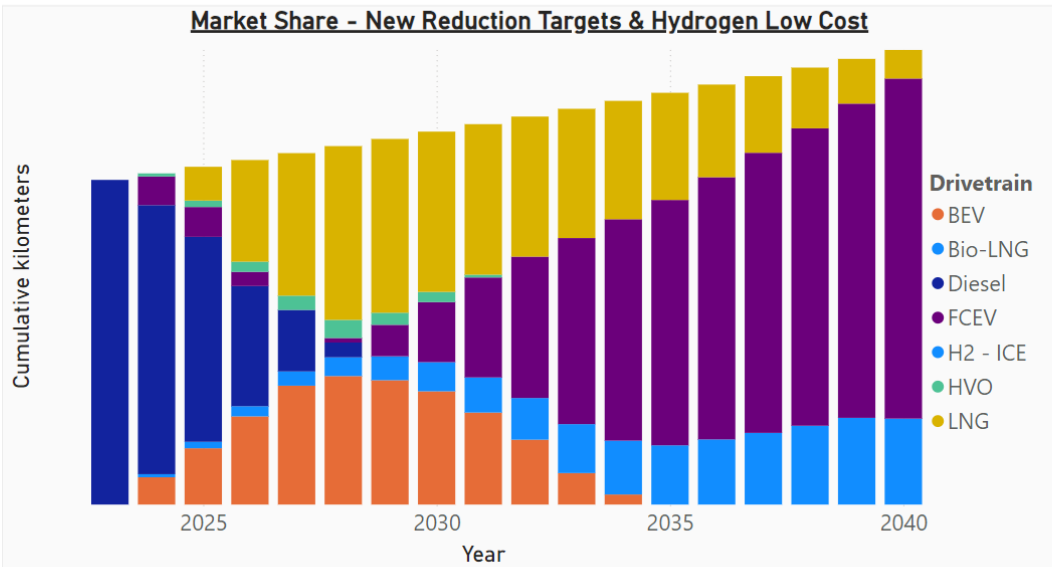


Figure 8 - Market share for High, Base and Low cost of hydrogen with average electricity price.

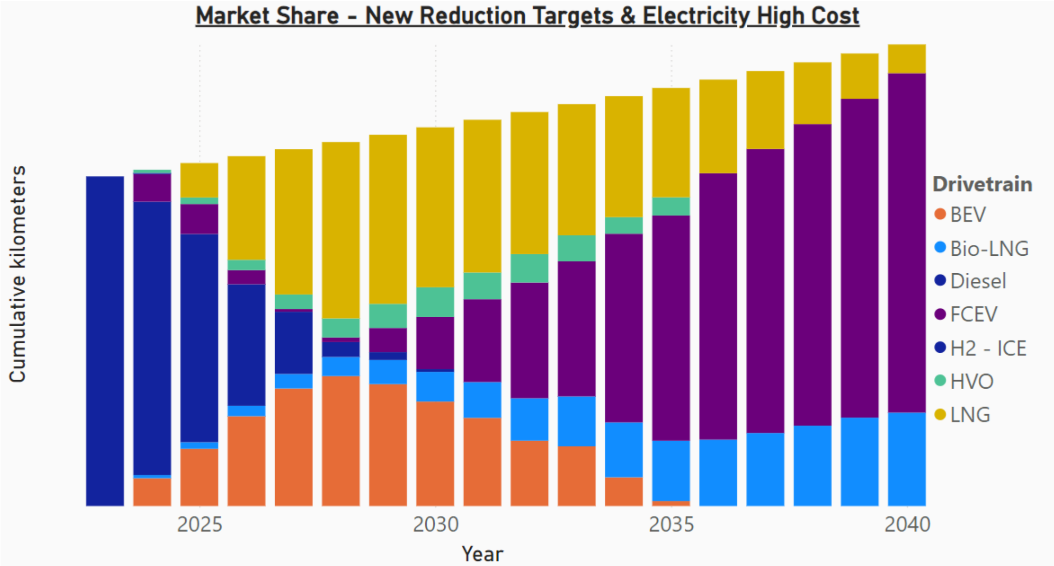
The effect of the Carbon Budget is immediately noticeable and results in a gradual decrease of diesel vehicles for all scenarios. As a result, there is the emergence of a diversified market comprised of BEVs, FCEVs, LNG, Bio-LNG and a small portion of HVO trucks to cover the demand.

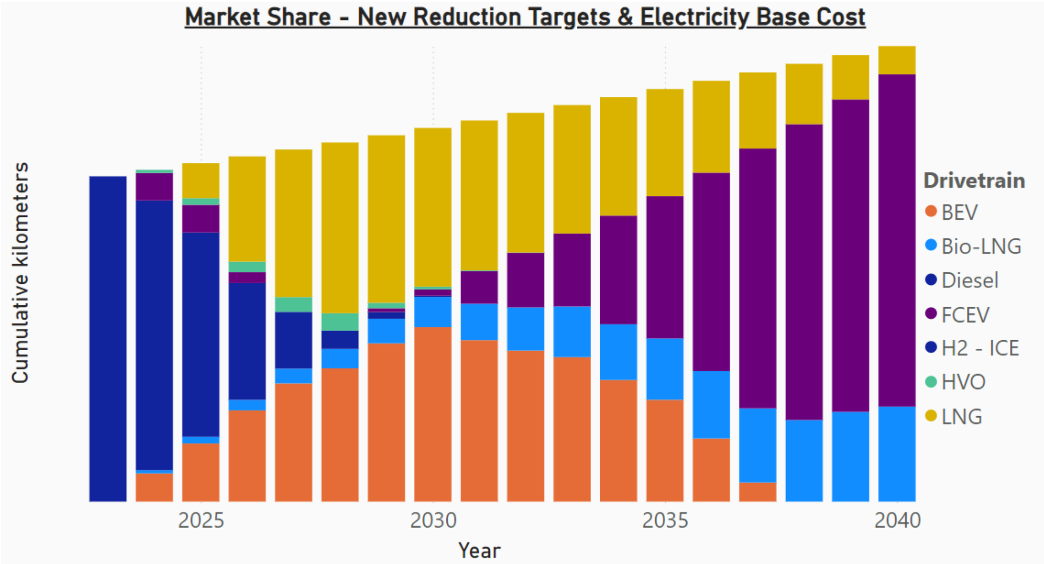
For all scenarios, there is an almost immediate and consistent increase in LNG drivetrains until 2027-2028, accounting for almost half of the market share by this time. After reaching this maximum point, this share gradually decreases in favor of zero-emission technologies, as a direct result of the Carbon Budget tending towards zero. The rise of Bio-LNG happens early and maintains a similar increasing trend throughout all years, with HVO having a more modest role, but the lack of bio-based fuel availability is very evident in their limited market penetration. It is not very noticeable in the figure, but there is a very small emergence in H_2 ICE vehicles from 2024 to 2025, accounting for approximately 1% of the total market share for all scenarios.

The main difference across all scenarios is the size of BEV and FCEV market share. Both these technologies emerge in the first year of the optimization, but their performance for the future varies between the different scenarios. Overall, BEVs experience a higher uptake rate earlier on than FCEVs. For a High and Base price of hydrogen case, the market share of FCEVs does not experience a noticeable uptake until after 2030, and goes on to cover approximately half of the final market share in 2040. For a Low price, the FCEV share increases gradually from 2029, takes over all of the BEV share by 2035, and positions itself as the clearly dominant zero-emission technology. Although the first years of all optimization scenarios favor BEVs, and they remain resilient in the High and Base hydrogen price scenarios by reaching minimum and not decreasing any further, there is a correlation between their loss in market share and the rise of FCEVs.

Electricity Price Scenarios

The results for the Base, Low and High cost of electricity are presented in Figure 9 considering an average price of hydrogen.





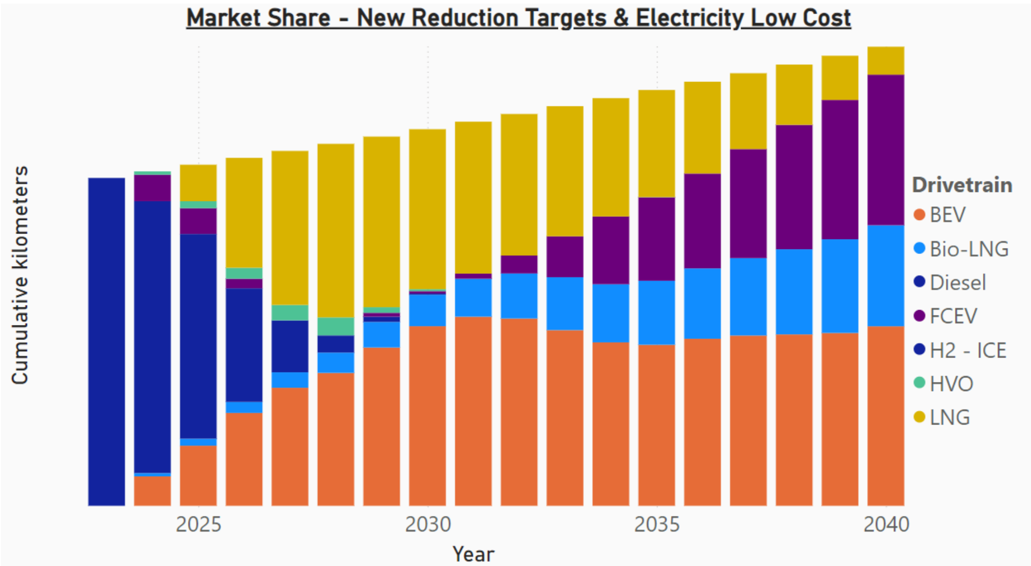


Figure 9 - Market share for Low, Base and High cost of electricity with average hydrogen prices.

