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Decarbonising road freight transport

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Decarbonising road freight transport is essential for achieving the EU's climate targets, as the sector remains a major emitter of greenhouse gases. Despite ambitious policies like the European Green Deal and Fit-for-55, emission reductions in transport have lagged behind other sectors. Without decisive action, transport emissions are projected to continue increasing, making it one of the less efficient sectors. Road freight plays a particularly dominant role, due to its heavy reliance on diesel-powered trucks.

As the EU's largest economies, France and Germany have a special responsibility to lead the way in freight transport decarbonisation. Their strong economic ties create significant cross-border transport flows, leading to shared externalities and common policy challenges. Aligning their strategies would strengthen domestic policies, improve infrastructure interoperability, and accelerate EU-wide regulatory alignment.

Modal shift, demand reduction and efficiency improvements can contribute to reducing emissions, but structural and operational constraints make them insufficient to achieve large-scale decarbonisation in the short and medium term. The most effective and scalable approach is to focus on reducing emissions from road transport itself. Battery-electric trucks are emerging as the leading technology, with rapidly improving battery performance, falling costs, and expanding charging infrastructure.

However, challenges remain, including the need for widespread charging infrastructure, adjustments to logistics operations, and ensuring grid capacity to support high-power charging. Public funding should accelerate the roll-out of fast-charging networks along major corridors and in private depots. We recommend targeted support during the ramp-up phase to rapidly establish a dense, reliable and interoperable recharging network that gives fleet operators the confidence to invest. Reinforcing European R&D in battery performance, fast-charging technologies and substitution of critical raw materials will also be essential. At the same time, the European regulation (AFIR) should be regularly reassessed to ensure that infrastructure deployment is in line with technological developments and realistic market demand.

Rail freight can and must play a part in efforts to decarbonise the sector. Given the current fragmentation of European rail networks and logistical constraints, efforts must focus primarily on flows where rail is relevant, such as high-traffic corridors and cross-border flows. Investments in interoperability on a European scale is essential to improve the reliability and attractiveness of rail. For the transition to be successful, the EU must ensure that its carbon pricing mechanisms, such as the Emissions Trading System and carbon-based truck tolls, create sufficient economic incentives for operators to transition away from diesel. Current pricing structures do not fully reflect the environmental and societal costs of freight movements, contributing to high and inefficient transport volumes. Also there is a high degree of uncertainty about future prices of carbon emissions in the transport sector. The EU should therefore adopt a harmonised framework to internalise these external costs through clear carbon pricing in freight transport.

Introduction

Transportation: A sector falling behind

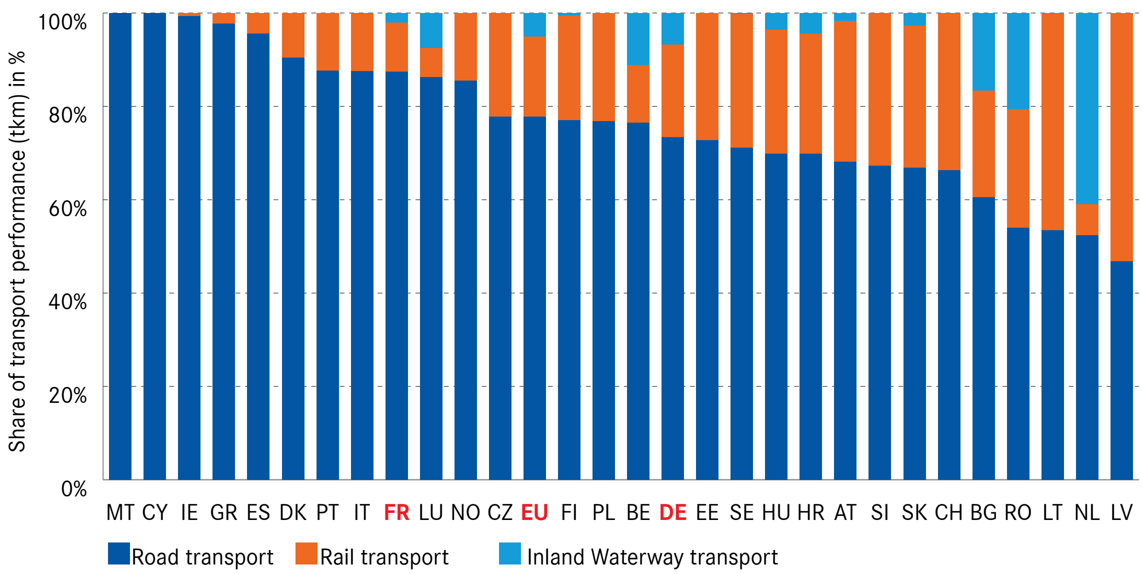
The EU and its member states, signatories of the Paris Agreement, have set the goal of limiting global temperature increases to 1.5°C above pre-industrial levels by the end of the century. The 2019 European Green Deal reiterates this objective, with the aim to achieve climate neutrality by 2050 (European Commission, 2023). The plan is intended to be comprehensive, covering a wide range of actions in all sectors of the economy. The Fit for 55 package sets an ambitious interim target: a reduction of greenhouse gas (GHG) emissions by at least 55% by 2030 compared to 1990 levels. Key measures include a strengthened Emissions Trading System (ETS), renewable energy targets, improved energy efficiency measures, and CO_2 emissions standards for vehicles. By 2023, emissions were 37% below 1990 levels, but progress remains insufficient. Current policies are projected to achieve only a 43% reduction by 2030, rising to 49% with additional measures-still short of the 55% goal.[1]

The transport sector remains a major challenge in emissions reduction, accounting for 29% of the EU's GHG emissions in 2022 (Transport & Environment, 2024a). Its emissions have declined at only one-third the rate of other industries, highlighting the sector's difficulty in making its transition. Freight transport plays a dominant role in this dynamic, accounting for over 30% of the sector's CO_2 emissions (European Commission, 2023). Without urgent policy intervention and accelerated technological change, transport emissions could rise to 44% of the EU's total by 2030 according to Transport & Environment. This trend is evident in France and Germany. In 1990, transportation accounted for 22.9% of France's total GHG emissions, increasing to 34% by 2023 and making it the largest emitting sector at 127 Mt CO_2 eq.[2] In Germany, transport's share of total emissions has risen from around 13% in 1990 to 21.6% in 2023 (155 Mt CO_2 eq).[3]

The high emissions from freight transport can largely be attributed to the dominance of road transport. According to Eurostat, in 2022, road freight accounted for 77.8% of total freight traffic in the EU (in tonne-kilometre, tkm), with higher shares in France (87.4%) than in Germany (73.4%) (Figure 1). Despite efforts to promote rail freight as a more sustainable alternative, its share remains comparatively low: 17.1% at the EU level, 19.8% in Germany, and only 10.6% in France (Eurostat, 2024).

Figure 1. Modal Split in domestic freight transport in Europe in 2022

Road freight transport dominates in almost all European countries



Notes: Delimitation according to the territorial principle. Includes total freight transport volume on the territory of the respective country by domestic and foreign nationals (incl. cross-border freight transport and transit traffic). MT-Malta, CY-Cyprus, IE-Ireland, GR-Greece, ES-Spain, DK-Denmark, PT-Portugal, IT-Italy, FR-France, LU-Luxembourg, NO-Norway, CZ-Czechia, EU-European Union (27), FI-Finland, PL-Poland, BE-Belgium, DE-Germany, EE-Estonia, SE-Sweden, HU-Hungary, HR-Croatia, AT-Austria, SI-Slovenia, SK-Slovakia, CH-Switzerland, BG-Bulgaria, RO-Romania, LT-Lithuania, NL-Netherlands, LV-Latvia. Estimated data for Belgium, Switzerland and the European Union.

Source: Eurostat.

