2035 Joint Impact Assessment of Greenhouse Gas Reducing Pathways for EU Road Transport

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Abstract

This study assesses the potential for decarbonizing EU road transport through several pathways, focusing on the feasibility of achieving impact by 2035. Through comprehensive literature review, we compare the distance-levelized cost, lifecycle GHG emissions, and scalability of combustion engine vehicles (three fuels), battery-electric vehicles (BEVs, three charging methods), and hydrogen fuel cell vehicles. We consider projected transport growth and the current age composition and use of vehicles in Europe, segmented into four regions.

Biofuels, hydrogen, and e-fuels are not found to have potential to significantly contribute to further GHG emissions before 2035 due to scalability and technological limitations. BEVs emerge as the only viable strategy for achieving zero tailpipe emissions at scale, with effective lifecycle GHG reductions constrained by the rate of decarbonization of steel production, battery production and EU electricity production. By 2035, embodied battery emissions are expected to be the dominant source of lifecycle emissions from electric vehicles.

The environmental benefits of a BEV transition are primarily limited by the rate at which the vehicle stock can be electrified, with new electric vehicle sales contributing primarily to decarbonization in Northern and Western Europe. Combining the expected buildout of static charging infrastructure with a proposed pan-European Electric Road System (ERS) network is found to greatly accelerate the transition to electrified road transport, including in otherwise late-to-decarbonize segments, by removing cost, weight, and supply barriers to retrofitting older combustion engine cars with new electric powertrains. Other effects of an ERS network are found to be substantially reduced embodied emissions from BEV production, resulting from reduced battery capacity per vehicle, and reduced levelized freight costs. However, possibly insurmountable political and bureaucratic barriers must be overcome ERS to play any meaningful part in decarbonization of road transport within the coming decade. If the barriers can be overcome, the economic and ecological rewards are substantial.

Despite identifying pathways for substantial emissions reductions, the study does not identify any technical pathway through which the EU road transport sector will not greatly exceed its fair share of global GHG emissions. In addition, our review of strategies to achieve modal shift and road transport demand reductions also fails to find indications that interventions in these areas will have GHG reduction effects of desired magnitude within the required timeframe, unless costs of vehicle ownership and use are raised substantially. Further policy research is urgently needed to find repeatable and socially just interventions through which total transport work, the size of the vehicle stock and embodied GHG emissions per vehicle can be reduced substantially across the entire EU before 2035.
1 Introduction

1.1 Motivation

Within the European Union (EU), road transport is lagging decades behind other sectors in terms of the observed rate of reduction in annual greenhouse gas (GHG) emissions. Regulators have defined gradually tightened caps on GHG emissions from new vehicles, but due to the long lifespan of vehicles, such measures take time before they impact total sectoral emissions. Ending the sales of combustion engine vehicles also requires very significant investments in new infrastructure to enable the operation of zero tailpipe emission vehicles, e.g., solar and wind farms, transformer stations, powerlines, charging infrastructure, hydrogen production plants, hydrogen transportation pipelines, hydrogen refueling stations, biogas refueling stations, etc. As investors in several of these technologies indicate that initial subsidies are required to reach economies of scale, and as the technologies can both compete and complement each other, unified data about different technologies are needed to enable direct comparison of the impact that different pathways may have on key performance indicators such as cost and sectoral GHG emissions.

In addition to adopting technologies that reduce the GHG intensity of transport, the EU expects further reductions from the rolling stock of vehicles through sustainable drop-in fuels, shifts to more sustainable modes of transport, and reduced total transport demand.

1.2 Contribution

This study is primarily a review of existing literature to compile information about the state of knowledge about the extent to which different proposed pathways can contribute to decarbonization of EU road transport by the year 2050. At the time of writing, national and EU targets for decarbonization of road transport indicate that any expectations of significant emissions reductions within the coming decade from this sector are unrealistic. Our assessment identifies both pathways that offer untapped potential for accelerated decarbonization, and pathways that may have shown early promise but that, based on up-to-date studies, do not appear to meet minimum criteria in terms of cost, scalability, or global warming impact.

In comparison with prior work, the first major contribution of this study is that it compiles knowledge about a wide range of decarbonization pathways, and that we facilitate direct comparison by deriving figures in standardized units. For most technologies, the literature is sufficiently mature to enable straightforward unit conversion, but where this is not possible, we perform additional calculations to arrive at the desired comparable units of measurement. Uncertainties are considered by including pessimistic (higher cost, greater emissions, lower scalability) and optimistic ranges for each parameter.

Our compiled data on distance-levelized cost, distance-levelized lifecycle GHG emissions and scalability potential in the coming decade are combined with data on the age composition of vehicles in different EU regions, and transport growth estimates, to forecast annual GHG emissions from EU road transport in the year 2035, and cumulative emissions assuming net zero is reached by 2050.

The second major contribution of this study is that we show how it can be technically and economically feasible to reduce GHG emissions associated with EU road transport substantially below current EU forecasts for the sector. However, we do not identify any combination of strategies that would allow sectoral emissions to decrease at rates in line with scientifically motivated targets for the entire EU economy. Furthermore, we find that extensive policy change would be required and that it is doubtful whether political change of such magnitude can be expected to take place at such a high rate. Additional work is required to identify ways to either overcome the political obstacles hindering adoption of low-cost solutions that can scale, or to overcome the cost and scalability challenges that are associated with solutions that have already gained political momentum.

1.3 Scope

Geographical scope: The study encompasses the European Union (EU), with analyses disaggregated for Northern, Western, Southern, and Eastern Europe to reflect regional disparities, primarily in terms of age composition of the rolling vehicle stock.

Temporal scope: Our primary focus is on assessing the potential for impact in the year 2035, one decade ahead at the time of writing. We estimate total remaining sectoral emissions until 2050 by assuming linear change in annual emissions from today until 2035 and from 2035 until 2050 (net zero).

Sectoral scope: The analysis is confined to the EU road transport sector, differentiating between light and heavy road traffic, where light refers to light duty vehicles (cars and vans) and heavy-duty vehicles refers to heavy duty trucks. However, it does not further segment these categories by vehicle class or mode of operation. Parameter assessments for heavy traffic represent heavy-duty vehicles, with adjustments on total driven distance at population level to match total sectoral emissions. Our sectoral scope is slightly broader than the traditional definition of the
transport sector, as our lifecycle emission estimates include not only tailpipe GHG emissions, but also GHG emissions from vehicle and battery manufacturing, fuel and electricity production, fuel distribution and hydrogen leakage.