The results show a similar story as the preceding section. LNG, HVO and H_2 ICE vehicles are present in a similar fashion across all scenarios, but are eventually displaced by an increased uptake of BEVs and FCEVs, and with a consistent share of Bio-LNG for all scenarios. A Base and High cost of electricity results in an initial uptake of BEVs, reaching maximums in 2030 and 2028, respectively. In both these scenarios, however, FCEVs eventually take over and are the only zero-emission vehicle technology left. In contrast, a Low cost of electricity results in BEVs covering a significant portion of the market for all years and do not experience a very drastic loss in share to FCEVs.

Influence of Well-to-Wheel (WtW) Emissions

Adopting a WtW emission quantification approach, as opposed to the current TtW scope, is presented in Figure 10. This section is intended to show the impact such a change in the regulatory landscape would have, but further analysis will only be drawn considering a TtW approach with current reduction targets.

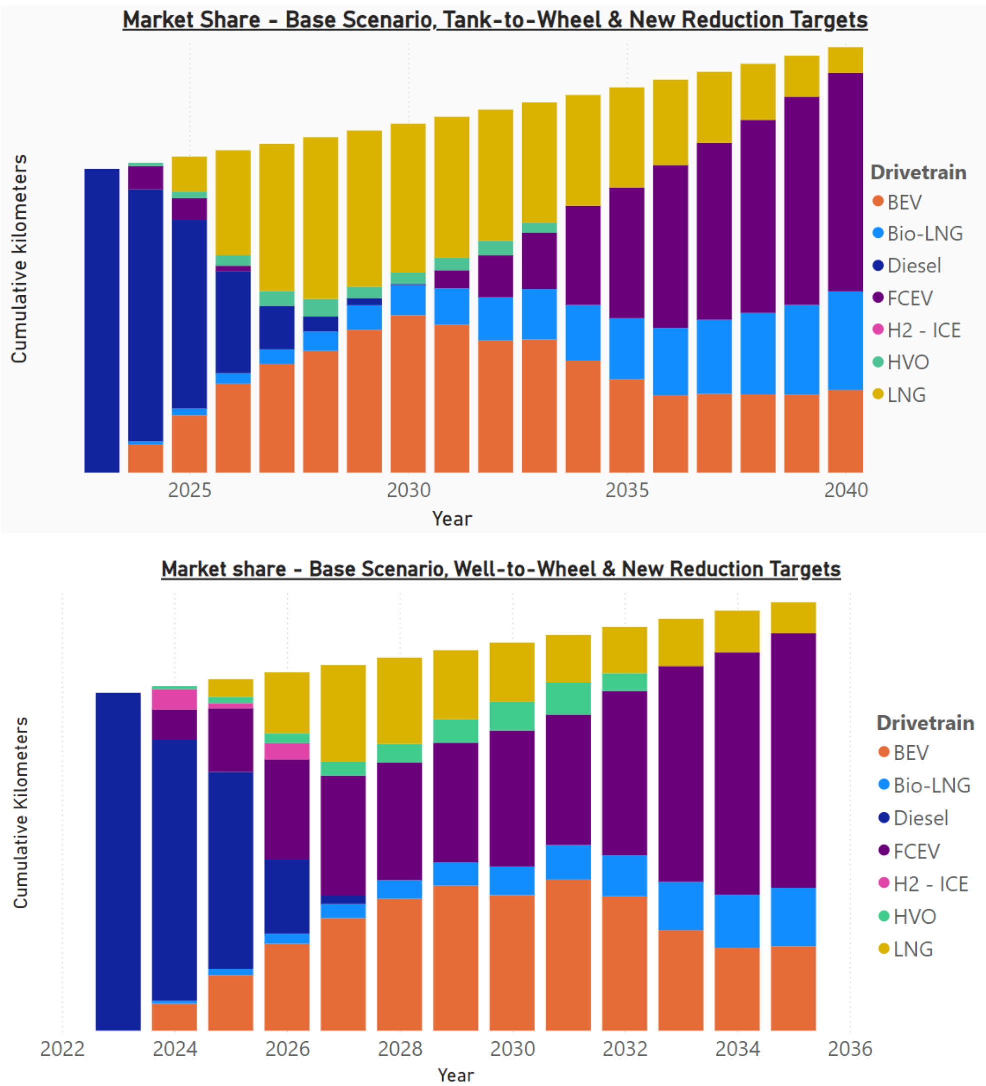


Figure 10 – Comparison of market share for Tank-to-Wheel and Well-to-Wheel emission quantification scenarios.

The impact of the new regulation is clearly visible in the much faster decline of diesel vehicles, as well as in the limited uptake of LNG vehicles, which results in the need to replace these drivetrains at an accelerated pace. There is a familiar mix of BEVs, FCEVs and Bio-LNG for all scenarios, with HVO having a more prominent role for a High cost of hydrogen. An important difference is that the WtW result cover only until 2035, as the optimization did not find a feasible solution for the remainder of the years. This will be discussed in a later section. Overall, the general trends presented in the previous sections remain consistent, albeit with a considerably smaller share of fossil-based technologies.

Hydrogen-Electricity Price Analysis

The general trend is for FCEVs and BEVs to be the dominant technologies in a decarbonized heavy-duty transport market. To further analyze the influence of the price of fuel, a sensitivity analysis was performed to compare the rate of uptake for FCEVs.

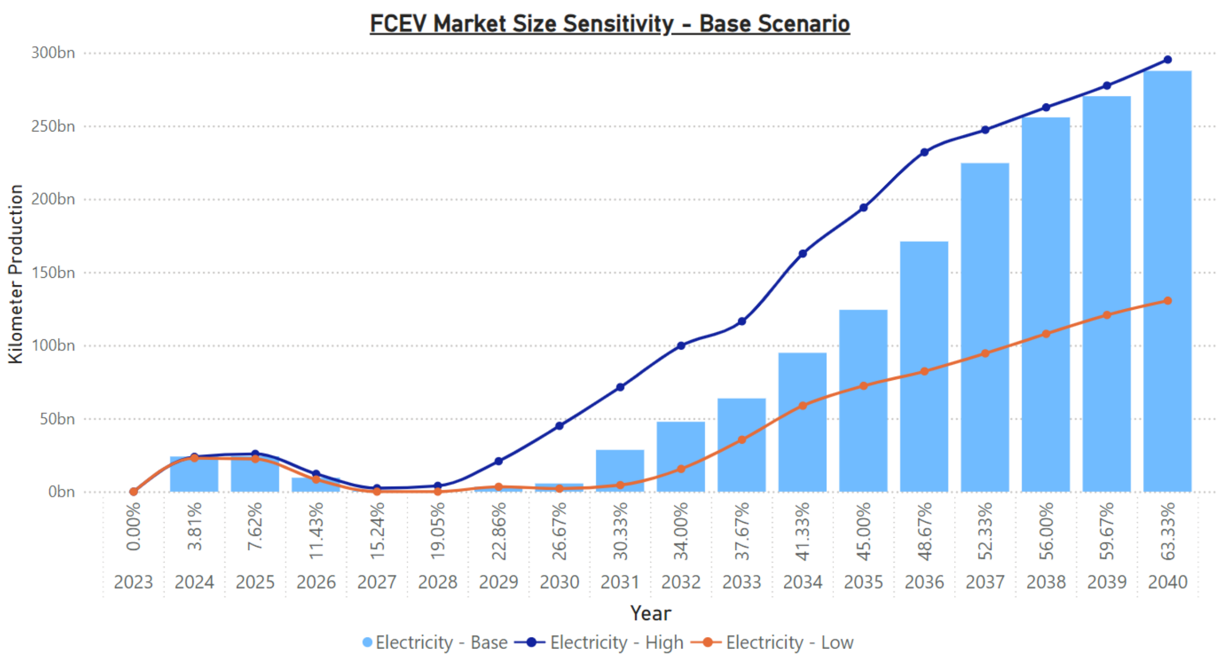
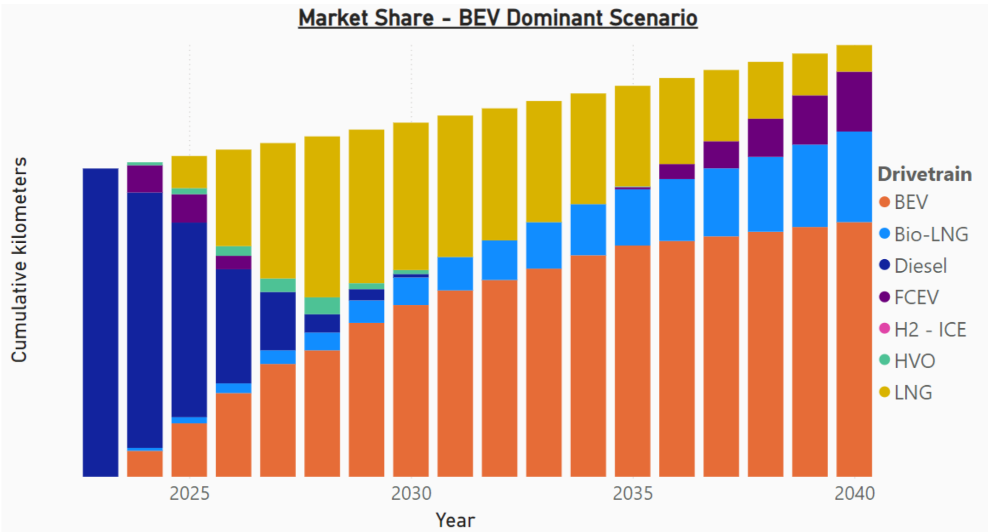


Figure 11 - Market size evolution of FCEVs per year and percentage drop in hydrogen price.