[1] European Environment Agency (2024a) : *Trends and projections in Europe 2024*.

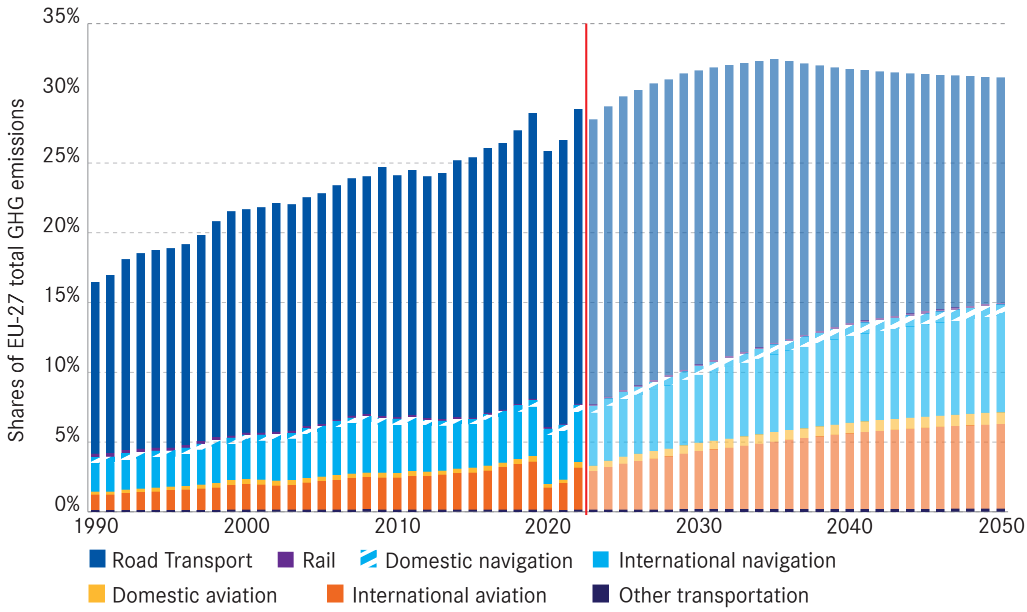
[2] Citepa (2024) : *Émissions de gaz à effet de serre et de polluants atmosphériques en France | 1990-2023*.

[3] UBA (2024a) : "Bausteine für einen klimagerechten Verkehr, Klimaschutzinstrumente im Verkehr, Kurzpapier", Federal Environment Agency and UBA (2024b) : "Treibhausgas-Emissionen in Deutschland".

The dominance of road freight transport comes with a significant environmental cost. Road freight, particularly heavy-duty vehicles (HDVs), is a major contributor to transport emissions due to its reliance on fossil fuels. In France, road total transport (freight and passengers) alone is responsible for 94% of the sector's GHG.[4] HDVs, despite making up less than 2% of the total vehicle fleet (Statistical Data and Studies Department, 2023), contribute disproportionately to emissions, accounting for 23% of road transport's total CO_2 output. In Germany, road freight transport is responsible for around 98% of the GHG emissions emitted by domestic freight transport (DLR, 2022). This pattern holds at the European level: in 2022, road transport was responsible for 95% of the EU's domestic transport GHG emissions, with HDVs representing 26% of that total[5] (Figure 2).

Figure 2. Transport's share of emissions by mode of transport in EU-27

Road transport offers greatest leverage for decarbonising transport



Note: Projections from 2023 rely on two scenarios: the Fit for 55 MIX scenario and the With Additional Measures (WAM) scenario, both incorporating the latest EU and national policies approved or announced. The Fit for 55 MIX scenario is aligned with reducing GHG emissions by at least 55% by 2030 compared to 1990 levels. The WAM scenario compiles 27 national projections reported by Member States including both implemented and planned measures to meet European Green Deal targets.

Source: European Environment Agency, 2024b.

Beyond carbon: The external costs of freight transport

The exchange of goods and services as well as the mobility of people is a basic prerequisite for the functioning of a market economy. At the same time, transport activities related to both domestic and international trade are often associated with considerable burdens and undesirable consequences for society and environment. Currently, many of these costs are only partially reflected in transport prices and thus represent external costs. As external costs are not internalised through an appropriate policy framework, neither transport companies nor their customers factor them into their decisions. Consequently, the volume of freight transport is inefficiently high. Moreover, if external costs and their internalisation vary across transport modes, the choice of the transport mode may be distorted.[6]

Quantifying the extent of external costs related to freight transport is complex. Besides several country specific studies (see e.g., Herry, 2016 for Austria; ARE, 2020 for Switzerland; Bieler and Sutter, 2019 for Germany), the European Commission[7] attempts to find adequate and comparable methodologies to evaluate the externalities and assess the costs related to transport activities at the European level. The main external cost categories examined by the European Commission's analysis, include

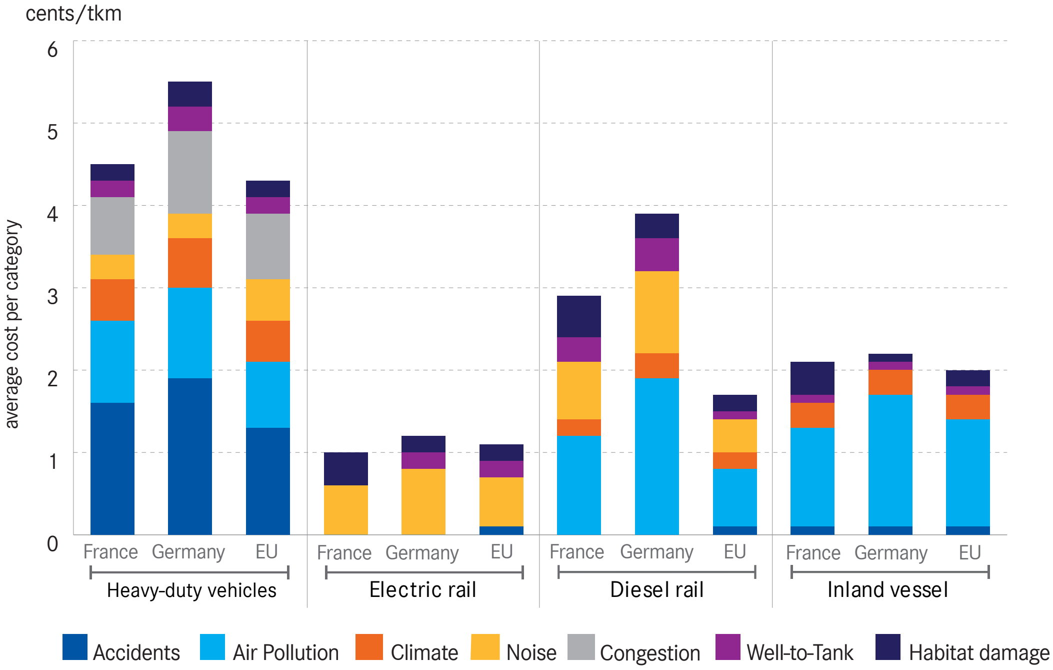
[4] Citepa (2024): *ibid*.

[5] European Environment Agency. (2024b): *Sustainability of Europe's mobility systems*.

[6] Leisinger C. and Runkel M. (2023): "Subventionen und staatlich induzierte Preisbestandteile im Güterverkehr auf Schiene und Straße", Forum Ökologisch-Soziale Marktwirtschaft.