Technological scope: We analyze combustion engine vehicles, battery-electric vehicles, and hydrogen fuel cell vehicles. For combustion engines, we consider fossil fuels, drop-in biofuels and drop-in electrofuels, also referred to in EU regulation as renewable fuels of non-biological origin (RFNBOs). For battery-electric vehicles, we consider static low-power charging, static high-power charging, and dynamic charging via electric road systems (ERS). ERS is considered for all traffic, as well as for only heavy vehicles, but is not further separated by technology. We also consider mid-life conversions of combustion engine vehicles to battery-electric vehicles. EU-wide adoption is considered for all technologies. We do not include battery swapping as a separate electrification strategy. Battery swapping may have several advantages, but we do not believe that this strategy will differ significantly from cable-based static charging in terms of new electric vehicle sales, embodied GHG emissions per electric vehicle, energy consumption, or potential to facilitate conversions from combustion engine vehicles to electric. For hydrogen fuel cell vehicles, we assume all refueling takes place via public stations, and discuss alternative pathways for green hydrogen to be supplied to these stations.

Indicators of analysis: For each propulsion technology, we estimate levelized transport cost excluding subsidies, levelized lifecycle GHG emissions, and the share of EU road transport that can at most use that technology in 2035. Distance-levelized performance is combined with forecast total transport work per EU region, to arrive at GHG estimates for all EU road transport. As all assessed technologies together do not scale to 100% of 2035 traffic, we assume all strategies are used to their maximum potential.

Soft interventions: In addition to our techno-economic assessment, we survey existing literature on demand-side strategies to reduce emissions. This review is complementary and not the primary focus of the study.
2 Background

2.1 GHG Emission Reduction Targets
To limit global warming to 1.5°C with 50% probability, the global remaining carbon budget as of January 2023 was around 250 Gt CO$_2$, equal to around six years of current global CO$_2$ emissions (Lamboll et al., 2023). How to distribute this remaining budget geographically is a topic of debate. While there is no established method to assign a remaining carbon budget to the EU, application of a range of methodologies resulted in estimates from 2020 onwards at -1 to -27 Gt CO$_2$-eq (Pelz et al., 2023), with negative values indicating that the EU had already surpassed the EU fair share. These allowances for the EU were based on an earlier approximately 35% higher assessment for the global budget.

The ‘Fit for 55’ policy package is an EU commitment to reduce the economy wide net GHG emissions to at least 55% below 1990 levels by 2030 (European Council, 2023). EU GHG reduction targets are still under debate, with its scientific advisory board recommending to further reduce economy-wide GHG emissions to 60–75% below 1990 levels by 2030 and 77–87% by 2035, to improve the global fairness of the EU’s contribution (European Scientific Advisory Board on Climate Change, 2023). The European Commission recently recommended economy-wide GHG emissions to be reduced by 90% by 2040 (European Commission, 2024b), which is the smallest reduction advised by ESABCC for the same year.

Forecasts however indicate a 55% reduction will be reached no earlier than 2035 (European Environment Agency, 2023e), from 4.7 Gt/year CO$_2$-eq in 1990 to 2.1–2.4 Gt/year by 2035 (European Environment Agency, 2023c). The current rate of reduction would put cumulative 2020–2035 GHG emissions at approximately 43 Gt CO$_2$-eq, with an additional 20 Gt remaining until net zero in 2050, i.e., several times above the EU GHG budget.

While the rest of the economy does achieve GHG reductions, even if at an insufficient rate, sectoral GHG emissions from EU road transport have increased from the 1990 reference year until today. By 2035, annual GHG emissions from road transport are forecast at four percent below 1990 levels (European Environment Agency, 2023d). With this forecast and net zero reached in 2050, cumulative 2023–2050 tailpipe emissions from road transport would amount to approximately 12 Gt CO$_2$, i.e., likely more than the total EU remaining carbon budget.

As a share of the total annual EU GHG emissions, road transport will then have increased from 13 to 25 percent between 1990 and 2035, with further relative increases expected. 25% is approximately the share of the total EU GHG budget that should be allocated to tailpipe emissions from road transport (Plötz et al., 2023). Of all GHG emissions from EU road transport in 2021, light duty vehicles of 71% and heavy-duty vehicles of 28% (European Environment Agency, 2023b). Light-duty vehicles are the fastest growing segment of the three, followed by heavy-duty vehicles.

Note further that only fossil tailpipe emissions are counted in official statistics for road transport. Transitions to so-called zero emission vehicles are associated with increased emissions in other sectors, e.g., production of electricity, sustainable liquid fuels, hydrogen, battery packs and steel. Emissions embodied in imports are allocated abroad. To facilitate straightforward comparisons between the real emissions reductions that different technical pathways can offer, we estimate lifecycle emissions for all technologies. This means that our figures cannot be compared directly to EU sectoral targets.

EU policy to phase out fossil fuels from road transport has thus far focused on tightened standards for new vehicles, culminating in a 2035 EU-wide sales ban on new cars and vans with non-zero tailpipe emissions (European Commission, 2023, p. 55) and a 2040 target of 90% reduction in total GHG emissions from new heavy-duty vehicles (EU HDV CO$_2$ Regulation, 2023). These targets for GHG emissions from road transport, particularly those for heavy duty vehicles, are significantly less ambitious than targets for other sectors. The ICCT estimates that the standards will bring about a mere 64% reduction in annual GHG emissions from EU heavy-duty vehicles by 2050 (Mulholland & Rodriguez, 2023), 20 years behind the rate of total reductions recommended by the European Commission. Ambitious further actions are still needed to reduce road transport emissions substantially within the next critical decade.

2.2 Related Work
In this article, numerous sources are used to support the assumptions in the different scenarios. Most of these focus on a specific aspect of decarbonization or technology, and therefore will not be mentioned here. Instead, they are listed in their respective sections. Here, we compile studies assessing transport decarbonization pathways at a higher level, assessing them with respect to certain parameters and within a specific geographical region. However, none of the studies compare the different scenarios in terms of their potential to upscale, their practical achievability and the time that it would take to implement them, given the enormous requirements in terms of, e.g., manufacturing capacity increase and infrastructure deployment and the limited time available.

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(Lin & Xie, 2014) and (Bai et al., 2023) point out that the highest potential for carbon emission reduction in China lays on reducing the carbon intensity of transport rather than reducing the total energy consumed in transport. This could be done by employing newer technological solutions, such as electric vehicles, in the transport sector. However, (Lu et al., 2022) states that, even if China is leading when it comes to EV production, sales, and ownership, electrification alone cannot meet the 2060 climate targets for China, since the continued inertia of fuel vehicles will slow the path towards carbon neutrality, which then depends on the forced elimination of fossil-fuel vehicles and more substantive decarbonization measures.