Figure 11Figure 11 shows the evolution in time of the FCEV market size for a base scenario, including the percentage decrease of the cost of hydrogen with respect to the year 2023. The bars show the yearly kilometers produced by FCEVs considering a Base electricity price, and lines show the variation in kilometers under High (blue line) and Low (orange) electricity prices.

FCEVs first appear to cover a portion of the market in 2024, although this is only short-lived and will not be considered for practical reasons. A High price of electricity would result in a faster and continuous uptake of FCEVs starting in 2029, and would require a 22.86% reduction in the cost of hydrogen. A Base price of electricity would require a 30% reduction in the price of hydrogen for a similar and continuous uptake of FCEVs in 2031. For both a High and Base electricity price we see that the total FCEV market growth reaches similar endpoints (close to 300 billion kilometers), suggesting that, in the long-term, the price of electricity will not have an impact on the market share for FCEVs. On the other hand, a Low price of electricity results in a much slower increase in FCEV market size, and even a 63% decrease in the cost of hydrogen would still result in a major loss of market size for these vehicles, in favor of BEVs. This is evident from the orange line in 2040 failing to reach 150 billion kilometers in 2040, as opposed to the almost 300 billion seen for a High and Base electricity price scenarios.

Evidently, the size of each segment is very sensitive to both the hydrogen and electricity prices. Figure 12 Figure 12 further illustrates this by presenting the two extremes in favor of BEVs or FCEVs.



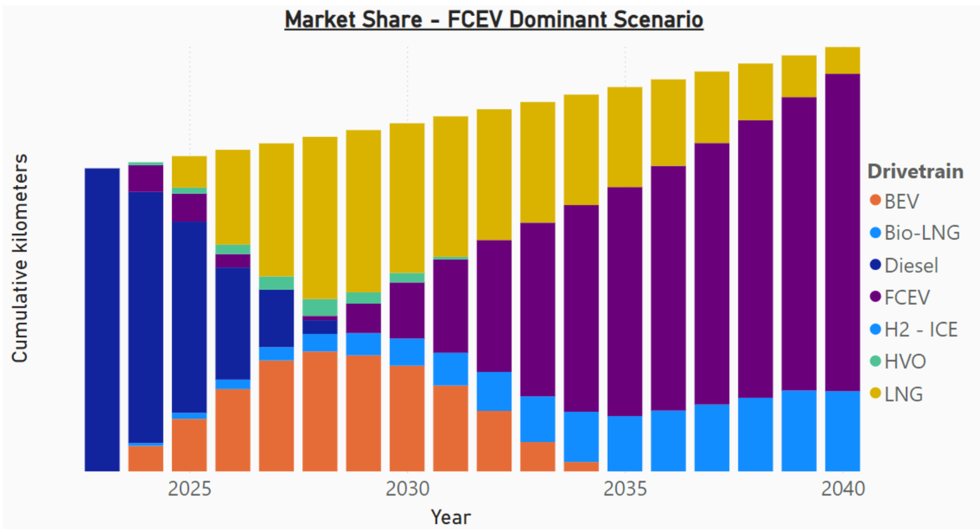


Figure 12 – Comparison of most extreme market share difference between BEVs and FCEVs.

The difference is quite straightforward, in a best case scenario for FCEVs they are the only zero-emission technology by 2040 and cover ~75% of all the market. In a best case scenario for BEVs, these cover ~60% of all the market in 2040, and have a much larger share than FCEVs.

An observable difference between both extremes is the presence of a small market share of FCEVs at the end of the BEV Dominant Scenario, whereas there are no BEVs left after 2034 in the contrary case. This is a consequence of BEV technology not being suitable to cover market segments that require very long ranges, resulting in the presence of other alternatives such as HVO and LNG, and ultimately FCEVs.

Weight and Range Segmentation

The results provide further insight into the drivetrain distribution for of each range and weight segments. Figure 13-Figure 15 show the evolution for the total amount of kilometers produced for BEV, FCEV, LNG, Bio-LNG and HVO drivetrains, per distance bucket (horizontal axis) and weight class (vertical axis), considering a hydrogen and electricity Base scenario.

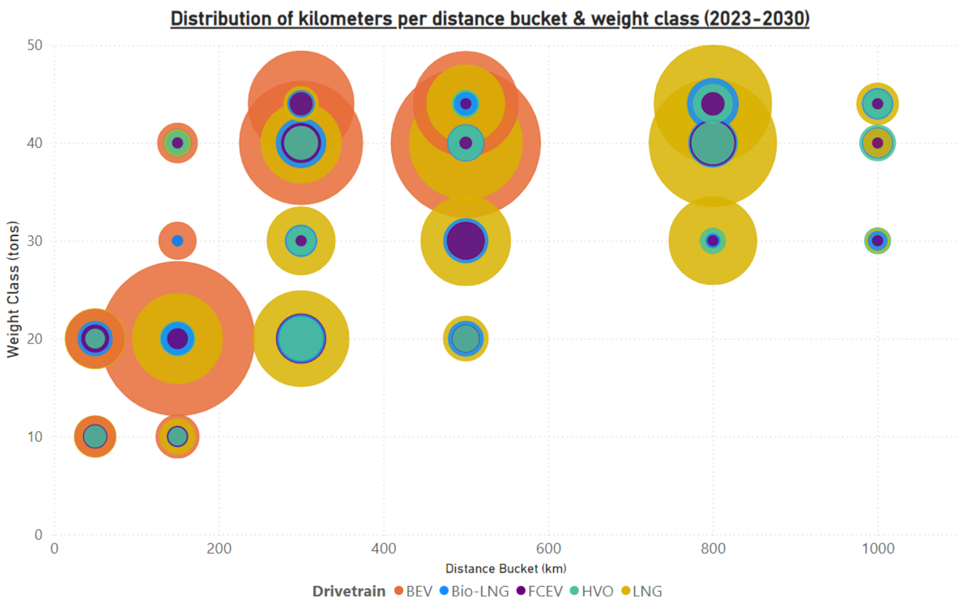


Figure 13 - Distribution of market share per distance bucket and weight class, 2023-2030.

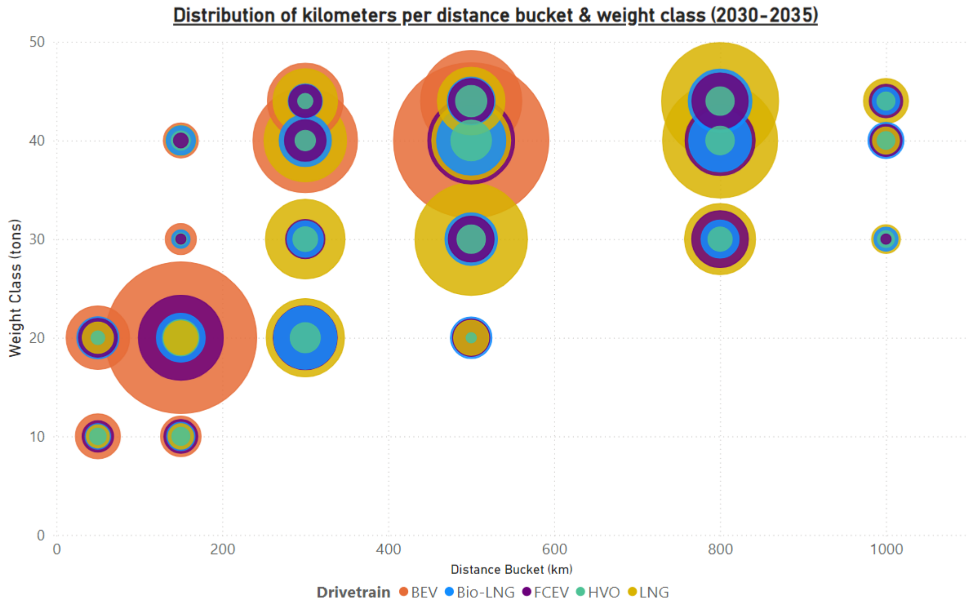


Figure 14 - Distribution of market share per distance bucket and weight class, 2030-2035.