[7] European Commission (2020): *Handbook on the external costs of transport, Directorate-General for Mobility and Transport.*

Figure 3. Transport externalities per category for France and Germany



Note: Average external costs in freight transport. Accidents: Personal injury, medical costs, administrative costs, consequential economic loss, property damage and other consequential accident costs. Air pollution: Damage to health, crop failures, material and building damage and loss of biodiversity. Climate: Costs due to rising sea levels, loss of biodiversity, water management problems, extreme weather events and crop failures. A CO_2 price of 100 euros per tonne was used as a basis. Noise: Physical and psychological impact of noise. Noise costs can only be reliably estimated for road and rail freight transport. Congestion: Costs due to delays and congestion. Congestion costs can only be reliably estimated for road transport. Well-to-tank: Costs of generating, converting, transporting and transmitting the required energy. For energy generation in rail freight transport, the electricity mix specific to rail transport is assumed. Other life cycle costs such as production, maintenance or disposal of the means of transport are not taken into account.

Source: European Commission, 2020. Data basis from 2016.

costs related to accidents, air pollution, climate change, noise, up- and downstream processes, habitat damage and congestion. In terms of overall costs, the analysis at the European level reveals that more than 50% of the total external costs of freight transport in the EU-28 are due to road freight transport. Accidents, air pollution and climate pollution account for more than half of average costs of freight transport externalities in Germany and France (Figure 3).

Studies assessing the current state of internalisation for various freight transport modes in the EU, France and Germany conclude that the overall degree of cost internalisation is low.[8] Internalisation is achieved with various policy measures, including market-based instruments (e.g. charges, taxes and tradable permits) and regulatory instruments (e.g. vehicle emission and safety standards, traffic restrictions) that vary by mode of transport and administrative level (EU, national, regional and local area) and partly also benefit from national tax exemptions. This internalisation is often in the sole responsibility of individual member states. Hence, negative environmental impacts and overall external cost coverage vary significantly across member states and transport modes. This is evident for example with regard to the truck toll. The EU has decided that, in the future, the truck toll must be linked to the vehicle's carbon emissions (EU Directive 2022/362). Germany was the first EU member state to introduce a carbon surcharge. CO_2 truck tolls are currently also in place in Austria and Hungary, for example, but not yet throughout the EU. In France, however, CO_2-based toll modulation on highways is not yet implemented andwill depend on future regulatory and contractual deve-lopments. The partial toll rate for carbon emissions alsodiffers considerably between countries that have alreadyimplemented it. The EU directive only defines a maximumamount.

The need for a coordinated Franco-German and European approach

France and Germany, the two largest economies in the European Union, share similar challenges in terms of freight transport decarbonisation. Their close economic ties and geographical proximity generate major cross-border flows, creating common externalities between the two countries. In this context, a coordinated Franco-German approach is particularly relevant: by aligning their

[8] European Commission (2019): "State of play of internalisation in the European transport sector", Directorate-General for Mobility and Transport; Direction Générale du Trésor (2021): Les usagers de la route paient-ils le juste prix de leurs circulations ?; GCEE, 2024.

strategies, the two countries can strengthen the impact of their respective policies. Franco-German cooperation can also provide momentum at the European level by encouraging a collective dynamic, facilitating the interoperability of infrastructures and the implementation of European initiatives to accelerate the decarbonisation of the sector.

Levers for decarbonisation: Assessing the options

While various options exist to decarbonise freight transport, their viability depends on two key criteria: their emission reduction potential and the feasibility of their rapid deployment. In other words, how much can each option contribute to reducing GHG? Can these options be implemented quickly enough to meet short- and medium-term climate targets?

Sobriety: Reducing the demand for transportation

Unlike strategies aimed at making vehicles cleaner, sobriety acts upstream, on the flow of goods, by limiting the distances travelled and optimising logistics circuits. Many projections of demand for freight transport indicate that it will continue to grow in the decades to come. According to the European Commission, international and domestic freight transport within the EU could grow by 25% by 2030 and by 50% by 2050, compared with 2015. The MIX-FF55 scenario, aligned with the objective of reducing emissions by 55% in 2030 compared with 1990, forecasts an increase in road freight transport of 19.4% in 2025 and 24.5% in 2030 compared with 2015.[9] More specifically, HDVs freight movements in Europe are expected to grow by 47% between 2015 and 2050 (Tölke & McKinnon, 2021).

Empirical evidence shows that demand for road transport is not very price-sensitive (de Jong et al., 2010; Musso et al., 2013; Wang and Zhang, 2017; Blechschmidt et al., 2022) and that there is a close correlation between freight transport performance and economic development, which is why large-scale avoidance is not to be expected. While a deep transformation of consumption patterns and supply chains remains difficult in the short term, sobriety needs to become a key policy priority in the long term. Reducing the most transport-intensive goods flows and relocating logistics circuits could limit the sector's carbon footprint. In France, for example, sobriety is already integrated into ecological planning trajectories, where relocation and logistics optimisation are presented as levers to counterbalance the growth in energy demand.

Efficiency improvements: Maximising current systems

Improving the efficiency of current systems represents an immediate lever for reducing GHG. Routes optimisation, using digital tools and advances in logistics to minimise unnecessary distances travelled, may lead to a reduction of fuel consumption and associated emissions. Similarly, consolidating shipments into fewer, larger units helps to limit the number of journeys, making transport more efficient. Technological advances are also improving the fuel efficiency of the vehicles themselves. Improved aerodynamics, reduced rolling resistance and lighter chassis are all innovations that can reduce fuel consumption and, consequently, CO_2 emissions (Basma & Rodriguez, 2023a). The maximum potential of CO_2 reduction per diesel-powered truck would be between 20% and 40% between 2016 and 2030, depending on the type of truck. The main advantage of these efficiency or sobriety measures lies in their immediate applicability to the existing fleet as a whole. They can thus provide short-term emission reductions. The gains associated are, however, not sufficient to achieve climate neutrality as freight transport would then still rely on fossil fuels. Moreover, the expected growth in freight demand, combined with potential rebound effects, should neutralise some of the gains in vehicle efficiency. Consequently, efficiency improvements can only serve as a complement, not as a substitute, to switching to low-emission drive technologies in road freight transport which offers a greater leverage for decarbonising freight transport.

Modal shift: Why rail can't be the only answer

In theory, shifting freight from road to rail is a relevant option, as rail freight produces fewer negative externalities than road transport,[10] particularly in terms of GHG emissions.[11] However, despite strong ambitions for modal shift at European and national levels, its implementation is coming up against major structural and economic obstacles, in France and in Germany. In both countries, growth targets for rail transport appear difficult to achieve. In Germany, the ambitious target set by the government of

[9] European Environment Agency. (2024b): *op.cit.*

[10] European Commission (2020): op.cit.

[11] See Empreinte database from Ademe and ITF (2022): "Mode Choice in Freight Transport", *ITF Research Reports*.

[12] SPD, Bündnis 90/Die Grünen and FDP (2021). Mehr Fortschritt wagen – Bündnis für Freiheit, Gerechtig- keit und Nachhaltigkeit, Koalitionsvertrag 2021-2025 zwischen der Sozialdemokratischen Partei Deutschlands (SPD), Bündnis 90/Die Grünen und den Freien Demokraten (FDP), Bundesregierung.

increasing the share of rail freight to 25% by 2030,[12] is unlikely to be achieved. In France, the target of doubling rail's modal share from 9% in 2019 to 18% in 2030 seems equally out of reach and echoes previous similar targets that have not been met in recent years.

The main obstacle to modal shift is the mismatch between rail services and freight transport needs. On the one hand, access to the rail network remains limited, due to chronic under-investment in infrastructure,[12] the lack of intermodal infrastructure (Nothegger, 2023), the saturation of existing tracks[13] and an often rigid organisation of rail transport that is poorly adapted to business needs (GCEE, 2024; Morvant, 2015). On the other hand, logistical constraints, such as tight delivery times and short distances, are better suited to road transport, while rail remains competitive mainly for heavy, homogeneous goods over long distances. Most freight in Europe is indeed transported over distances of less than 200 km and involves consignment weights of up to 30 tonnes (GCEE, 2024). In most such cases, transportation by rail instead of truck is not possible or not competitive.[14] Moreover, taking into account the goods currently transported in intermodal transport units over distances of more than 300 km, the modal shift potential from road to rail would be only 6% in Germany and less than 2% in France (GCEE, 2024). Consequently, shifting freight transport from road to rail in order to accelerate decarbonisation is only possible to a limited extent.