In the US, two ambitious regulations have been introduced which will substantially impact the transport system: the Infrastructure Investment and Jobs Act (US Congress, 2021) and the Inflation Reduction Act (US Congress, 2022). In 2022, the United States Department of Energy (DOE), Department of Transportation (DOT), Environmental Protection agency (EPA) and Department of Housing and Urban Development (HUD) signed a joint memorandum of understanding to formalize their collaboration and coordination on transportation decarbonization. In a common document called The US National Blueprint for Transportation Decarbonization (US Department of Energy, 2023), they propose concrete measures to reach 80 – 100 % emissions reductions by 2050 in line with the US Long-Term Strategy, through increased conveniency, reducing the amount and length of travelling through better land-use and planning, increased transportation efficiency through better rail and public transportation, and the transition to clean technologies. These measures are specified for all transport modes in the periods before 2030, between 2030 – 2040, and between 2040 – 2050.

In (Hoehne et al., 2023), transportation energy use and emissions in the US are evaluated for 2173 long-term scenarios, focusing on the impacts of different technologies, fuels, policies, and changes in travel behavior and choices. The results show that a rapid and widespread transition to EVs is a key requirement for the decarbonization of on-road passenger and freight mobility, assuming a decarbonization of the electricity sector, followed by a reduction of the overall travel demand. (Pinto De Moura, 2022) also highlights rapid electrification of both light-duty and heavy-duty vehicles as the main strategy to mitigate transport GHG emissions in the US and points out the unprecedented needs in both renewable electricity generation and transmission.

The UK Government has also published a Path to Net-Zero Transport (UK Department for Transport, 2021) in which different measures are proposed to achieve the goal of zero-emission transport by 2050. In this plan, a modal shift to public and active transport is highlighted as priority one, supported by infrastructure and urban & transport planning, followed by the decarbonization of road vehicles and freight transport.

In (Rinaldi et al., 2023) the trade-offs between battery and hydrogen solutions for different decarbonization pathways for the transport sector in Switzerland are analyzed, using a whole energy system perspective (i.e. including residential, commercial, industrial and transport sector, with electricity, heat, hot water and hydrogen as energy carriers). The study finds that a larger share of FCEVs leads to higher system cost, higher emissions, and lower self-sufficiency in energy supply, mostly due to their lower round trip efficiency.

A strategy for the decarbonization of the Danish transport system is proposed in (Kany et al., 2022). With a high share of international aviation and maritime transport, Denmark will require a higher share of bio- and electrofuels. According to the authors, the focus should be on lowering the growth of transport demand in inefficient modes, e.g. car travel, promoting a modal shift towards public and active transport modes. Moreover, a strategy of heavy electrification is suggested, comprising all light duty vehicles, most trucks and buses, all railways and national ferries and short-distance flights.

Different scenarios for the electrification of both light duty vehicles and heavy-duty vehicles in Sweden considering Electric Road Systems (ERS) and Battery Electric Vehicles (BEVs) are compared in terms of the system costs in (Márquez-Fernández et al., 2022). Solutions with ERS result in lower system cost as long as ERS are sufficiently deployed so that they support a size reduction of the vehicle batteries. In that case, ERS that can be used by all vehicle types (light and heavy-duty vehicles) are to be preferred, since they result in higher utilization of the ERS infrastructure. In (Rogstadius, 2022) hundreds of scenarios are simulated in order to identify the most cost-efficient charging infrastructure deployment for heavy duty vehicles in Sweden, accounting for the interactions between competing solutions. The results show that a rapid electrification of heavy duty vehicles is necessary to reach Sweden’s and the EU’s emission reduction targets. Depot charging and ERS are the most cost-effective solutions early in the transition process, when much traffic still runs on diesel, while addition of public fast charging stations become most cost effective when a large share of the truck traffic is already electrified. However, no single type of charging infrastructure is essential for deep electrification of heavy truck traffic in Sweden, and the most substantial cost reduction comes from the transition from diesel to electric operation.

In (Craglia, 2022), the feasibility of decarbonizing heavy-duty trucks in Europe is assessed. 1000 unique scenarios are developed for each of the zero-emission technologies considered: Battery Electric Vehicles (BEVs), Electric Road Systems (ERS) and hydrogen Fuel Cell Electric Vehicles (FCEVs), across nine different vehicle size segments. The result shows that zero-emission vehicles will be cost-competitive with their diesel counterparts before 2040 – although the exact time depends on the vehicle size. BEVs with a fast-charging infrastructure and ERS vehicles
perform similarly in most scenarios, and more research is needed to understand which technology can offer the most significant financial and CO₂ savings while accounting for real-world constraints. PCEVs, however, are only cost-competitive in a small number of marginal cases. Policy measures are also essential to accelerate the adoption of ZEVs. (IKEM, 2022) also presents a combination of Electric Road Systems (ERS) and fast charging infrastructure (Megawatt Charging Systems, MCS) as the most effective and fastest option to decarbonize heavy-duty transport in Europe. However, it conditions the future role of ERS to political decisions, to be taken at national and EU level. Thus, the report includes a comprehensive overview of the legal and political framework concerning greenhouse gas emissions in the transport and energy sectors.

A recent scenario assessment from the Potsdam Institute concluded that EU road transport by 2050, as shares of final energy, will depend on approximately 60–85% direct electrification in both light and heavy segments, 10–40% hydrogen fuel cells in the heavy segments, and the remainder combustion engines, of which a significant share is synthetic hydrogen-based fuels (Schreyer et al., 2024).

In (Transport & Environment, 2020) the renewable electricity production requirements necessary to decarbonize transport in Europe are assessed, considering electric vehicles, hydrogen, and electrofuels. The study shows that there is enough renewable generation potential in the EU to cover the additional electricity demand from transport. Up until 2030 road vehicles will be the major consumers, but after that shipping and aviation will dominate.

Finally, in (Emodi et al., 2022) a systematic literature review of transport decarbonization strategies in the Global South is presented. Significant differences are found between countries attending to their location (Asia, Africa or South America), their level of development and whether they have access to domestic oil production. The study shows that decarbonizing the transport sector may reduce government revenues from fuel tax, lead to competition for alternative fuels by transport, industries and building sector, crowd out low-income consumers in favour of high-income earners and have a rebound effect on travel behavior. Financing decarbonization policies and addressing the associated challenges require special mechanisms that should be monitored and adjusted to ensure these policies evolve and align with the country’s transport, environmental, social, and economic needs.

2.3 Measures to Reduce Road Traffic

To be able to reach the GHG emission reduction targets, it is often argued that there is a need not only for a transition to alternative fuel options, but also to reduce demand for road transport, both through a reduction in transport work and through shifts to other transport modes. However, such a reduction in transport demand is absent from both recent historical developments and from forecasts of future demand (Müller & Reutter, 2021). Rather, available evidence at best points to a reduced rate of increase in total traffic demand.