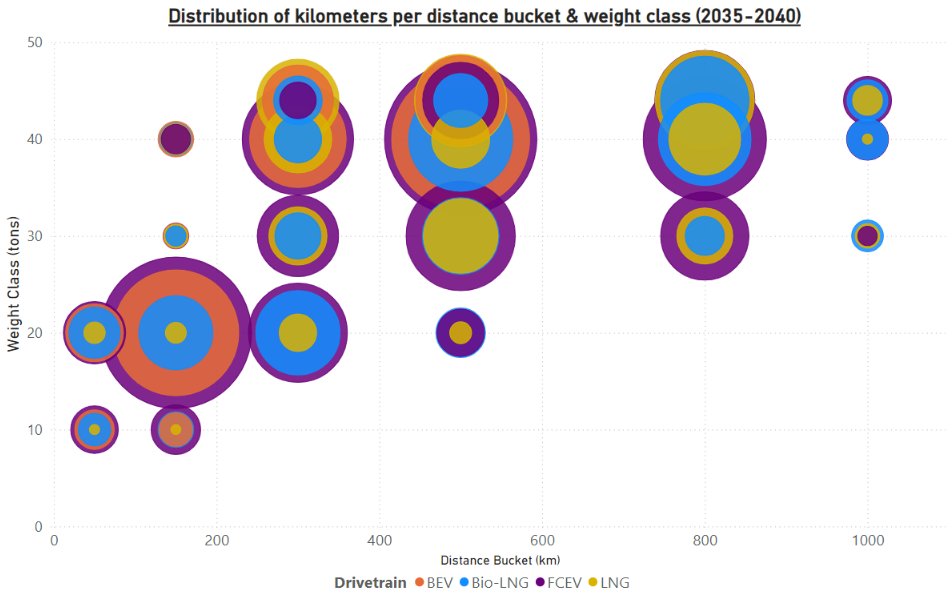


Figure 15 - Distribution of market share per distance bucket and weight class, 2035-2040.

As expected, LNG, HVO & Bio-LNG drivetrains have a presence across almost every weight and range combination, which can be attributed to their ability to cover all ranges while maintaining a low TCO. FCEVs are also relatively well distributed, and although they have a later uptake than other drivetrains, they are able to cover short, medium and longer ranges for all weight buckets, which can also be attributed to the technology not being constrained by a limited range. On the other hand, BEVs are absent in the longer range segments, with the bulk of their respective market share falling in the short distances for all weights, and medium distances for only the heavier trucks. This may also imply that short-to-medium range segments are the first candidates for decarbonization, such as last-mile and intercity deliveries, as it is already cost effective to operate ZEVs within these ranges, and fossil-based vehicles should remain for the longer ranges until FCEV technology is able to improve from an economic standpoint.

5. Discussion

The results of the present work show that there is great diversification with respect to the technology that will be deployed to cover the heavy-duty transport demand, in particular, in the short and medium term. In other words, there will be market segmentation, both in total share and in individual weight and distance buckets. There is no silver bullet technology or fuel to decarbonize the heavy-duty road transport market; rather, periods of dominance of one drivetrain over another are expected, resulting from a combination of fuel prices and regulation. For the longer term, a mix of FCEVs and BEVs is expected as a result of carbon regulation, competitive technologies and fuel prices.

A Diversified Transport Sector

To fully understand this segmentation, and to what extent a drivetrain is present or not in the future heavy-duty market, it is important to recap what they each bring to the table and any important underlying factors. The diesel drivetrain is a well-established and price-effective technology that allows to cover great distances on a single full tank, but suffers from high carbon emissions and a rising cost of fuel. LNG boasts similar attributes to diesel in terms of vehicle performance and technology costs, with a modest edge as it may benefit from lower fuel costs and slightly less emissions from the combustion process. There are, however, additional non-tailpipe emissions resulting from venting evaporating methane into the atmosphere to alleviate tank pressure (Mottschall, Kasten, & Rodriguez, 2020); a kilogram of natural gas has a global warming potential (GWP) 28 times higher than a kilogram of CO_2 (EPA, 2024). Both diesel and LNG technologies are fossil-based, and for the sake of transport decarbonization, can only play transitory roles, with LNG facilitating short-to-medium term emission reduction at a lower cost.

In terms of non-fossil technologies, Bio-LNG and HVO would be the next in line as key contenders given their diesel drivetrain-like capabilities, with low emissions and fuel costs. The major drawback is the limited feedstock availability, cutting down a great portion of their potential market share, and even more so if there is high demand for biofuels in harder-to-abate sectors, such as aviation or maritime transport (Wojcieszyk, Kroyan, Kaario, & Larmi, 2023).

An alternative approach is to increase the share of bio-fossil blends (already a relevant market practice) to significantly cut on short-term carbon emissions, all while making use of existing infrastructure.

Such blends could be considered a clear candidate for use in remote areas or very long journeys, at least until the zero-emission drivetrains are able to cover these market segments. Although decarbonizing via biofuels may seem very attractive from a transport company's perspective due to the limited impact on their operations, maintenance costs, lower risk and more stringent carbon reduction targets will result in a higher demand and increase in price for biofuels, which can lead to the exploitation of regulatory loopholes (Transport & Environment, 2023). Furthermore, there is significant uncertainty in Europe on the future of internal combustion engines, with the EU banning the sale of new passenger and light-duty vehicles with these characteristics after 2035 (European Parliament, Council of the European Union, 2023), raising questions for the future of heavy-duty regulation. Even though HVO and Bio-LNG drivetrains fall into the 'low-emission' heavy-duty vehicle category, they still have internal combustion engines and produce non-carbon related emissions, such as nitrogen oxides (NO_x), particulate matter (PM) and noise pollution. Were the EU to push for more regulation in these categories, the future of these low-emission ICE vehicles would be in jeopardy; one would expect that by this time zero-emission technologies will be developed enough to fully penetrate all market segments.

Although H_2 ICE drivetrains do not play a major role in any of the scenarios described herein, there may be some benefits to their adoption. These vehicles combine a lower CAPEX, similar to diesel trucks, rapid decarbonization, no payload constraints (other than the need for a hydrogen storage tank) and no requirements for precious or rare earth metals. They would make use of the same refueling infrastructure as FCEVs, though typically with a lower fuel economy for most operating loads, meaning they could share the costs for developing a hydrogen supply chain. The drawback for early adoption remains the high cost of hydrogen, and by the time this decreases enough, the (higher efficiency) FCEV technology cost will have also decreased. H_2 ICEs may have a niche to cover in very high load applications, such as construction trucks, vehicles that require multiple auxiliary power outputs (ie. refrigerated trucks) or in areas that do not have access to high purity hydrogen (Sens, et al., 2021). Even so, the role of H_2 ICE drivetrains will probably remain limited in the overall road transport market, and could have even more barriers if the EU leans towards banning internal combustion engines.

This leaves the only two remaining technologies for long-term (and full) decarbonization: BEVs and FCEVs, both considered zero-emission vehicles in the EU. From a strict cost perspective, the price of fuel remains the ultimate deciding factor as to which technology has the greater market share, with very noticeable extremes as seen in Figure 12. It is reasonable to predict that transport companies will go with the option with the lowest TCO, assuming there is abundance of fuel, and they can meet their weight and range requirements. Technology may also prove critical in limiting operational capability, as is evident from the Low price of electricity scenario, where hydrogen still maintains a niche as the only zero-emission technology able to cover long-range segments. This factor may be even more relevant under cold weather conditions, where a BEV may experience up to a 42% loss in range at near-freezing conditions (Zhao, et al., 2022); such low temperature conditions are common during the winter months in some areas of Western Europe.

Nonetheless, if a major breakthrough were to be achieved for battery technology in terms of energy density and charging capability, and combined with a low price of electricity, the entire market could shift in favor of BEVs. Until then, it will be difficult for transport companies to be comfortable operating a limited range vehicle that may be restricted to overnight-charging due to high daytime grid congestion and energy intermittency.

The split in market share between BEVs and FCEVs is very sensitive to price variations, where the difference between a Base and a Low cost of electricity can result in very significant reduction in market size for FCEVs, and vice versa. Although TCO optimization has been a well-established method in the literature for comparing two or more technologies, marginal price differences can cause one solution to be greatly favored over another. In practice, however, there is room for a scenario where both BEV and FCEV technologies have comparable TCO's, and marginal price differences will not be enough to determine the size of their respective market segments. Hence, transport companies will have to consider additional underlying factors when choosing with vehicles to operate in their fleets. The most notable underlying considerations for BEV and FCEV vehicles are further explored below, but the extent of their influence on the future heavy-duty market is yet unknown and is, thus, a topic for further research.

Implications of Stronger Regulation

Strong regulation, combined with a sound rollout and financing strategy, is key in promoting widespread adoption of low and zero-emission technologies. Without a stern and joint outlook, the future heavy-duty transport market will comprise a mix of diesel and LNG trucks due to their low cost, practicality and current market position.

The newly adopted EU emission reduction targets have a major impact on the rate at which fossil-based vehicles are replaced with low and zero-emission drivetrains, and will require major investments in both technology and supporting infrastructure. Although emissions are currently quantified on a Tank-to-Wheel basis, there appears to be a strong push to eventually make a shift to Well-to-Wheel, as per the latest proposal from the European Commission (2023) for heavy-duty vehicles. This would exert further pressure on all relevant stakeholders, requiring a significant push for renewable energy penetration, further grid expansion and supply-demand management, and a major rollout of zero-emission vehicles.