The revival of rail seems to be a European challenge, but some countries, including France, have seen an even greater fall in the modal share of rail transport since the second half of the 20th century. While the structure of rail freight transport differs between France and Germany, it does not entirely explain the gap observed between the two countries. Indeed, our analysis shows that, even after controlling for these factors, a significant gap remains, that may be explained by other factors such as the earlier opening up to competition in Germany, the lack of attractiveness of French ports or the quality of service of the railway infrastructure manager.

Rail freight transport also suffers from a lack of interoperability between European countries. Currently, the lack of harmonisation between national rail systems severely limits the efficiency of international transport corridors (Stoll et al., 2017, Autorité de Régulation des Transports, 2023, *op. cit.*). Differences between technical standards, safety rules, signalling systems and network management lead to breaks in logistics chains and increase transport costs and times. These incompatibilities are a particular brake on the competitiveness of rail compared with road, which benefits from much greater homogeneity within the European Union. European Rail Traffic Management System (ERTMS), a system designed to standardise signalling and train control systems across Europe, would reduce costs and improve the fluidity of cross-border operations. However, its implementation remains slow and incomplete. 8% of European lines were equipped with ERTMS in 2022,[15] and the investment needed to extend this system to all the corridors of the Trans-European Network (TEN-T) remains considerable.

Road freight decarbonisation as the greatest leverage

Although major challenges remain, under current conditions decarbonising road transport offers the greatest leverage for decarbonising freight transport. Despite initial decarbonisation initiatives (battery-electric and hydrogen-powered trucks, alternative fuels), 97% of heavy goods vehicles registered in the EU in 2023 were still diesel-powered, with France and Germany each accounting for 30% of sales (Musa et al., 2024). Several technological solutions are available for decarbonisation, each with varying levels of technological maturity, terms of payload, energy efficiency, range, acquisition cost, operating cost, refuelling times and charging times (GCEE, 2024). Electrification now appears to be the most effective solution for drastically reducing CO_2 emissions from road freight. Thanks to the rapid fall in battery costs and the gradual deployment of high-power recharging infrastructures, battery-electric trucks (BET) are becoming a credible and competitive alternative to diesel trucks.

Decarbonising road freight transport: Focusing on BET

Technologies to decarbonise road freight transport: Exploring the different options

Recent studies suggest that the potential of battery-electric drive systems in long-distance freight transport has been significantly underestimated in the past (Hoekstra, 2019; Liimatainen et al., 2019; McKinnon, 2021; Nykvist & Olsson, 2021; Bhardwaj & Mostofi, 2022). BET are powered by lithium-ion batteries. Rapid advancements in

[12] See Autorité de Régulation des Transports (2023): "Scénarios de long terme pour le réseau ferroviaire français (2022-2042)" ; Sénat (2022): "Rapport d'information fait au nom de la commission des finances sur la situation de la SNCF et ses perspectives" and GCEE (2024)

[13] Deutsche Bahn (2023) : *Infrastrukturzustands- und -entwicklungsbericht 2022*, Leistungs- und Finanzierungsvereinbarung.

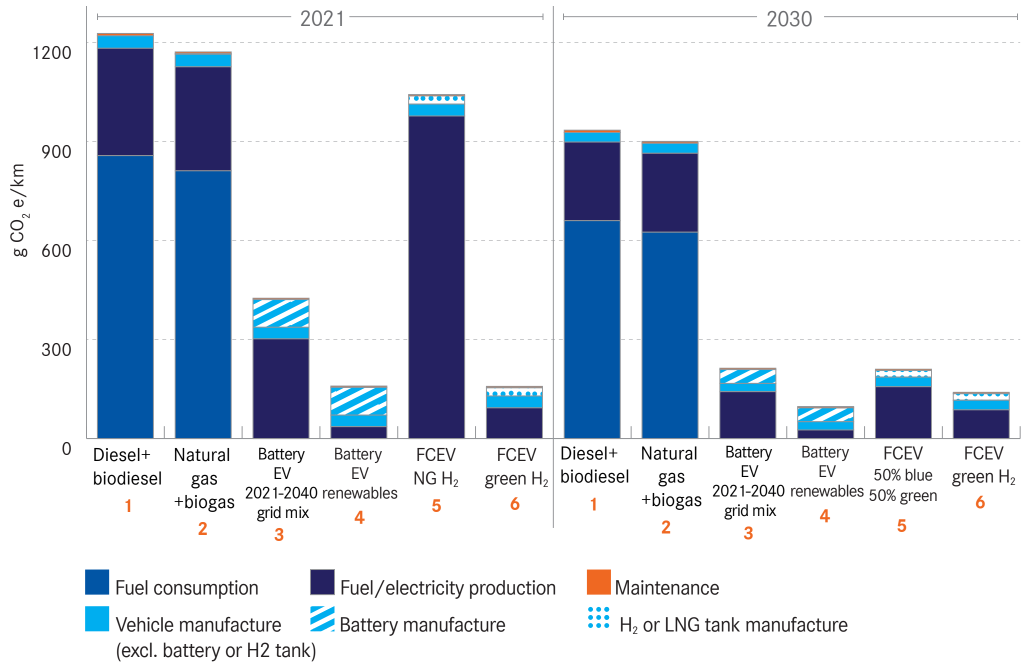
[14] See ITF (2022): op.cit., and UBA (2022): "Hebel zur Gestaltung eines treibhausgasneutralen und umweltschonenden Güterverkehrs, Klimaschutzinstrumente im Verkehr", *Kurzpapier*, Federal Environment Agency.

[15] IRG-Rail (2024): *12th Annual Market Monitoring Report.*

battery technology now enable heavy commercial vehicles to achieve ranges of around 500 kilometers without notable payload losses, with further breakthroughs expected in the near future. The cost of batteries have fallen by 85% in a decade and set to fall by a further 40% by 2030, which is also contributing to a steady decline in the cost of manufacturing such trucks (Orangi, et al., 2024; IEA, 2024; Link et al., 2024). This trend can be explained by lower raw material costs and increased battery production capacity, a direct consequence of massive investment in the electrification of transport. In terms of emissions, BET allow significant emission reduction over their entire life cycle: a battery electric 40-t truck produced in 2021 can reduce emissions by 65% compared with a similar diesel truck with an average electricity mix in Europe, and up to 87% if the electricity used comes from renewable sources (O'Connell et al., 2023) Figure 4. They are also benefiting from synergies with the electric passenger vehicle market, particularly in terms of recharging infrastructure and battery improvements. Scaling BET for long-distance operations will however require a robust public charging infrastructure along major freight corridors.

Figure 4. Lifecycle GHG emissions of 40-t tractor-trailer driven in the EU in 2030 to 2049

BET enable important reductions in GHG emissions



Notes: Life-cycle GHG emissions of heavy-duty vehicles (HDVs) produced in 2021 and 2030, covering vehicle production, maintenance, recycling, and fuel and electricity production and consumption (excluding infrastructure emissions). Best-in-class HDVs available in 2021 are considered and are compared with estimates of the equivalent HDVs expected to be available in the EU in 2030. Energy consumption reflects real-world driving conditions. 2030 vehicles are assumed to have 25% lower energy consumption than 2021 models, with an average lifetime of 20 years. 1 The diesel mix includes 7% biodiesel, and 2 natural gas contains 5% biomethane. Battery electric HDVs use either average 3 EU-grid electricity or 4 100% renewable electricity (67% wind, 33% solar, including emissions from equipment manufacturing). For hydrogen HDVs, the study compares 5 (2021) fossil hydrogen (SMR) 5 (2030) 50% blue hydrogen (SMR with CCS) and 50% green hydrogen, 6 green hydrogen (renewable electrolysis).