Several studies investigate the future demand if implementing indicated policies. Takman and Gonzalez-Aregall (2023) reviewed 93 policy instruments in the EU, 27 of them were at EU level, 53 on national level and 13 at local level. Most of the policies focused on railway, a large part on waterways and about one fifth of the policies promoted the use of both rail and sea. 15% of the identified policy instruments investigated were set to discourage road transportation overall. Takman and Gonzalez-Aregall also investigated evaluations done regarding the follow-up the efficiency of such policies and found that only 20 of the 93 were evaluated, indicating that authorities have difficulties in understanding how to evaluate the effectiveness of their policies, often due to the lack of measurable targets. EU policy instruments were however often evaluated as having poor or mixed performance. (Pinchasik et al., 2020) investigated scenarios for the Nordic countries. They found that the best CO₂ emission reductions coming from various suggested policies, did not even exceed 3.6 % in 2030. It will be important to understand how to evaluate current policies and to understand the effects that particular policies might have on the overall outcome, to be able to set efficient policies if we are going to reach set targets by 2050.

When incorporating adaption and mitigation plans set by 133 nations in response to the COP21 into the IEAs mobility model (MoMo), (Mulholland et al., 2018) found that set policies would yield an increase in emissions by 56% between 2015-2050. If instead using input that would include factors such as fuel taxes, distance-based pricing, wide-speed data-sharing as well as investments in zero-carbon infrastructure among other factors, emissions could be reduced by 60%. Policies including cost seems to have a large impact on driving behavior. In a British review of price and income elasticities in demand for road transport, a 10% increase in real fuel price was associated with a 2.5% decrease in fuel consumption within a year, building up to a 6% reduction in the longer run (Hanley et al., 2002) – effects on traffic were smaller. A 10% change in real income was associated with a 10% long-term increase in fuel consumption. Simulations for Sweden indicate that if driving costs are increased by 50% then the travel demand by car will decrease with 23.8 %, while other types of travel such as by rail or bus will increase by 13.4 % and 15.3% respectively (Trupina Dreven, 2023). Since total distance travelled by car is much greater than the other two modes, these relative changes imply that only 10% of the reduced car travel is shifted to other modes, with a 21% reduction in total travel (Tufvesson & Ågerbäck, 2012). High-income groups have been identified to respond less to cost increases than low-income groups (Vasudevan et al., 2021).

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Cost is not the only aspect to consider, (Batty et al., 2015; Bernardino et al., 2015; Li et al., 2024) all mention other aspects to consider such as safety and security, comfort, travel time and availability of other types of travel, as well as factors making it less attractive to drive, such as congestion charges, parking regulations and urban planning to encourage walking (Takman & Gonzalez-Aregall, 2023). Interventions within cities have great impact potential, as about 71-75% of the global energy related GHG emissions are produced in the cities (Linton et al., 2022). We do not have data on the urban share of road traffic, but suspect it is similar. Modal shift requires alternatives, which may be easier to increase the availability of within urban than rural areas.

As air pollution in cities causes apparent health issues, municipalities and cities like Milan, Toronto, Paris and New York are taking action to create greener and cleaner urban areas by creating city zones with restrictions for cars to access the areas, as well as removing or limiting parking areas (Linton et al., 2022). In Milan, a fee was introduced for combustion engine cars in the city during specific time windows of a week, resulting in a 49% total decrease of cars in the city and a 5% increase in electric cars (C40 Cities, 2015). Other actions are free public transit tested in Park City or congestion pricing such as the case in New York (Linton et al., 2022).

(Gibson & Carnovale, 2015) analyzed the effects on travel from the Milan road pricing policy. They showed that pricing had a considerable effect on reducing traffic and pollutions, but the effect is dependent on the availability of public transit. In Belgium cities such as Brussels, Leuven and Ghent have taken on so called circulation plans to diminish the possibilities for thoroughfare within the cities. Parking areas have been removed to make space for recreation, walking and biking in the city centers. Within the first to three years the cities reduced the amount of car travel between 6% and 28%, while public transit and biking increased by 12 % and 8 – 18% respectively. The circulation plan also resulted in a 18% reduction of CO2 emissions, in the city of Ghent (Gustavsson Binder et al., 2023).

An extensive review of soft interventions to reduce transport demand was conducted in (Semenescu et al., 2020). The review concluded that the most effective interventions were the ones targeting social, cultural and moral norms, with an average effect size of approximately 32% decrease in car modal split share. This was followed by interventions targeting knowledge and awareness of own driving behavior, with an average effect size of approximately 14% decrease in car modal split share.

For the present study, we require assumptions about the total change in light and heavy road traffic in the EU by 2035. As it is not within the scope of the present study to explicitly model the impact on transport demand from interventions such as those mentioned here, we rely on European Commission forecasts for EU passenger and freight transport between 2015 and 2040 by transport mode, from a 2024 impact assessment report that includes a substantial modal shift from road to rail (European Commission, 2024a). Based on this source, and further assumptions that the rate of change in transport demand is constant and that a change in transport activity equals a change in total driven distance, light road traffic is expected to increase approximately 10% between 2024 and 2035, while heavy road traffic is expected to increase approximately 20%, with only small variations between evaluated scenarios.

### 2.4 Assumptions about Direct Electrification

Full electric vehicles need access to a charging infrastructure. We make a difference between the charging needs related to daily commuting, and the charging needs related to long distance travel. Ideally, all electric vehicles should have access to night charging that would cover the energy needed for daily commuting for cars and a large part of the daily operation of trucks. This can be the case for anyone who has a car parking or garage place related to a villa or an apartment building, or a goods terminal parking position for trucks. However, those who need to park at a random place along a street cannot be expected to have access to overnight charging.

Electric energy supply for long distance travel with electric vehicles is studied in two alternative versions: I) A network of static fast charging stations along the TEN-T road networks and II) An Electric Road Systems (ERS), covering the same TEN-T road networks. It is assumed that ERS play the same role for an EV as a network of fast charging stations in providing energy for trips longer than the battery-range. ERS provides a possibility to unlimited driving range by recharging the EV batteries and simultaneously providing instantaneous traction power while driving. A society based on a network of fast charging stations needs a certain “density” of such stations along the roads (number of fast chargers per km) and the road network must be reachable from any point to facilitate long distance travel. Similarly, a society with ERS needs a certain “density” of roads equipped with ERS (km ERS per km road), reachable from anywhere to provide EVs with unlimited driving range.

Those vehicles that have no access to night-charging will in either case use fast chargers or ERS to provide the bulk of the charged energy needed for daily commuting.