On top of that, if the scope of regulation were to shift into considering the entire life-cycle emissions of vehicles and their components, and not only limited to the production and use of fuel, entire supply chains would fall under intense scrutiny. This would have strong implications for the energy intensive and highly pollutant mining activities for critical raw materials found in BEVs and FCEVs. If such is the case, strict standards for material recycling are to be expected, particularly for battery technology, as its critical materials, such as lithium and cobalt, make up the bulk of the energy storing capacity, in addition to a short lifetime and a very high anticipated demand (Zachary, Bird, Yu, & Ma, 2022). Fuel cells are not immune to this issue, as the critical materials used, such as platinum and palladium, are scarcer, but are only present as catalysts and make up a much smaller portion of the overall device.

The introduction of a more comprehensive emission scope, including WtW and life-cycle emissions, would likely result in the need to partly review how achievable the new reduction targets are within the proposed timeline. Under the considered demand profile and the optimization setting of this work, a 90% sector-wide carbon reduction in 2040 (consistent with the EU's carbon reduction targets) proved to be infeasible for a WtW emission scenario, even when assuming that the entire market could be covered by zero-emission technologies with 90% renewable energy penetration. From the perspective of the optimization setting, aggressive carbon reduction targets require an equally adequate response from the technology and fuel supply side to yield a feasible solution.

This raises the question as to whether such targets are achievable, in terms of availability of truck and fuel supply, rate of adoption and the degree of accountability for the relevant parties. From a transport company's perspective, it adds significant uncertainty to investment plans and operations concerning zero-emission vehicles in the short-to-medium term. This is particularly true for BEVs, as their WtW emissions are tied to the emissions from the electric grid, which may vary per country and are presently higher than green hydrogen or HVO, on a per energy basis.

The Future Energy System & Fuel Prices

From a market perspective, investment in electrification could be considered a sound strategy for full decarbonization, given that this is required for both charging electric vehicles and increasing green hydrogen production for mobility. In this study, the decision to decouple these two sectors was taken to test the market response from the perspective of transport companies, and not to consider an entire energy system. In practice, however, the levelized cost of green hydrogen would be expected to evolve as a function of the levelized cost of electricity, where the latter is expected to decrease as more renewable sources penetrate the energy mix. Although this assumption is generally true from macro scale and in the long-term, the need for extremely big investments in grid electrification assets, intermittency and the possibility of importing and storing large amounts of hydrogen, may result in significant fuel price fluctuations and the local decoupling of prices.

One example of the EU's strategy targeting the electricity grid investments, the European Grid Expansion Action Plan (European Commission, Directorate-General for Energy, 2023), aims at developing a more decentralized, digitalized and flexible electricity system, able to accommodate the increasing share of renewable energy. The EU Action Plan estimates an approximate investment of €584 billion through 2030, but this does not come without the EU having raised concerns for permit wait times (up to 10 years for high voltage projects) and significant cost run-offs. Furthermore, a 2024 report by the European Round Table for Industry (ERT) and the Boston Consulting Group (BCG) estimates larger investments in upgrade, expansion and power storage for electricity grids of €700 billion and €2.3 trillion until 2030 and 2050, respectively. It is evident that the capital expenditure of increasing electrification will be very significant, and although most of the financing is planned to come from a combination of public funds and market instruments, it is unclear the effect this will have on electricity prices.

In the case of green hydrogen, significant investments are also foreseen, with a large amount tied to or included within the electricity grid upgrade and storage packages as a key strategy to balance the intermittent electricity loads. Ambitious projects, such as the European Hydrogen Backbone (EHB), propose the implementation of large hydrogen networks connecting several EU states as a cost-effective way of transporting hydrogen (European Hydrogen Backbone, 2023). Although the capital expenditures are valued at €25 billion by 2030, and €88 billion by 2050 (European Round Table for Industry, 2024), green hydrogen projects will benefit from a substantial scale-up to support network intermittency. As is the case today, it is likely that the majority of hydrogen will be used for industrial processes (IEA, 2019), but the transport sector may benefit from the infrastructure expansion for use in these other sectors, as well as from local renewable energy clusters in areas with limited access to the grid. Hydrogen imports, which are foreseen as part of the EHB project, may also play a key role in providing security of supply at a competitive price during periods of low renewable energy generation in Europe, further resulting in the local decoupling of hydrogen from electricity prices. Large volumes of hydrogen can also be imported via pipelines or ships, and make use of a large array of gas transport assets and infrastructure, allowing for a cost-effective alternative to domestic production (European Clean Hydrogen Alliance, 2023).

In a world where grid congestion and demand for electricity will be at the highest, hydrogen as a fuel for heavy-duty may prove to be a very viable alternative in terms of matching supply and demand, and insuring fuel security and diversification. The issue that plagues hydrogen nowadays are the high costs at the refuelling station, and although these will benefit from a high degree of renewable energy penetration and economies of scale, it may not be enough to make it attractive to transportation companies. Decarbonization in the sector has proved to be a costly endeavour, which calls for governments to bridge the gaps in price through subsidies if the sector is to fully meet the EU's carbon reduction targets.

6. Conclusions & Recommendations

The heavy-duty road transport sector has proven to be of critical importance to the European trade and economic development, moving millions of tons within and to neighboring countries, and all of this is made possible by operating a massive fleet of diesel trucks. The path to decarbonization will require efforts from multiple stakeholders and significant investments in technological development, infrastructure and fuel production. This study assesses the available drivetrains to meet the EU's carbon reduction targets, and provides insight into the future market segmentation from the perspective of the transport companies. It quantifies certain selection criteria to optimize the total cost of ownership of transport, while respecting the carbon reduction targets, and further discusses underlying factors that may play a significant role.

The results show that there will be significant segmentation and diversification in the short to medium term, as economics and carbon reduction targets play a major role in determining the future mix of trucks. Ultimately, fossil-based vehicles could be entirely phased out in favor of zero-emission trucks, where the market share is split between battery electric and fuel cell electric vehicles.

It can be concluded that three key factors will influence the future segmentation in a decarbonized heavy-duty sector. The first one is related to the economics of the vehicles, particularly, to the **price of fuel**. In a decarbonized sector, FCEVs could potentially cover up to 75% of the market by 2040 if the price of hydrogen drops by 60% or more, and the price of electricity remains relatively constant. In contrast, a high price of hydrogen would result in FCEVs being limited to heavier and long-haul routes, while BEVs would cover the bulk of short and medium-distance transport. Were battery technology to experience a breakthrough in terms of energy density, resulting in higher ranges for BEVs, the future of FCEVs would rely on competitive fuel pricing.

Furthermore, underlying implications may have important consequences, including the customer's perspective, renewable energy intermittency, security of supply, critical material supply chains, and the sheer magnitude of infrastructure upgrade costs that will partially affect the price of fuel. The degree to which these issues will affect the future transport market is unknown, but it shows that the total cost of ownership alone may not be enough to set a hardened market outlook.

Nonetheless, low transport costs appear to trigger a very rapid uptake of vehicles, which can be significant during the transition years in between, as it will catalyze further development in supporting infrastructure, create consumer loyalty and will more likely be perceived as a viable alternative. It may be the case that whichever drivetrain technology is the first to enjoy adoption at a larger scale will have an important edge.

The second influencing factor is the **availability of bio-based fuels**, which has important implications for the size of their respective market segment. HVO and, in particular, Bio-LNG drivetrains have produced very competitive results from cost and decarbonization perspectives, but are severely held back by the lack of feedstock availability, and thus not being able to cover more than 10-20% of the future sector demand.

The third factor relates to the critical **role of regulation**, which will be key to influence the degree of uptake necessary to meet carbon reduction targets. Most notably, it has significant influence on the future market share of fossil-based vehicles and in how quickly these disappear altogether. Some questions do arise regarding the need to review the effectiveness of the EU’s new reduction targets to achieve deep decarbonization, in particular the inclusion of a more stringent regulatory landscape to include Well-to-Wheel or life-cycle emissions. Adopting such a scope for emission quantification would, however, require a strong regulatory push to achieve such targets, including comprehensive monitoring throughout the entire energy value chain, and allocating appropriate efforts and funding for the rollout of zero-emission vehicles and development of relevant infrastructure.

In the context of decarbonization of the heavy-duty road transport sector, five key recommendations can be drawn for their respective stakeholders.

First, although the results show a wide diversification in technology until the medium-term, LNG drivetrains are prominent throughout all scenarios. This provides an opportunity for energy companies to make use of existing assets for fuel production, and for transport companies to acquire these vehicles as an immediate and cost-effective form of decarbonization. Given that regulation will eventually limit LNG-related carbon emissions, it would be most effective in exploiting such assets while there still exists the possibility and to provide an effective bridge to set up long-term decarbonization. This could also open the door for investments in developing a Bio-LNG supply chain, which can benefit from the existing LNG infrastructure while offering near-zero TtW emissions.

Second, transport companies should target last-mile and intercity segments as the first candidates for decarbonization. The high efficiency of BEVs, combined with modest payloads and ranges, and the proximity to several charging points makes this approach a viable first option. A successful rollout in these segments is more likely to have an impact on the customer's leniency to adopt new technologies for longer distance routes, such as FCEVs.

Third, energy companies, financial institutions and governments should consider investments in electrification as a suitable strategy, given that this can be used both directly in BEVs and for hydrogen production. Furthermore, hydrogen is expected to have a major role in a future renewable energy sector, which can be exploited from a transport perspective. By pursuing a similar roadmap, significant investment costs throughout the hydrogen supply chain (excluding those related to the refueling stations) can be shared amongst various sectors to minimize long-term risks.