Source: O'Connell, Pavlenlo, Bieker, & Searle, 2023.

Fuel-cell electric trucks (FCET) are another option for electrifying road transport. Due to the higher energy density of compressed hydrogen, FCET potentially offer longer ranges and shorter refueling times compared to BET. Manufacturers are currently testing vehicles suitable for long-distance freight transport with ranges of up to 1,000 kilometers. However, this requires hydrogen tanks with greater storage capacity than in the past (Frieske et al., 2023; Zerhusen et al., 2023). This has implications for building a suitable refuelling infrastructure. So far, hydrogen refuelling stations have mainly been planned for passenger cars with a pressure level of 700 bar. For trucks however, a lower pressure of 350 bar is required, which only a part of the already existing refuelling stations can provide. It is also still unclear whether hydrogen in FCET will be used in gaseous or liquid form in future, which entails corresponding uncertainty for the construction of new refuelling stations. Moreover, their energy efficiency is much lower than that of BET. Today, an electric truck consumes 50% less energy than a hydrogen truck to cover the same distance, due to the energy losses involved in producing, transporting and converting hydrogen (Basma et al., 2022). In addition, green hydrogen, which could reduce emissions by 89%, is still in short supply and expensive to produce (O'Connell et al., 2023). With conventional hydrogen, the potential reduction in emissions compared with a diesel truck is only 15%. This technology could be suitable for certain niches, such as transporting goods over very long distances or for specialised uses, but its widespread deployment is compromised by the challenges associated with its cost, efficiency and infrastructure availability. Hydrogen is also in competition for use in industries and sectors such as aviation and maritime transport, where battery-electric solutions are not viable.[16]

Other alternatives are also based on the electrification of road transport. Battery-swapping stations (BSS) involve a robot replacing an empty battery with a full one. The whole process takes around ten minutes – the same time it takes to refuel a diesel truck. Some studies consider this technology to be a promising addition to the construction of a nationwide charging infrastructure, as lengthy charging breaks can be avoided and there is no need to build network capacity (Vallera et al., 2021; Zhu et al., 2023). However, such a system requires a significantly larger battery capacity, leading to additional costs and greater pressure on critical raw materials. Electrified road systems (ERS) would enable trucks to be recharged in real time using catenaries or induction systems, but their large-scale deployment could only be envisaged after 2030 due to their high cost and the lack of sufficient political support.

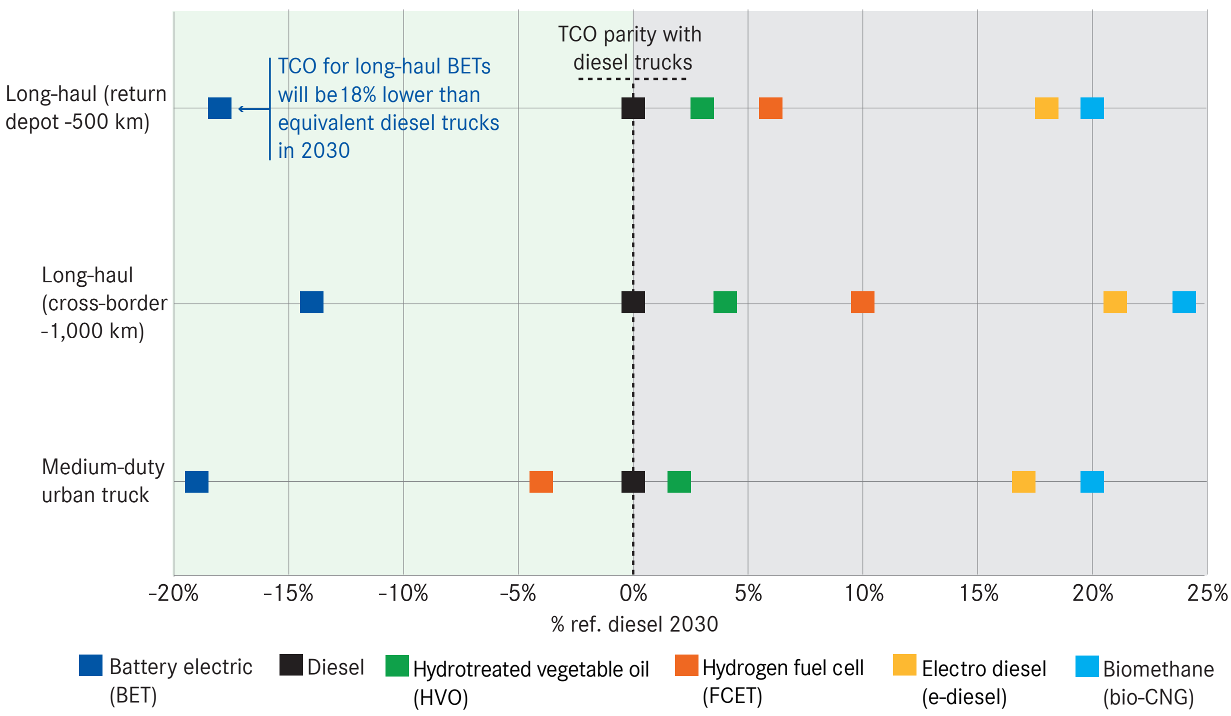
As an alternative to the electrification of drive systems there are discussions about the possibility of running trucks with internal combustion engines on fuels either made from biogenic residual and waste materials (e.g. biodiesel) or derived from electrical energy and carbon dioxyde (e-fuels). Their carbon footprint depends on a variety of influencing factors and can range from a large reduction in emissions to an increase in emissions compared with trucks using conventional fuels (Wietschel et al., 2019). However, given high production costs and limited quantity, it is unclear to what extent such fuels will be available for road freight transport in future (SGPE, 2024; European Court of Auditors, 2023; Ueckerdt et al., 2021). Their use will probably be reserved for sectors where direct electrification is more difficult, such as aviation and shipping (Figure 4).

Comparison of Total Cost of Ownership (TCO): BET's leading the race to TCO parity

A competitive total cost of ownership (TCO) is crucial to the market success of any drive technology. TCO takes into account not only the cost of purchasing a vehicle but also all aspects of its subsequent use over the vehicle's entire life cycle. The TCO in the truck industry is influenced by multiple factors. These include the type of truck —whether light, medium, or heavy-duty— and the operational profile,

Figure 5. TCO difference to diesel truck for alternative truck drives in 2030

BET achieve cost parity with diesel trucks faster than alternative technologies



Notes: The TCO is calculated by converting all fixed and operational expenses into discounted cash flows over a 5-year truck ownership period, using a 9.5% discount rate. Costs include retail price, residual value, financing, infrastructure, fuel/energy, maintenance, labor, insurance, and taxes. Location-specific costs reflect European averages. No fuel price subsidies are considered.

Source: Basma and Rodriguez (2023)

such as urban, regional, or long-haul usage. Additionally, traffic conditions and utilisation rates, energy prices (electricity, diesel, or hydrogen), as well as public incentives and subsidies, all play a significant role in determining TCO.