#### 2.4.1 A Square Road Network Model

The uneven shape of the European land area, the uneven geographical distribution of the road network and the uneven distribution of the traffic flow both geographically and in time makes it difficult to establish a general rule
for the need for a density of a fast-charging network or an ERS network. A somewhat useful simplification is to assume that a real land area is shaped as a square with an evenly distributed square road network. If the square modelling is applied to EU-27, with 4.2 million km² land area, the equivalent of the TEN-T Core network (48200 km, excluding the UK) or Comprehensive network (132574 km, excluding the UK) corresponds to a square road network with 170 km or 62 km side. This implies that from anywhere in that square area the distance to a TEN-T road on average would be less than 85 km (to the Core network) and 31 km (to the comprehensive network). These distances are easily reached with all modern electric cars or trucks and serve as an indication only that equipping the TEN-T Core and/or the Comprehensive road network with either fast chargers or ERS has the potential to provide long trip energy supply for EV's.

2.4.2 Required Fast Charging Network Density

The need for fast charging is unevenly distributed in time both time and space, with variations over hours/days/weeks, with local variations in AADT (Annual Average Daily Traffic) flow and differences between cars and heavy-duty vehicles. The country in the world that has the longest experience of a fast-growing fleet of electric cars is Norway. Currently, the electric car fleet in Norway is about 24% of the total car fleet (Norway Car Statistics, 2024). The fast charger network density (number of full electric cars per fast charger) for cars in Norway has since 2018 settled at a level that corresponds to 100 full electric cars per 1 fast charger (Norway Fast Charger Statistics, 2024). This fast charger density level is empirically established to avoid unreasonable waiting times at fast charging locations for cars during high traffic. An empirically established fast charger density for trucks remains to be defined.

If the empirically established Norwegian fast charger density for cars is applied to EU-27, with about 250 million private cars, a fully electrified fleet would need about 2.5 million fast chargers. Distributed along the TEN-T comprehensive road network (132574 km), this corresponds to 19 fast chargers per kilometer in average. With the AFIR recommendation of access to a fast charger every 60 km, it also corresponds to 2200 fast charging stations with 1100 fast chargers for cars per station. NB! This is an average and should be expected to be much higher in densely populated areas with high traffic flows and vice versa for sparsely populated areas.

The predicted fast charger density is empirically found but must still be challenged. There are several reasons that the future fast charger density required in EU with only full electric cars will be lower than predicted here; I) the prediction is based on Norwegian users that are “early adopters” that can be expected to have higher requirements than future “late majority” might have, II) future BEV’s can probably sustain higher charging power than the current fleet, thus shortening charging times and reducing the need for fast chargers. However, we see no reason that the prediction is an order of magnitude wrong. Thus, the fast charger density needed in EU-27 with only full electric cars, even if lower than the empirically deduced in Norway, may still be a formidable challenge to implement.

2.4.3 Required ERS Network Density

We evaluate ERS as a charging option for daily use with the equivalent function of a fast-charging infrastructure. Thus, we assume that the same ERS technology is distributed across the TEN-T core or comprehensive road networks, with a density (km ERS per km road) high enough to be reached by any EV (car or truck) within similar distances as a fast charger network density (number of fast chargers per km road) can be reached. Without a common standard and a similar distribution as a fast-charging network, ERS will not facilitate long distance travel for either cars or trucks and will thus not play an important role in abating CO2 emissions from road traffic. Sparsely populated areas like northern Scandinavia are assumed to use less or no ERS and instead provide charging via fast chargers.

We model ERS for only heavy vehicles with the total road network length of the TEN-T Core network (48200 km), and ERS for both light and heavy vehicles with the total length of the TEN-T Comprehensive network (132574 km), see Figure 2-1.
2.4.4 EV Charging Alternatives Analyzed

The analysis of full electric vehicles is divided in two scenarios:

I) A fast-charging based infrastructure that provides energy for all long-distance trips of both Cars and Trucks and for daily commuting energy to those who do not have access to night charging, and

II) An ERS-based infrastructure for that provides energy for all long-distance trips and for daily commuting energy to those who do not have access to night charging.

In case II) we include Trucks only or Trucks and Cars. One reason to consider ERS for cars is the challenging numbers of fast chargers presented in section 2.4.2.
3 Method

The main part of this study is a quantitative comparison of the extent to which different technologies can contribute to decarbonization of EU road traffic. This comparison consists of several steps. First, we define common equations used to calculate the levelized cost and greenhouse gas (GHG) emissions associated with each technology. Then, values for all input parameters are identified in scientific and grey literature. Uncertainty is handled by including both pessimistic and optimistic assumptions for each parameter. How the ranges have been determined for individual parameters is documented in the following section, but ranges typically reflect values representative for different vehicle segments, European member states, or possible future development.

Conflicts in literature are discussed, and handled quantitatively either by selecting those sources that we deem more credible, or by using ranges from the literature as optimistic and pessimistic assumptions. Input parameters that we have been unable to find direct sources for in the literature are estimated through calculations, to close the gap between available evidence and the input data we require for the subsequent steps of the analysis.

All parameter estimates are for the year 2035. For all technologies, we estimate levelized cost, levelized GHG emissions and scalability. We exclude subsidies and economic incentives to the best of our ability, which means our figures can be used in socio-economic calculations, but they may not accurately represent prices paid by end users of the different technologies. All costs are excluding value-added tax (VAT) in 2023 year’s monetary value.

Equations 1 and 2 define our metrics for technoeconomic comparison. The following section lists the values of all input parameters as well as the calculated levelized costs and GHG emission rates.

\[
C_{\text{tot}}^{\text{eq/km}} = \frac{C_{\text{veh}}^e + (1 + C_{\text{cap}}^e) (C_{\text{veh}}^m + C_{\text{fuel}}^m + C_{\text{maint}}^m + G_{\text{tot}}^{\text{veh}} + G_{\text{tot}}^{\text{fuel}} + G_{\text{tot}}^{\text{inf}}) + F^e_{\text{UEC/km}} + T_{\text{road}}^e}{D_{\text{km}}} \quad \text{Eq. 1}
\]

\[
G_{\text{tot}}^{\text{kg/km}} = \frac{G_{\text{tot}}^{\text{veh}} + G_{\text{tot}}^{\text{fuel}} + G_{\text{tot}}^{\text{inf}}}{D_{\text{km}}} + F^e_{\text{UEC/km}} \quad \text{Eq. 2}
\]

Superscripts indicate the unit of the variable and are omitted in subsequent sections.