Fourth, it is critical for all stakeholders to anticipate the change in the regulatory scope, especially with regards to more stringent life-cycle emissions for the various technological components. It is in the interest of OEMs and energy companies to establish key strategic partnerships and green practices throughout their respective value chains. An example is investing in and creating an environment for the recycling of critical materials, such as those found in batteries and fuel cells, as such components are likely to be affected by more comprehensive regulatory standards. Doing so from an early stage may also help from a public relations perspective, and in avoiding penalties and disruptions of future operations.

Five, energy providers should not, in colloquial terms, put 'all of their eggs in the same basket'. There is clear segmentation in the transport sector, and even so in the long-term. Each technology may be able to cover a specific niche at some point in time, and any new fuel-producing infrastructure will most likely be able to be adapted to cover a variety of sectors. The future energy mix will benefit from a variety of sources, and this will likely hold true for the transportation sector.

7. Bibliography

ACEA. (2024). *New commercial vehicle registrations: vans +12.6%, trucks -4%, buses +23.3% in Q1 2024*. Retrieved from ACEA: https://www.acea.auto/cv-registrations/new-commercial-vehicle-registrations-vans-12-6-trucks-4-buses-23-3-in-q1-2024/#:~:text=Diesel%20maintained%20its%20dominance%20in,up%20from%201.4%25%20last%20year.

Aguilar, P., & Groß, B. (2022). Battery electric vehicles and fuel cell electric vehicles, an analysis of alternative powertrains as a mean to decarbonise the transport sector. *Sustainable Energy Technologies and Assessments*.

Ahluwalia, R., Peng, J., Roh, H., Papadias, D., Wang, X., & Aceves, S. (2023). Liquid hydrogen storage system for heavy duty trucks: Capacity, dormancy, refueling, and discharge. *International Journal of Hydrogen Energy*.

Ajanovic, A., Sayer, M., & Haas, R. (2024). On the future relevance of green hydrogen in Europe. *Applied Energy*.

Apostolou, D., & Xydis, G. (2019). A literature review on hydrogen refuelling stations and infrastructure. Current status and future prospects. *Renewable and Sustainable Energy Reviews*.

Aryanpur, V., & Rogan, F. (2024). Decarbonising road freight transport: The role of zero-emission trucks and intangible costs. *Scientific Reports*.

Assefa Hagos, D., & Ahlgren, E. (2018). Well-to-wheel assessment of natural gas vehicles and their fuel supply infrastructures – Perspectives on gas in transport in Denmark. *Transportation Research Part D: Transport and Environment*, 14-35.

Balu, J., & Karunamurthy, K. (2022). Recent progress in hydrogen fuelled internal combustion engine (H2ICE) – A comprehensive outlook. *Materials Today: Proceedings*.

Banza, C., Casas, L., Haufroid, V., De Putter, T., Saenen, N., Kayembe-Kitenge, T., . . . Smolders, E. (2018). Sustainability of artisanal mining of cobalt in DR Congo. *Nature Sustainability*.

Basma, H., & Rodriguez, F. (2023). *A total cost of ownership comparison of truck decarbonizaton pathways in Europe.* Washington DC: Inernational Council on Clean Transportation.

Basma, H., & Rodriguez, F. (2023). *The European Heavy-Duty Market Until 2040: Analysis of Decarbonization Pathways.* The International Council on Clean Transportation.

Bonabeu, E. (2002). Agent-based modeling: Methods and techniques for simulating human systems. *PNAS*, 7280-7287.

Boschat, J., Boigontier, T., Catanzariti, M., Debarre, R., & de Temmerman, G. (2022). *Decarbonizing heavy-duty road transport in Europe.* Kearney.

Chen, A., & Kasikitwiwat, P. (2011). Modeling capacity flexibility of transportation networks. *Transportation Research Part A: Policy and Practice*, 105-117.

Chiandussi, G., Codegone, M., Ferrero, S., & Varesio, F. (2012). Comparison of multi-objective optimization methodologies for engineering applications. *Computers & Mathematics with Applications*, 912-942.

Cunanan, C., Tran, M.-K., Lee, Y., Kwok, S., Leung, V., & Fowler, M. (2021). A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles. *Clean Technologies*.

Delgado, O., Rodriguez, F., & Muncrief, R. (2017). *Fuel Efficiency Technology in European Heavy-Duty Vehicles: Baseline and Potential for the 2023-2030 Time Frame.* The International Council on Clean Transportation.

Department for Energy Security and Net Zero. (2023). *Greenhouse gas reporting: conversion factors 2023*. Retrieved from GOV.UK: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2023

Dinex. (2020). *Well-to-Wheel Insights*. Retrieved from Dinex: https://www.dinex.net/news-and-events/news/202006-well-to-wheel-insights

Durbin, D., & Malardier-Jugroot, C. (2013). Review of hydrogen storage techniques for on board vehicle applications. *International Journal of Hydrogen Energy*.

El Helou, R., Sivaranjani, S., Kalathil, D., Schaper, A., & Xie, L. (2022). The impact of heavy-duty vehicle electrification on large power grids: A synthetic Texas case study. *Advances in Applied Energy*.

EPA. (2024). *Understanding Global Warming Potentials*. Retrieved from Unithed States Environmental Protection Agency: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

EPA. (2024). *Understanding Global Warming Potentials*. Retrieved from United States Environmental Protection Agency: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials

European Automobile Manufacturers' Association. (2023, December). *ACEA*. Retrieved from ACEA Truck Fact Sheet: https://www.acea.auto/files/ACEA_truck_fact_sheet.pdf

European Clean Hydrogen Alliance. (2023). *Learnbook: Hydrogen Imports to the EU Market.*

European Comission. (2024). *European Commission*. Retrieved from Energy, Climate Change, Environment: https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/reducing-co2-emissions-heavy-duty-vehicles_en

European Commission, Directorate-General for Climate Action. (2023). *Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulation (EU) 2019/1242 as regards strengthening the CO_2 emission performance standards for new heavy-duty vehicles and integrating reporting obligations, and repealing Reg.* European Commission, Directorate-General for Climate Action.

European Commission, Directorate-General for Energy. (2023). *Grids, the missing link - An EU Action Plan for Grids.*

European Court of Auditors. (2023). *The EU's support for sustainable biofuels in transport.* European Commission.

European Court of Auditors. (2023). *The EU's support for sustainable biofuels in transport - An unclear route ahead.* European Court of Auditors.

European Hydrogen Backbone. (2023). *Implementation Roadmap - Cross Border Projects and Costs Update.* Retrieved from The European Hydrogen Backbone (EHB) initiative.

European Hydrogen Observatory. (2023). *Hydrogen Refuelling Stations*. Retrieved from European Hydrogen Observatory: https://observatory.clean-hydrogen.europa.eu/hydrogen-landscape/distribution-and-storage/hydrogen-refuelling-stations#:~:text=Since%202015%2C%20the%20total%20number,of%20cars%20at%20700%20bar.

European Parliament, Council of the European Union. (2023). *Regulation (EU) 2023/851 of the European Parliament and of the Council of 19 April 2023 amending Regulation (EU) 2019/631 as regards strengthening the CO2 emission performance standards for new passenger cars and new light commercial vehicles in line with.* European Parliament, Council of the European Union.

European Parliamentary Research Service. (2024). Revision of the Weights and Dimensions Directive.

European Round Table for Industry. (2024). *Strengthening Europe's Energy Infrastructure.*

European Union. (2024). *Eurostat*. Retrieved from Eurostat: https://ec.europa.eu/eurostat/en/

Fink, S., & Benz, F. (2019). Flexibility planning in global inbound logistics. *Procedia CIRP*, 415-420.

Fradj, N. B., Jayet, P. A., & Aghajanzadeh-Darzi, P. (2016). Competition between food, feed, and (bio)fuel: A supply-side model based assessment at the European scale. *Land Use Policy*.

Frieden, F., & Leker, J. (2024). Future costs of hydrogen: a quantitative review. *Royal Society of Chemistry*. doi:https://doi.org/10.1039/D4SE00137K

Garcia, R. (2005). Uses of Agent-Based Modeling in Innovation/New Product Development Research. *Journal of Product Innovation Management*, 380-398.

Genovese, M., & Fragiacomo, P. (2023). Hydrogen refueling station: Overview of the technological status and research enhancement. *Journal of Energy Storage*.

Genovese, M., Blekhman, D., & Fragiacomo, P. (2024). An Exploration of Safety Measures in Hydrogen Refueling Stations: Delving into Hydrogen Equipment and Technical Performance. *Hydrogen*.

Guandalini, G., & Campanari, S. (2018). Well-to-wheel driving cycle simulations for freight transportation: battery and hydrogen fuel cell electric vehicles. *2018 International Conference of Electrical and Electronic Technologies for Automotive*, 1-6.

Gustaffson, M., Svensson, N., Eklund, M., Oberg, J. D., & Vehabovic, A. (2021). Well-to-wheel greenhouse gas emissions of heavy-duty transports: Influence of electricity carbon intensity. *Transportation Research Part D: Transport and Environment*.