Various studies estimate and compare the TCO for different truck drive technologies (Mareev et al., 2018; NPM, 2020; Basma et al., 2021; Jöhrens et al., 2022; Meunier et al., 2022; Göckeler et al., 2023). Across studies, BET are consistently identified as achieving cost parity with diesel trucks faster than alternative technologies. For example, Basma and Rodriguez (2023b) analysed TCO by taking into account truck acquisition costs, European-average fuel prices, maintenance expenses, and European-average road tolls, taxes, and levies. Their study covered all truck types, from long-haul freight vehicles to urban delivery trucks. They project that BET will become the least costly decarbonisation pathway for most truck classes before 2030. This is due to their significantly lower operational expenses, which outweigh their higher initial purchase costs. The study further predicts that fuel-cell trucks powered by green hydrogen will achieve cost competitiveness with diesel trucks by 2035. On the other hand, trucks equipped with conventional combustion engines running on alternative low-greenhouse-gas fuels, such as hydrotreated vegetable oil (HVO), e-diesel, or bio-compressed natural gas (bio-CNG), are expected to face economic challenges, particularly due to high fuel costs and the lower energy efficiency of these vehicles. By 2030, the TCO for these vehicles is projected to be 15% to 45% higher than that of zero-emission alternatives like BET. Figure 5

At the country level, Basma et al. (2021) predict that BET can reach TCO parity with diesel tractor-trailers in Germany and France even earlier than on an average European level. The report analyses the impact of various policy measures to accelerate the adoption of BET, including purchase incentives, exemptions from road tolls, and the inclusion of the transport sector in the EU Emissions Trading System. The results show that BET can achieve TCO parity with diesel tractor-trailers during this decade for all the considered countries, even without policy support. By combining the policy measures examined in the study, TCO parity can be achieved immediately in Germany and France.

BET: Paving the way for suitable road freight

While numerous solutions for decarbonising road freight transport may become technically viable in the long run, not all are equally practical in the short to medium term. Considering different criteria assessing the likelihood of

Figure 6. Alternative truck drives and their contribution to decarbonised freight transport

<table>
<tr><th></th><th>Technology readiness[1]</th><th>Competitiveness[2]</th><th>Emission reduction potential</th><th>Fast deployment[3]</th></tr>
<tr><td>BET (short-distance)</td><td>TRL 9</td><td>Probable</td><td>Probable</td><td>Probable</td></tr>
<tr><td>BET (long-distance)</td><td>Vehicle: TRL 8/9</td><td rowspan="3">Probable</td><td rowspan="3">Probable</td><td rowspan="3">Probable</td></tr>
<tr><td></td><td>Charging with < 350 kW: TRL 8</td></tr>
<tr><td></td><td>Charging with > 1 MW: TRL 6/7</td></tr>
<tr><td>BET with battery swap</td><td>TRL 8/9</td><td>Uncertain</td><td>Probable</td><td>Uncertain</td></tr>
<tr><td>FCET</td><td>Vehicle: TRL 8/9</td><td rowspan="2">Challenging</td><td>Short-term challenging</td><td rowspan="2">Challenging</td></tr>
<tr><td></td><td>High-flow-rate refuelling: TRL 4</td><td>Long-term possible</td></tr>
<tr><td>Overhead line trucks</td><td>TRL 8</td><td>Possible</td><td>Probable</td><td>Challenging</td></tr>
<tr><td>Trucks with e-fuels</td><td>TRL 6</td><td>Improbable</td><td>Improbable</td><td>Improbable</td></tr>
</table>

Notes:

[1] The ETP Guide to Clean Energy Technologies is an interactive framework in which the International Energy Agency (IEA) provides information on over 550 individual technology concepts and components for the entire energy system that contribute to achieving the goal of climate neutrality. For each of these technologies, the guide contains information on the Technology Readiness Level (TRL). The TRL is a scale for assessing the development status of new technologies on the basis of a systematic analysis. The method was developed in 1988 by NASA for the assessment of space technol- ogies, and has since become established as an assessment standard in other areas of various technology sectors. The IEA uses a scale from 1 («initial idea») to 11 («proof of stability reached»).

[2] Competitive total cost of ownership.

[3] Rapid market ramp-up.

Source: ITF (2023), GCEE (2024).

[16] Rouault B. and Schuller A. (2022): "Hydrogène bas-carbone : quels usages pertinents à moyen terme dans un monde décarboné ?", *Carbon4*.

a technology effectively contributing to freight decarbonisation in the near future, BET currently have the highest chance of gaining a strong market presence (ITF, 2023; GCEE, 2024). Figure 6 BET have emerged as the most promising solution for rapid decarbonisation, particularly in short- and medium-distance freight transport, where they already offer cost advantages and operational readiness. The market is gaining significant momentum, with manufacturers and governments making substantial investments in BET production and infrastructure—manufacturer projections indicate that BET could account for 50% of truck sales by 2030.[17] Moreover, ongoing advancements in battery and charging technology are increasingly narrowing advantages in range and refuelling time, making the widespread adoption of alternative technologies in road freight transport also for long-distance transport less likely (Plötz et al., 2022; Albatayneh et al., 2023; Orangi et al., 2024). Given these factors, and ongoing challenges with alternative technologies, battery electric trucks currently represent the most mature and market-ready technology for road freight transport.

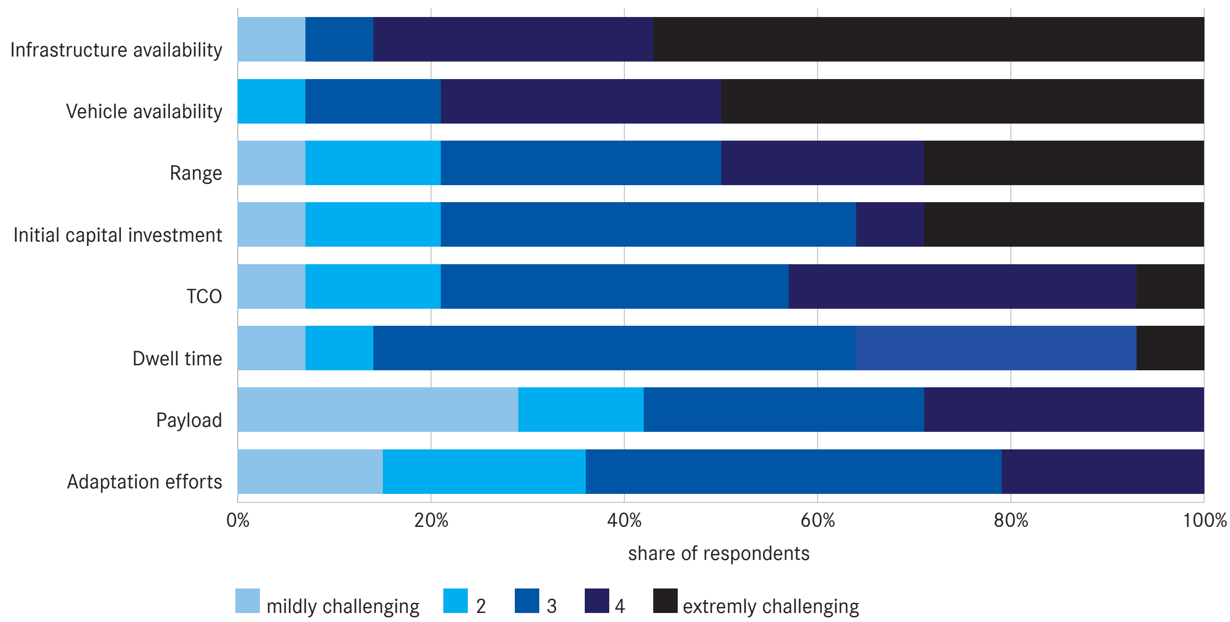
Challenges in establishing a BET-centric strategy

Although there is little doubt that BET in conjunction with stationary (fast) charging infrastructure will play a central role in decarbonising road transport, challenges remain (Heining et al., 2024). BET still have significantly higher vehicle costs compared to diesel trucks. Moreover, initial operational adjustments in transport processes are required, leading to lower user acceptance, particularly in long-haul applications. The demand for critical raw materials for large batteries remains moreover a concern.