- \( C_{\text{tot}} \) is the total levelized cost per vehicle km.
- \( C_{\text{veh}} \) is the purchase price of the vehicle.
- \( C_{\text{cap}} \) is the cumulative scrappage loan value paid over the vehicle lifetime, in percentage of the vehicle purchase price.
- \( C_{\text{veh}} \) is the residual scrappage value of the vehicle, in percentage of the purchase price. In vehicle types with batteries, the residual value of the full vehicle is the value-weighted average of the ratios for battery and remaining vehicle. \( D \) is the lifetime distance driven.
- \( C_{\text{maint}} \) is the levelized maintenance cost per vehicle km.
- \( C_{\text{fuel}} \) is the product cost of the energy carrier, including necessary supply chains and distribution infrastructure, but excluding taxes.
- \( T_{\text{road}} \) is a tax on the energy carrier applied equally regardless of propulsion technology, based on a conversion of current fuel taxes.
- \( T_{\text{fuel}} \) is a tax that internalizes the social cost of fossil CO\(_2\) emissions. We apply the same tax rate to fossil GHG emissions from fuel production, fuel combustion, electricity production, and vehicle and battery manufacturing.
- \( G_{\text{tot}}^{\text{veh}} \) is the \( CO_2 \)-eq well-to-wheel fossil greenhouse gas intensity per unit of energy carrier (UEC).
- \( F \) is the fuel or energy consumption per vehicle km.
- \( G_{\text{tot}}^{\text{fuel}} \) is the total levelized \( CO_2 \)-eq intensity per vehicle km. \( G_{\text{veh}} \) is the sum of \( CO_2 \)-eq GHG emissions from the manufacturing phase of the vehicle.

We also provide scalability estimates, i.e., at most how much of the total EU traffic work can be powered by each technology solution in 2035. The methodologies used for these scalability estimates differ between technologies.

The unified metrics are subsequently used to compare the attractiveness to vehicle owners and transport operators of the evaluated technologies in terms of cost and GHG emissions rates. While emissions rates give an indication of the feasibility of achieving reduction targets, cost estimates indicate how likely infrastructure investors and vehicle and transport buyers are to resist policies that favor a certain technology.

Finally, the scalability estimates for each technology are combined with forecasts of total transport work, to estimate total annual fossil GHG emissions, comparing reductions under expected and more ambitious scenarios.
4 Data Collection

4.1 Fossil Fuels

Table 4-1: Parameter values used in analysis of ICEVs using fossil fuels.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Light vehicles</th>
<th>Heavy vehicles</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pessimistic</td>
<td>Optimistic</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Optimistic</td>
<td>Optimistic</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pessimistic</td>
<td>Optimistic</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Optimistic</td>
<td>Optimistic</td>
<td></td>
</tr>
<tr>
<td>(D)</td>
<td>km</td>
<td>150 000</td>
<td>260 000</td>
<td>(Sharpe &amp; Basma, 2022; Statista, 2023; TRATON, 2022) and Tallis Blalack, personal communication</td>
</tr>
<tr>
<td>(C_{veh})</td>
<td>€</td>
<td>42 000</td>
<td>25 000</td>
<td>See text</td>
</tr>
<tr>
<td>(C_{cap})</td>
<td>%</td>
<td>31%</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>(C_{res})</td>
<td>%</td>
<td>31%</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>(C_{maint})</td>
<td>€/km</td>
<td>0.08</td>
<td>0.04</td>
<td>(Sharpe &amp; Basma, 2022; Gössling et al., 2022; Trafikverket, 2020)</td>
</tr>
<tr>
<td>(C_{fuel})</td>
<td>€/liter</td>
<td>1.3</td>
<td>0.8</td>
<td>See text</td>
</tr>
<tr>
<td>(GHG_{ref})</td>
<td>kg/liter</td>
<td>3.4</td>
<td>3.3</td>
<td>(Delgado et al., 2017; ICCT, 2023; Rogstadius et al., 2023)</td>
</tr>
<tr>
<td>(F)</td>
<td>liter/km</td>
<td>0.060</td>
<td>0.054</td>
<td>See text</td>
</tr>
<tr>
<td>(GHG_{veh})</td>
<td>kg</td>
<td>4 200</td>
<td>3 500</td>
<td>(Kawamoto et al., 2019; O’Connell et al., 2023)</td>
</tr>
<tr>
<td>(C_{tot})</td>
<td>€/km</td>
<td>0.58</td>
<td>0.20</td>
<td>Eq. 1</td>
</tr>
<tr>
<td>(GHG_{tot})</td>
<td>kg/km</td>
<td>0.23</td>
<td>0.18</td>
<td>Eq. 2</td>
</tr>
<tr>
<td>Scalability</td>
<td>%</td>
<td>100%</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

4.1.1 Cost

Lifetime distance today for light vehicles is approximately 230 000 km (Mock & Díaz, 2021). We assume a significantly lower pessimistic value as there are active efforts to disincentivize use of ICEVs, and we believe such disincentivizing policies will become more feasible to implement as lower-emission alternatives become more competitive. Lifetime distance for heavy vehicles is based on prior ICCT assumptions (O’Connell et al., 2023), which are in agreement with other sources we have found.

Current fossil fuel prices \((C_{fuel})\) were estimated based on average national diesel prices including taxes and VAT (Cargopedia, 2024), subtracting the national VAT rate (Your Europe, 2022) and subtracting total national diesel taxes excluding VAT (Hoffer, 2023). Lower and upper bounds for 2035 diesel prices were estimated based on the spread of 10-year changes in EU oil price forecasts for 2030 and 2050 from 2017 (Duć et al., 2017) and of 10-year forecasts in a UK study from 2013 (DECC, 2013). Total cost of ownership for petrol vehicles is assumed to be within the range of optimistic and pessimistic values for diesel vehicles and is not separately modelled. When including both light and heavy vehicles, most of EU traffic runs on diesel today. Tailpipe CO\(_2\) emissions per distance for diesel and petrol vehicles are nearly identical (ICCT, 2019).

Vehicle capital costs are estimated using 3-5% loan interest above inflation, applied over 5-10 years with linear loan pay-back, for a total of 8% to 31% of the purchase value.

A simplified representation of national tax structures was selected, by using a non-GHG and a GHG tax component. The non-GHG tax component is applied equally to all propulsion technologies, both as a kilometer tax on energy carriers and on embodied emissions from vehicle manufacturing. The GHG component is multiplied by the GHG intensity of the fuel or electricity. For fossil fuels, pessimistic and optimistic values for non-GHG tax were 0.2 and 0.1 €/liter. These figures were based on the current spread between EU member states of total diesel taxes today (0.33-0.62 €/liter (Hoffer, 2023), of which varying shares are emissions-motivated).

The GHG valuation, applied in the calculations as a tax, was set based on the European Commission’s recommended shadow cost of carbon for year 2035; 390 €/ton CO\(_2\)e. This corresponds to approximately 1.3 €/liter,
which is a significant increase over current fuel taxes. Just like incentives and subsidies may alter the price of using other technologies, taxation of fossil fuels in 2035 may remain at levels far below the social cost of carbon.