H2.LIVE. (2024, June 10). *H2.LIVE*. Retrieved from H2.LIVE: https://h2.live/en/

Heid, B., Martens, C., & Orthofer, A. (2021). *How hydrogen combustion engines can contribute to zero emissions.* McKinsey & Company.

Henry, W., Luz, A., & Kayode, S. O. (2024). Advancements in Battery Technology for Electric Vehicles: A Comprehensive Analysis of Recent Developments.

Hildermeier, J., & Jahn, A. (2024). *The power of moving loads: Cost analysis of megawatt charging in Europe.* Regulatory Assistance Project.

Holton, O. T., & Stevenson, J. W. (2013). The Role of Platinum in Proton Exchange Membrane Fuel Cells. *Platinum Metals Review*.

Hunter, C. A. (2018). *Market Segmentation Analysis of Medium and Heavy Duty Trucks with a Fuel Cell Emphasis.* National Renewable Energy Laboratory.

IEA. (2019). *The Future of Hydrogen.* IEA.

International Renewable Energy Agency (IRENA). (2021). *Hydrogen*. Retrieved from International Renewable Energy Agency: https://www.irena.org/Energy-Transition/Technology/Hydrogen

JEC. (2021). *JEC Well-to-Wheels study version 5: a look into the carbon intensity of different fuel/powertrain combinations in 2030.*

Joint Research Centre. (2022). *Advanced Biofuels in the European Union.* Clean Energy Tehcnology Observatory.

Keller, V., Lyseng, B., Wade, C., Scholtysik, S., Fowler, M., Donald, J., . . . Rowe, A. (2019). Electricity system and emission impact of direct and indirect electrification of heavy-duty transportation. *Energy*.

Ko, S., & Shin, J. (2023). Projection of fuel cell electric vehicle demand reflecting the feedback effects between market conditions and market share affected by spatial factors. *Energy Policy*.

Kulovic, M. (2004). Freight Transport Costs Model Based on Truck Fleet Operational Parameters. *Technology and Management of Traffic Review*, 321-325.

Laidoui, F., Bessedik, M., & Tayeb, F. B.-S. (2023). A game-theoretical constructive approach for the multi-objective frequency assignment problem. *Applied Soft Computing*.

Lakshmi, D. N., Kanwar, P., Sandhyaa, R., & Laksmhi Priiya, S. (2017). *Energy Efficient Electric Vehicle Using Regenerative Braking System.* International Journal of Advance Research, Ideas and Innovations in Technology.

Lokeshgupta, B., & Sivasubramani, S. (2018). Cooperative game theory approach for multi-objective home energy management with renewable energy integration. *IET Smart Grid*.

Macal, C. M., & North, M. J. (2010). Tutorial on agent-based modelling and simulation. *Journal of Simulation*, 151-162.

Miao, J. (2023). Review on Electrode Degradation at Fast Charging of Li-Ion and Li Metal Batteries from a Kinetic Perspective. *Electrochem*.

Monaharan, Y., Hosseini, S. E., Butler, B., Alzhahrani, H., Senior, B. T., Ashuri, T., & Krohn, J. (2019). Hydrogen Fuel Cell Vehicles; Current Status and Future Prospect. *Applied Sciences*.

Mordor Intelligence. (2023). *Europe Medium and Heavy-duty Commercial Vehicles Market SIZE & SHARE ANALYSIS - GROWTH TRENDS & FORECASTS UP TO 2030 Source:*

https://www.mordorintelligence.com/industry-reports/europe-medium-and-heavy-duty-commercial-vehicles-market. Mordor Intelligence.

Mottschall, M., Kasten, P., & Rodriguez, F. (2020). *Decarbonization of on-road freight transport and the role of LNG from a German perspective.* The Internatinal Council on Clean Transportation (ICCT).

Mulholland, E. (2024). *The revised CO2 standards for heavy-duty vehicles in the European Union.* The International Council on Clean Transportation.

Nikola Corporation. (2024). *Tre-FCEV*. Retrieved from Nikola Motor: https://www.nikolamotor.com/tre-fcev

North American Council for Freight Efficiency. (2019). *Guidance Report: Electric Trucks Where They Make Sense.* NACFE.

Pardhi, S., Chakraborty, S., Tran, D.-D., El Baghdadi, M., Wilkins, S., & Hegazy, O. (2022). A Review of Fuel Cell Powertrains for Long-Haul Heavy-Duty Vehicles: Technology, Hydrogen, Energy and Thermal Management Solutions. *Energies*.

Parviziomran, E., & Berggvist, R. (2023). A cost analysis of decarbonizing the heavy-duty road transport sector. *Transportation Research Part D: Transport and Environment*.

Pelkmans, L. (2017). *Drop-in biofuels for international marine and aviation markets.* IEA Bioenergy.

Pelletier, S., Laporte, G., & Laporte, G. (2014). Battery Electric Vehicles for Goods Distribution: A Survey of Vehicle Technology, Market Penetration, Incentives and Practices. *CIRRELT*.

Prussi, M., Laveneziana, L., Testa, L., & Chiaramonti, D. (2022). Comparing e-Fuels and Electrification for Decarbonization of Heavy-Duty Transports. *Energies*.

Prussi, M., Yugo, M., de Prada, L., Padella, M., Edwards, R., & Lonza, L. (2020). *JEC Well-to-Tank Report v5.* European Comission. Retrieved from https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/jec-well-tank-report-v5

Prussi, M., Yugo, M., De Prada, M., & Edwards, R. (2020). *JEC Well-To-Wheels report v5, EUR 30284 EN.* Luxembourg: Publications Office of the European Union. doi:doi:10.2760/100379

Ragon, P.-L., & Rodriguez, F. (2022). *Road freight decarbonization in Europe.* Washington DC: ICCT.

Ralls, A. M., Leong, K., Clayton, J., Fuelling, P., Mercer, C., Navarro, V., & Menezes, P. L. (2023). The Role of Lithium-Ion Batteries in the Growing Trend of Electric Vehicles. *Materials*.

Rangaiah, G. P., Feng, Z., & Hoadley, A. F. (2020). Multi-Objective Optimization Applications in Chemical Process Engineering: Tutorial and Review. *Processes*, -.

Reverdiau, G., Le Duigou, A., Alleau, T., Aribart, T., Dugast, C., & Priem, T. (2021). Will there be enough platinum for a large deployment of fuel cell electric vehicles? *International Journal of Hydrogen Energy*.

Rivard, E., Trudeau, M., & Zaghib, K. (2019). Hydrogen Storage for Mobility: A Review. *Materials*.

Rodriguez, F. (2020, May 12). *LNG Trucks: A Bridge to Nowhere*. Retrieved from The Internatioal Council on Clean Transportation: https://theicct.org/lng-trucks-a-bridge-to-nowhere/

Rout, C., Li, H., Dupont, V., & Wadud, Z. (2022). A comparative total cost of ownership analysis of heavy duty on-road and off-road vehicles powered by hydrogen, electricity and diesel. *Heliyon*, E12417.

Sandaka, B. P., & Kumar, J. (2023). Alternative vehicular fuels for environmental decarbonization: A critical review of challenges in using electricity, hydrogen, and biofuels as a sustainable vehicular fuel. *Chemical Engineering Journal Advances*.

Seemungal, L., Arrigoni, A., Davies, J., Weidner, E., & Hodson, P. (2021). *Decarbonisation of Heavy Duty Vehicle Transport: Zero emission heavy goods vehicles.* Luxembourg: European Comission.

Sens, M., Danzer, C., von Essen, C., Brauer, M., Wascheck, R., Seebode, J., & Kratzsch, M. (2021). *Hydrogen Powertrains in Competition to Fossil Fuel based Internal Combustion Engines and Battery Electric Powertrains.* IAV GmbH.

Sharpe, B., & Basma, H. (2022). *A meta-study of purchase costs for zero-emission trucks.* Washington DC: International Council on Clean Transportation.

Sharpe, B., & Basma, H. (2022). *A meta-study of purchase costs for zero-emission trucks.* International Council on Clean Transportation.

Shirizadeh, B., Ailleret, A., Cartry, C., Douguet, S., Gehring, T., Maden, S., . . . Truby, J. (2024). Climate neutrality in European heavy-duty road transport: How to decarbonise trucks and buses in less than 30 years? *Energy Conversion and Management*.

Slattery, M., Dunn, J., & Kendall, A. (2021). Transportation of electric vehicle lithium-ion batteries at end-of-life: A literature review. *Resources, Conservation and Recycling*.

Smajla, I., Sedlar, D. K., Drljaca, B., & Jukic, L. (2019). Fuel Switch to LNG in Heavy Truck Traffic. *Energies*.

Squadrito, G., Maggio, G., & Nicita, A. (2023). The green hydrogen revolution. *Renewable Energy*.

Statista. (2022). *Total oil demand in the European Union (EU-27) in 2012 and 2022, by product type*. Retrieved from Statista: https://www.statista.com/statistics/1327197/eu-oil-demand-by-product/

Tamba, M., Krause, J., Weitzel, M., Ioan, R., Duboz, L., Grosso, M., & Vandyck, T. (2022). Economy-wide impacts of road transport electrification in the EU. *Technol Forecast Soc Change*.

Tesla. (2024). *Semi*. Retrieved from Tesla: https://www.tesla.com/semi

The Oxford Institute for Energy Studies. (2024). *Green Hydrogen Imports into Europe: An Assessment of Potential Sources.* Oxford Institute for Energy Studies.