BET rely heavily on a robust charging network for both short- and long-distance operations. Infrastructure availability is the first barrier to adoption perceived by fleets. Figure 7 When building the charging infrastructure for BET, it is essential to distinguish between different charging scenarios. Simulations indicate that depot charging alone will be sufficient to cover the majority of freight transport in Germany in the medium term (Speth and Plötz, 2024). However, for long-haul freight transport, the demand for public charging stations is significantly higher (Puls, 2022). Studies suggest that the initial demand for high-capacity public charging points will be relatively low, as vehicles with regional deployment profiles and shorter ranges are expected to be electrified first (Jöhrens et al., 2022; Speth and Plötz, 2024). Nevertheless, given the substantial challenges in establishing a public charging infrastructure for BET, no time must be lost in its implementation. While an existing international standard in the form of the Combined Charging System (CCS) can be used for slow charging for overnight depot use, which is especially suitable for urban and regional freight, a new standard is required for scenarios involving higher charging power. Such a standard in the form of the Megawatt Charging System (MCS), enabling recharging within the legally mandated 45-minute break required after four and a half hours of driving, is already in the process of being

Figure 7. Importance of key barriers to the transition to zero-emission freight vehicles

Lack of publicly accessible charging and refueling infrastructure dedicated to trucks viewed as a primary roadblock to a faster transition by fleets



Notes: As perceived by the fleets surveyed by Ragon & Rodriguez.
Source: Ragon & Rodriguez, 2022

standardised, with the planned rollout starting in 2025. The Alternative Fuel Infrastructure Regulation (AFIR), adopted by the European Parliament in 2023, establishes standardized requirements for the development of infrastructure supporting alternative fuels across Europe. Most recently, various private sector players have announced plans for the construction of specific truck charging points, some of which have already been implemented (European Commission, 2025).

Building a public charging infrastructure for BET depends on efficient grid integration, requiring significant infrastructure planning and investment. There are energy system challenges, particularly regarding grid stability and integration, although for Germany (GCEE, 2024) and France[18] studies suggest that freight electrification represents a manageable share of overall electricity consumption. In addition, the combined recharging needs of heavy-duty vehicles and light-electric vehicles are highly complementary. The more charging points are clustered locally and the faster charging takes place, the more electricity is required at a particular location at any one time. This often requires an expansion or conversion of the distribution grid. The conditions for grid connection are determined by the local distribution grid operators. While electrification of road freight is expected to account for a noticeable share of future electricity demand, intelligent charging strategies, such as time-of-use tariffs, can help manage peak loads and reduce grid expansion needs. Logistics centers also offer potential for self-sufficient energy generation through photovoltaic systems. However, large-scale charging hubs may require high-voltage grid connections, leading to long realization times and high investment costs.

As charging times for BET remain significantly longer than refueling times for diesel trucks, the transition to low-emission vehicles will require substantially more space for parked and charging vehicles. This is particularly challenging for high-capacity public chargers along highways, where parking shortages for trucks are already a well-documented issue.[19] Without sufficient infrastructure expansion, bottlenecks could disrupt logistics operations. To mitigate this, introducing european-wide reservation systems for public charging stations could help optimise truck routes and ensure reliable access to charging points. Addressing these spatial constraints early on is crucial to facilitating a smooth transition to sustainable freight transport.

[17] Avere (2024): "Camions électriques, démêlons le vrai du faux."

Policy recommendations: Prioritising BET for maximum impact and developing infrastructures

Reaffirm EU's determination to meet its climate commitments

At a time when the effects of climate change are being felt more and more, the Green Deal now faces mounting political and economic pressure. The global landscape has shifted, with international competition, energy price volatility, and political dynamics reshaping the EU's climate agenda. Some governments and industries are calling for regulatory rollbacks, arguing that stringent environmental policies undermine economic growth and competitiveness. The second Trump administration, coupled with the EU's economic slowdown, has intensified debates about deregulation. However, any dilution of the Green Deal policies would jeopardise the EU's ability to meet its climate commitments, delaying the transition to a carbon-neutral economy and increasing the long-term costs of inaction. Although it is difficult to put a figure on the cost of the consequences of global warming and on the cost of investment needed to mitigate it, many studies show that the cost of inaction is much greater than the cost of action (Stern, 2006; IPCC, 2023; Ademe, 2023; Kotz et al., 2024). In this context, a Franco-German approach can strengthen efforts to promote an ambitious European policy.

Addressing the challenge of growing freight demand

In order to ensure the long-term viability of decarbonising freight transport, it is essential to tackle the growing demand for freight transport in parallel with efforts to electrify the sector. While the electrification of road freight is a viable solution for significantly reducing emissions, it may not be sufficient on its own if demand continues to grow at the current rate, in addition to the fact that it does not address all the other transport externalities. It is essential to start thinking now about Europe-wide strategies to contain the growth in freight demand and to plan for a long-term decoupling of economic development and transport volumes. Addressing this issue early on will ensure that freight transport remains aligned with climate objectives while mitigating broader externalities and supporting sustainable economic growth. First and foremost, fully internalising the external effects of freight transport contributes to this goal. The CO_2 component of the truck toll as well as the second European emissions trading system (EU ETS II), which will include the transport sector, play a decisive role here. This requires the design of these instruments to provide a sufficient incentive to achieve carbon neutrality. However, there is a high degree of uncertainty about future prices of carbon emissions in the transport sector (GCEE, 2024).

Recommendation 1: Internalise the external effects of freight transport through a europe-wide standardised policy framework, as otherwise the volume of freight transport will remain inefficiently high. Secure planning certainty about the future price of carbon emissions in the transport sector.

Prioritising BET: Focusing on high impact solutions

In the debate on transitioning road freight transport to low-emission drive technologies, it is often argued that a broad technological portfolio is necessary to reduce GHG emissions quickly and effectively. However, current market developments, alongside systematic considerations regarding energy efficiency, energy system integration, and medium-term emission reduction potential, suggest that a clear focus on stationary charged BET is advantageous (GCEE, 2024; Heining, 2024). Firstly, this aligns with market reality and supports ongoing private-sector activities. Secondly, BET represent the most plausible pathway for effective climate protection in the short and medium term. Moreover, there are high technical and market uncertainties with regard to alternative low-emission drive technologies remaining that do not lead to one obvious substitute for BET. A strategic focus on BET for decarbonizing road freight transport can therefore be considered as a no-regret measure. Clear government communication on BET as a central technology could provide truck manufacturers and operators with the certainty needed for future investments. In contrast, political support for too many alternative technologies could create planning uncertainty for vehicle manufacturers, infrastructure providers, and logistics companies, ultimately delaying the transition to sustainable freight transport.

Recommendation 2: Prioritise battery-electric trucks (BET) as the central technology for decarbonising road freight transport in the short run.

Overcoming barriers to BET adoption

Market-based control instruments such as the future European emissions trading system EU-ETS II and the carbon-based truck toll in Germany aim to internalise the external effects of freight transport and provide technology-neutral incentives for its decarbonisation. This requires the design of these instruments to provide a sufficient incentive to achieve carbon neutrality. However, even if the price of carbon emissions corresponds to the external costs of GHG emissions, market imperfections such as network externalities, coordination problems and knowledge externalities can still slow down decarbonisation and provide a barrier for the switch from diesel trucks to BET.

Network effects make the market ramp-up of BET more challenging (Li et al., 2017; Springel, 2021; Rapson & Muehlegger, 2023). Companies will only transition to low-emission trucks if a reliable charging infrastructure is available. The ongoing private-sector efforts to expand charging infrastructure for BET should therefore continue to receive state support, as this helps mitigate network externalities. Public funding will be particularly necessary to accelerate the deployment of MCS-infrastructure along highways – crucial for long-distance heavy commercial vehicles – as well as for charging stations at private depots, which are essential for the electrification of local and distribution transport. However, such funding should be limited to the market ramp-up phase. France has schemes to support the funding of MCS that could be generalised elsewhere in Europe. The provision of necessary land and grid connections plays a decisive role in infrastructure expansion, with the AFIR providing an important regulatory framework. The EU has recently announced to allocate nearly €422 million to 39 projects that will deploy alternative fuels supply infrastructure along the trans-European transport network (European Commission, 2025). With this public funding, the support of approximately 2,500 electric recharging points for light-duty vehicles and 2,400 for heavy-duty vehicles along the European TEN-T road network will be financed, which will mostly be established by private companies or business combinations.