After unit conversions, the tax rates in Table 4-1 are used for all technologies.

### Table 4-2: Tax rates on greenhouse gas (GHG) emissions and driven distance.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Pessimistic</th>
<th>Optimistic</th>
<th>Pessimistic</th>
<th>Optimistic</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{gas}</td>
<td>€/kg CO₂-eq</td>
<td>0.25</td>
<td>0.1</td>
<td>0.25</td>
<td>0.1</td>
<td>See text</td>
</tr>
<tr>
<td>T_{road}</td>
<td>€/km</td>
<td>0.012</td>
<td>0.005</td>
<td>0.054</td>
<td>0.024</td>
<td>See text</td>
</tr>
</tbody>
</table>

#### 4.1.2 Greenhouse Gas Emissions

Well-to-wheel (WTW) GHG emissions from diesel were taken from figure 56 in (Prussi et al., 2020), converted to kg/liter using 38 MJ/liter. Well-to-tank emissions were assumed to have slight potential for improvement by 2035, resulting from discontinued production from the hardest-to-extract sources, lower-carbon hydrogen used in oil refineries, and electrified distribution chains. We use WTW GHG emissions for combustion fuels since we for other technologies include upstream emissions from electricity and battery production.

#### 4.1.3 Scalability

No scalability cap is assumed for fossil fuels, i.e., both supply and distribution capacity are expected to be sufficient to meet demand from road transport.

### 4.2 Biofuels

#### Table 4-3: Parameter values used in analysis of ICEVs using biofuels.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Pessimistic</th>
<th>Optimistic</th>
<th>Pessimistic</th>
<th>Optimistic</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_{fuel}</td>
<td>€/liter</td>
<td>2.3</td>
<td>1.1</td>
<td>2.3</td>
<td>1.1</td>
<td>See text</td>
</tr>
<tr>
<td>GHG_{fuel}</td>
<td>kg/liter</td>
<td>1.2</td>
<td>0.7</td>
<td>1.2</td>
<td>0.7</td>
<td>See text</td>
</tr>
<tr>
<td>C_{tot}</td>
<td>€/km</td>
<td>0.58</td>
<td>0.19</td>
<td>1.04</td>
<td>0.48</td>
<td>Eq. 1</td>
</tr>
<tr>
<td>GHG_{tot}</td>
<td>kg/km</td>
<td>0.10</td>
<td>0.05</td>
<td>0.35</td>
<td>0.18</td>
<td>Eq. 2</td>
</tr>
<tr>
<td>Scalability</td>
<td>%</td>
<td>5%</td>
<td>10%</td>
<td>5%</td>
<td>10%</td>
<td>See text</td>
</tr>
</tbody>
</table>

#### 4.2.1 Scalability

The IEA estimates the global supply potential of liquid biofuels, from primarily sustainable crops, and some inclusion of waste and residue oils, to be 9 EJ by 2030. This is approximately the same amount of fuel as is consumed by a non-electrified EU road transport system, but the EU hosts only approximately 17% of the world’s cars, and biofuels have many other uses outside of road transport. EU policy states that of all transport energy, including non-road transport, approximately 10% should come from biofuels (Transport Policy, 2021). The EU target includes non-drop-in fuels, such as biogas, which require new or modified vehicles. We use the EU target as the optimistic assumption for Scalability, i.e., the share of EU road transport that can run on biofuels in 2035, while in the pessimistic assumption, a greater share of these supply-limited fuels is allocated to aviation and shipping.

#### 4.2.2 Cost

While none of the authors are biofuel experts, we consider the IEA supply cap estimates to be approximately in agreement with the EU targets and we therefore use the IEA estimate of USD 25/GJ to USD 50/GJ as the value for C_{fuel} (excluding taxes and converted to €/liter using 38 MJ/liter, 1 USD = 1 EUR and 20% markup).

IEA Bioenergy indicates that biofuel supply could be increased five to ten times above our optimistic assumption (IEA, 2023), but this would require feedstocks such as agricultural and forestry residues, municipal solid waste, short rotation woody crops and forestry plantations. Using such feedstocks would also result in product costs several times above those we have assumed (IEA Bioenergy, 2020), which we consider to be prohibitively high. Therefore, we do not assume such biofuels are extensively used in road transport.

#### 4.2.3 Greenhouse Gas Emissions

Our assumptions about the GHG intensity of biofuels are based on regulation that biofuels used in the EU must have a carbon footprint at least 65% lower than fossil fuels (Transport Policy, 2021), with some advanced biofuels offering up to an 80% reduction (Advanced Biofuels Association, n.d.).

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4.3 Battery Electric with Static Charging

Table 4-4: Parameter values used in analysis of BEVs with static charging.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Light vehicles</th>
<th>Heavy vehicles</th>
<th>Heavy vehicles</th>
<th>Heavy vehicles</th>
<th>Heavy vehicles</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>Km</td>
<td>200 000</td>
<td>260 000</td>
<td>1 248 000</td>
<td>1 560 000</td>
<td>See text</td>
<td></td>
</tr>
<tr>
<td>$C_{veh}$</td>
<td>€</td>
<td>44 573</td>
<td>24 316</td>
<td>288 474</td>
<td>187 917</td>
<td>See text</td>
<td></td>
</tr>
<tr>
<td>$C_{sys}$</td>
<td>%</td>
<td>6%</td>
<td>14%</td>
<td>8%</td>
<td>18%</td>
<td>See text</td>
<td></td>
</tr>
<tr>
<td>$C_{veh}$</td>
<td>€/km</td>
<td>0.04</td>
<td>0.02</td>
<td>0.1</td>
<td>0.05</td>
<td>50% of ICEV</td>
<td></td>
</tr>
<tr>
<td>$C_{fuel(slow)}$</td>
<td>€/kWh</td>
<td>0.38</td>
<td>0.24</td>
<td>0.38</td>
<td>0.24</td>
<td>(Lanz et al., 2022)</td>
<td></td>
</tr>
<tr>
<td>$C_{fuel(fast)}$</td>
<td>€/kWh</td>
<td>0.45</td>
<td>0.25</td>
<td>0.45</td>
<td>0.25</td>
<td>(Lanz et al., 2022)</td>
<td></td>
</tr>
<tr>
<td>$GHG_{tot}$</td>
<td>kg/kWh</td>
<td>0.09</td>
<td>0.05</td>
<td>0.09</td>
<td>0.05</td>
<td>See text</td>
<td></td>
</tr>
<tr>
<td>$F$</td>
<td>kWh/km</td>
<td>0.19</td>
<td>0.17</td>
<td>1.02</td>
<td>0.92</td>
<td>See text</td>
<td></td>
</tr>
<tr>
<td>$G$</td>
<td>kg</td>
<td>17 123</td>
<td>7 262</td>
<td>1 199 004</td>
<td>53 378</td>
<td>See text</td>
<td></td>
</tr>
<tr>
<td>$C_{fuel(slow)}$</td>
<td>€/km</td>
<td>0.43</td>
<td>0.16</td>
<td>0.87</td>
<td>0.41</td>
<td>Eq. 1</td>
<td></td>
</tr>
<tr>
<td>$C_{fuel(fast)}$</td>
<td>€/km</td>
<td>0.48</td>
<td>0.17</td>
<td>0.94</td>
<td>0.42</td>
<td>Eq. 1</td>
<td></td>
</tr>
<tr>
<td>$GHG_{tot}$</td>
<td>kg/kWh</td>
<td>0.10</td>
<td>0.04</td>
<td>0.18</td>
<td>0.08</td>
<td>Eq. 2</td>
<td></td>
</tr>
<tr>
<td>Scalability</td>
<td>%</td>
<td>46%</td>
<td>61%</td>
<td>19%</td>
<td>40%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3.1 Cost