Transport & Environment. (2023). *Truck CO2: Europe's chance to lead.* Transport & Environment.

U.S. Department of Energy. (2023). *Hydrogen and Fuel Cell Technologies Office*. Retrieved from Energy Efficiency & Renewable Energy: https://www.energy.gov/sites/default/files/2023-03/h2iqhour-02222023.pdf

Vasiljevic, S., Aleksandrovic, B., Glisovic, J., & Maslac, M. (2022). Regenerative braking on electric vehicles: working principles and benefits of application. *IOP Conference Series: Materials Science and Engineering*.

Verger, T., Azimov, U., & Adeniyi, O. M. (2022). Biomass-based fuel blends as an alternative for the future heavy-duty transport: A review. *Renewable and Sustainable Energy Reviews*. doi:10.1016/j.rser.2022.112391

von Colbe, J. B., Ares, J.-R., Barale, J., Baricco, M., Buckley, C., Capurso, G., . . . Dornheim, M. (2019). Application of hydrides in hydrogen storage and compression: Achievements, outlook and perspectives. *International Journal of Hydrogen Energy*.

Vujanovic, D., Momcilovic, V., Bojovic, N., & Papic, V. (2012). Evaluation of vehicle fleet maintenance management indicators by application of DEMATEL and ANP. *Expert Systems with Applications*, 10552-10563.

Williams, M. C. (2011). Chapter 2 - Fuel Cells. *Fuel Cells: Technologies for Fuel Processing*.

Wojcieszyk, M., Kroyan, Y., Kaario, O., & Larmi, M. (2023). Prediction of heavy-duty engine performance for renewable fuels based on fuel property characteristics. *Energy*.

Xue, X., Li, J., Suh, X., Abdul-Manan, A. F., Du, S., Liu, H., . . . Zhao, M. (2022). Systematic assessment on the decarbonization pathway of China's .

Yu, K., Cadeaux, J., & Song, H. (2016). Flexibility and quality in logistics and relationships. *Industrial Marketing Management*, 211-225. doi:http://dx.doi.org/10.1016/j.indmarman.2016.09.004

Zachary, B., Bird, R., Yu, X., & Ma, J. (2022). Lithium-Ion Battery Recycling–Overview of Techniques and Trends. *ACS Energy Letters*.

Zhang, Q., Vonderembse, M. A., & Lim, J.-S. (2005). Logistics flexibility and its impact on customer satisfaction. *Emerald*, 71-95.

Zhao, C., Li, Y., Yang, Y., Wan, S., Yu, F., Yu, C., . . . Shen, X. (2022). Research on electric vehicle range under cold condition. *Sage Journals*.

Zhao, R., Neighbour, G., Han, J., Mcguire, M., & Deutz, P. (2012). Using game theory to describe strategy selection for environmental risk and carbon emissions reduction in the green supply chain. *Journal of Loss Prevention in the Process Industries*, 927–936.

Znidaric, A. (2015). *Heavy-Duty Vehicle Weight Restrictions in the EU.* European Automobile Manufacturers' Association.

8. Appendixes

Appendix 1

Optimization

Methods Reviewed

- Multi-Integer Linear Programming: all relationships are linear, and some decision variables can only take integer values.
- Goal programming: multi-criteria decision making by balancing trade-off in conflicting objectives. Each measure is given a goal (target value) such that deviations from this target are minimized.
- Multi-objective evolutionary algorithm: find a set of optimal solutions without resorting to a reduction of the objectives to a single objective, and then using the concept of *dominance* to distinguish between Pareto solutions. Key advantage is the generation of multiple trade-off solutions from conflicting objectives.

Advantages

- Simple to visualize constraints and there are many solvers and methods to approach these problems.
- Possible to adapt preferences during process.
- Very objective, as the only goal is to optimize the objective function(s).
- Pareto set of solutions allows to see the greater picture.

Disadvantages

- Not all solutions may be generated, and important solutions can be overlooked.
- Leads to having to choose one solution from a big set of solution, meaning it may be impractical.
- Some methods can be very biased as criterions are given different priorities

Game Theory (GT)

Types of Game

Cooperative: analyze when and how players can compete or cooperate as coalitions to create and capture value.

Non-cooperative: ‘every-man-to-himself’, where players try to maximize own benefit based on the moves of other agents and information available.

Biform games: combination of both, where 1st phase is non-cooperative (players independently determine coalition value) and 2nd phase is cooperative (coalitions create and capture value).

Advantages

- Provides a best path for a different combination of factors and scenarios.
- Oversees how and where players can cooperate and how they can capture value.
- Flexibility allows to test mixed strategies and incorporate a reward and punishment system.

Disadvantages

- Suffers from self-imposed constraints as to what players can do.
- Relies on the assumption that all players act rationally and are 100% self-interested and utility maximizing.
- Having more than 2 players adds a great deal of complexity, leading to having to sort all stakeholders into two major groups (or players) with similar objectives.

Agent Based Modelling (ABM)

Key elements include:

Agents

- Autonomous and self-directed, can function independently in its environment and in its interactions.
- Self-contained, clearly distinguishable party from other agents.
- Varying state and subset of attributes.
- Social, its dynamic interactions influence its behaviour.
- Adaptive, can modify behaviour over time.
- Goal-driven, must achieve its goals (not necessarily maximize objectives) and compares the outcome of his behaviours relative to its goals.

Interactions

- Important to specify who is connected to who, and how they interact.
- Only local information is available to an agent, as these are decentralized systems, and this information is obtainable by its closest *neighbouring* agents (variable).

Environment

- Used to provide information to the agent on his position relevant to other agents. May also include certain constraints, such as infrastructure capabilities, policies, etc.

Advantages

- Capture emergent phenomena.
- Agents exhibit memory, learning and adaptation.
- Simple changes at earlier stages can have a dramatic impact later, including network effects, which can lead to unanticipated behaviours and scenarios.
- Provides a natural description of a system.
- Good at modelling risk, including sources of randomness in certain places.
- Can consider both rational and irrational behaviour in agent decision-making.
- Useful when complex individual behaviour cannot be modelled with equations.

- Simulation adds the benefit that one can identify where the losses come from and test mitigation procedures for new scenarios and sensitivity.
- Flexible.
- Able to add more agents and vary their complexity (behaviour, rationality, learning and evolution, etc).

Disadvantages

- High degree of complexity.
- Model must be tailored for specific application and have a good level of description, adding complexity.
- Adds difficult to quantify factors (irrational behaviour, subjectivity, etc).
- Inputs have a drastic effect on the output, important to determine how results will be assessed.

Appendix 2

Visual Work-Flow Representation of Optimization Tool used for Segmentation Path

Step 1 – Excel Input

	A	B	C	D	E
1	DRIVETRAIN	VEHICLE_SIZES	FUEL	YEAR	DISTANCE_BUCKET
2	ICE Diesel	<10_ton	LNG	2023	50
3	BEV	10-20_ton	HVO	2024	150
4	FCEV	20-30_ton	H2 (FC)	2025	300
5	H2 ICE	30-40_ton	Electricity	2026	500
6	LNG	40+_ton	Diesel	2027	800
7	HVO		H2 (ICE)	2028	1000
8				2029	
9				2030	
10				2031	
11				2032	
12				2033	

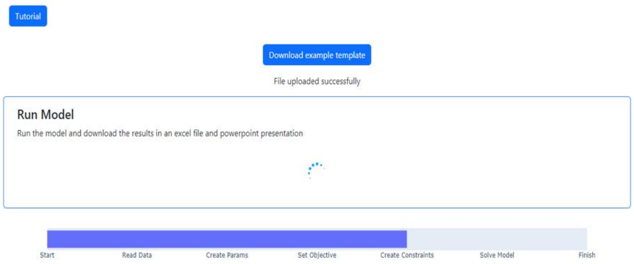
Figure 16 - Excel input parameters for Segmentation Path

The first step is to download an Excel and fill in the following categories:

- Years for which the optimization will run.
- Drivetrains and fuels to be included in the optimization.
- Vehicle sizes and distance buckets.
- Vehicle demand in kilometers per distance bucket and vehicle size.
- Planned Yearly Vehicle Investments.
- Carbon Budget per year.
- Fuel Cost & Emission data.
- Vehicle Cost and Consumption data.

Step 2 – Python Code & Server Upload

This step includes running the Python code to generate a link to a server where the Excel input file is uploaded.



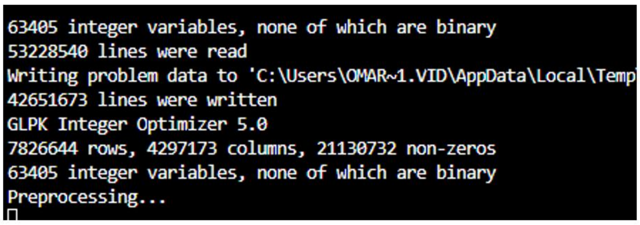


Figure 17 - interface of internal server & solver terminal.

Step 3 – Download Excel File with Results

After finding a solution, the server produces a downloadable Excel file with the following result categories:

- Active Vehicles.
- Bought Vehicles.
- Bought Fuels.
- Produced Kilometers.
- Retired Vehicles.

This study focuses on the Bought Fuels & Produced Kilometers sheets, as these are representative of the total market share.