Recommendation 3: Provide public funding to accelerate the deployment of Megawatt Charging System (MCS) infrastructure along highways, and charging stations at private depots. Limit this funding to the market ramp-up phase.

[18] Enedis (2024): "Electrification of the long-distance heavy duty vehicle fleet".

[19] Enedis (2024): *ibid.* ; BaST (2019) : *Lkw-Parksituation im Umfeld der BAB 2018, Bundesweite Erhebung der Lkw-Parksituation an und auf BAB in Deutschland in den Nachtstunden*, Federal Highway Research Institute; BGL (2019).

Evaluations suggest that the AFIR targets may be overly ambitious in the short term and insufficient in the long term. Some analysis estimate that the required charging capacity may exceed demand by 25% in the near future but could fall short by 80% by 2030 (Ragon et al., 2022). In Germany, a charging network with 1.7 MW capacity every 60 km is deemed optimal for seamless freight transport, while strategic station placement could achieve significant coverage with fewer locations (Balke et al., 2024a, 2024b). For France, a study conducted by the grid operator and road freight operators (Enedis, 2024) suggest that AFIR requirements exceed estimated charging needs on 69% of the core TEN-T network and 34% of the comprehensive TEN-T network. This suggests that while AFIR provides a critical framework for infrastructure expansion, its minimum capacity requirements may not align with future demand.

BET currently have higher vehicle costs compared to diesel trucks. Purchase incentives could help accelerate market adoption. However, studies suggest that infrastructure funding is often a more effective intervention.

The European BET market, which is currently largely dominated by European manufacturers (Mulholland and Ragon, 2024), could be impacted by the growing arrival of Chinese manufacturers, as has happened in the electric passenger vehicle market (T&E, 2024b; ACEA, 2024; Ezell, 2024). Thanks to its complete control of the value chain, combining battery production, vehicle assembly, and cost optimisation through economies of scale, China has made its mark in the European market. For now, most of the electric trucks sold in Europe are still produced by European manufacturers, mainly because their range is better suited to the needs of the European market, but this situation could change (Dungs, 2024; Cimino, 2024). The improved performance of Chinese models and the establishment of assembly plants in Europe could accelerate their rise. This phenomenon could be amplified if the European manufacturers are unable to meet European demand, which is set to increase over the next few years. The potential evolution of the market calls for a broader reflection on truck industrial policy in Europe. While the goal of an industrial policy can be reasonably justified for geostrategic and technological reasons, it is also essential to consider environmental, economic, and social implications. Supporting European industries could for example help to reduce the carbon footprint associated with supply chains and create or maintain jobs within the EU.

Research and development activities typically generate knowledge spillovers, leading to inefficiently low private-sector R&D investments. Government intervention should therefore target these market imperfections through measures such as coordination efforts by public agencies or direct research funding. Public support for BET research can improve the technology, for example in addressing early-stage challenges associated with MCS during the initial market introduction. By 2030, further advancements in battery technology could moreover enable significant improvements in energy density, thereby increasing BET range (Thielmann et al., 2020). The development of sodium-ion batteries also holds promise for reducing dependency on critical raw materials while enhancing performance (IEA, 2024).

Recommendation 4: Take into account the environmental, economic, and social implications of truck industrial policy in Europe, with a view to support the vitality of the European BET manufacturing sector. Bring public support for BET research, for example in addressing early-stage challenges associated with MCS during the initial market introduction.

The role of complementary technologies and an adaptive policy approach

With major advances in battery and charging technology, BET should be able to meet nearly all road freight transport needs in the future, with only a few niche applications as possible exceptions. However, if critical challenges — such as building a nationwide charging and grid infrastructure—are not addressed quickly enough, other low-emission drive technologies such as FCET, battery swapping systems or overhead-line hybrid trucks could also contribute to freight decarbonisation, all of which have their individual advantages and disadvantages (Heining et al., 2024). While these technologies are technically viable, their widespread adoption is unlikely in the near future due to existing technological and market barriers. Instead, they are expected to complement rather than replace BET.

To maintain flexibility, policymakers should adopt an adaptive approach that continues to develop, test, and demonstrate alternative technologies alongside BET. This would ensure that complementary options remain available if needed. At the same time, it is important to avoid locking into specific complementary solutions too early. Significant uncertainties remain regarding the infrastructure needs, the availability of green hydrogen, and the overall role of FCET in freight transport. Still, the AFIR mandates the parallel development of charging and refueling infrastructure for both BET and FCET by 2030. Since the rollout of infrastructure for low-emission transport must be coordinated at the European level, it would be advisable to reassess the AFIR's infrastructure requirements for alternative fuels, and to allow flexibility if the relevance of the hydrogen solution is not demonstrated.

Recommendation 5: Reassess and allow flexibility on the requirements placed on the infrastructure for alternative fuels regulated by the AFIR.

Being pragmatic about the potential of rail while improving interoperability in Europe

While modal shift remains a relevant solution for certain types of flow, it cannot be a general solution for decarbonising freight transport given the structure of demand and current logistics strategies. In the past, rail transport took off when it proved naturally more competitive than road transport. However, once the electrification of road transport is complete, this relative competitiveness will be further strengthened in favour of road transport, which will combine both low emissions and logistical flexibility. Focusing rail investments on areas where it can provide real added value, such as high-volume corridors and cross-border flows, seems more appropriate than promoting a general modal shift. This is particularly true for long-distance transport, where rail remains relevant, as the electrification of road freight over these distances is likely to take longer. In this context, improving rail interoperability in Europe, particularly through the deployment of the ERTMS, could play a significant role in facilitating cross-border operations. The cost of deploying ERTMS along the entire TEN-T network is estimated at €29 billion, a substantial amount that has aroused reservations, particularly in France and Germany, two countries that are lagging far behind other European countries. In France, the equipment plans for 2044 will not even be enough to meet the European targets set for both 2030 and 2040. The 64-km Brenner Base Tunnel, which forms part of the Scandinavia-Mediterranean Corridor, could relieve much of the burden on transalpine freight traffic between Austria and Italy from 2032 onwards. However, the four-lane expansion of the rail link from the German side – the Brenner northern approach – is not expected for another 20 years (DB InfraGO and ÖBB Infra, 2024). The threat of a reduction, or even withdrawal, of European funding is adding further pressure, and could prompt some countries to reconsider their commitment without clear financial support. ERTMS remains essential for harmonising European standards. Italy is a good example of the benefits of a clear and ambitious timetable, with a plan to equip its entire network by 2036 (Autorité de Régulation des Transports, 2023). Moreover, delays in implementation increase costs in the long term,[20] which should motivate countries to speed up their efforts. Given that the effectiveness of ERTMS depends on its harmonised adoption by all countries, coordinated deployment at European level is essential. It is therefore crucial to ensure the continuity of European funding, starting with designated corridors, in order to fully take advantage of ERTMS while limiting the risk of sprinkling in fundings. Furthermore, the introduction of a common operating language would further strengthen interoperability.

Recommendation 6: A general modal shift towards rail freight is unrealistic in the near future. Focus rail investments on areas such as high-volume corridors and cross-border flows. Support the coordinated deployment of the European Rail Traffic Management System (ERTMS) on designated corridors and strengthen interoperability with a common operation language.

[20] SCI (2024) : ETCS - European Market Outlook 2024.

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