The optimistic assumption for lifetime driven distance ($D$) for light vehicles is the same as for ICEVs, while the pessimistic assumption centers the interval on today’s average (Mock & Diaz, 2021). Lifetime distance for heavy vehicles was set to 20% above that of ICEVs, based on personal communication with experts at truck OEMs Scania CV and Volvo, first reported in (Rogstadius et al., 2023). The assumption is based on reasoning that the ICE powertrain is what limits both the technical and economic lifetimes of heavy-duty ICEVs today. Once electric powertrains are mature products, the lifetime of heavy-duty BEVs is expected to be longer than for current vehicles, as the vehicles will be less complex and cheaper to maintain. In addition, introductions of new Euro-classes have been driving vehicle replacement in the past decades, and we see no reason why forced replacement will take place in the same way for BEVs. Though some data show BEVs have lower utilization than ICEVs prior to 2020, we assume this is due to limitations in charging infrastructure and vehicle range that we assume will be fully resolved by 2035.

The upfront vehicle cost ($C_{veh}$) is estimated as 80% (König et al., 2021) of the equivalent combustion vehicle cost (Neugebauer et al., 2022) plus the cost of the battery system. The battery system cost in turn is estimated from the assumed usable range on a full charge, the estimated charge window used and the expected battery pack cost. The expected usable range for full electric light vehicles in 2035 is in (Slowik et al., 2023) assumed to be in the interval 240–640 km and in (Mock & Diaz, 2021) 350–550 km. In this analysis we assume that the usable range interval in 2035 will be 350–600km, both representing averages of B- and E-segment cars. For heavy vehicles we assume that the corresponding interval is 500–700 km, both regarded as averages of medium-duty and heavy-duty trucks in 2035. We also assume a 2x higher battery system cost for trucks due to the difference in economy of scale on battery system manufacturing for heavy vs light vehicles verified by current estimations to be 3x by 2025 (Spiller, 2023). The charge window used to provide the ranges is assumed to be in the interval 92–96% for cars (Nigel, 2022) and 80–85% for trucks (battery specialist at truck OEM, personal communication). The battery pack cost is estimated at 63$/kWh in 2035 (Slowik et al., 2023), which we increase to allow for vehicle OEM margins and expand to the intervals 70-90€/kWh for light vehicles and 2x higher for heavy vehicles(140-180 €/kWh), as explained above. All intervals mentioned represent pessimistic and optimistic assumptions. Heavy vehicle costs are assumed averages for all truck and bus types, excluding trailers.

The relative residual value of the EV ($C_{res}$) in [%] is estimated to be in the interval 5% to 10% of the purchase cost of the EV. The vehicle maintenance cost ($C_{main}$) is estimated to be 50% of that of a fossil fueled vehicle (Vehicle Technologies Office, 2021). This is a rough estimate, but a lower cost compared to fossil fueled vehicles is motivated since a BEV has significantly fewer serviceable parts and less brake-wear.

Static charging, i.e. charging while parked, is separated on I) slow charging at Level 1 or 2 (AC up to 22 kW assuming an on-board charger), and II) fast charging at Level 3 (DC over 100 kW, assuming off-board chargers). The levelized energy costs ($C_{fuel(slow)}$) with slow charging and fast charging ($C_{fuel(fast)}$) respectively include the equipment cost, the installation cost, the operation and maintenance cost, network fees and energy cost, but exclude taxes and levies (Lanz et al., 2022). In the slow charging case, the equipment cost is only the “wallbox” and the on-board charger is...
assumed to be included in the vehicle purchase. We increase charging costs given by the source by 8% to account for losses during charging (Elpiniki Apostolaki-Iosifidou et al. 2018).

2035 fast charging costs for heavy vehicles are assumed to be lower than for light vehicles. This assumption is based on current prices of 0.399 €/kWh at Milence stations, and on personal communication with Andreas Kammel (Traton). We have not identified any public source that we deem provides a more reliable estimate of the levelized cost of public fast charging for heavy vehicles.

### 4.3.2 Greenhouse Gas Emissions

The greenhouse gas emissions (GHG\_fuel) from electricity are extrapolated from 2030 forecasts of CO₂-intensity of electricity generation in EU-27 until 2030 (European Environment Agency, 2023c) that indicates a range of 50 g/kWh to 70 g/kWh. This value is increased by 8% for usable energy, due to charging losses (Apostolaki-Iosifidou et al., 2017).

Energy consumption (F) for both light and heavy-duty vehicles were estimated based on conversion ratios for combustion engine fuel consumptions. This method was selected to minimize bias introduced by selecting too high or too low values for either propulsion technology. The conversion ratios were estimated by taking the average reported fuel and energy consumption values for ten popular ICE passenger car models and ten popular battery electric models, averaging the consumptions and calculating a conversion ratio from liter to kWh. The same procedure was followed for heavy trucks, using five popular models. Resulting energy consumptions were validated against reported averages for light-duty vehicles (Mock & Díaz, 2021). Energy consumption for heavy-duty vehicles was validated using a combination of I) 1.1 kWh/km reported in real-world tests for a 40 ton truck (Volvo Trucks, 2022a), II) a heuristic provided by Nils-Gunnar Vägstedt at Scania CV AB (personal communication, 2023), according to which energy consumption is $0.5 + 0.5 \times \frac{\text{GTW}}{40 \text{ km}}$, at motorway speeds, level roads and including regenerative breaking, and III) an assumption that average heavy vehicles on EU roads including current load weight 30 tons. Energy consumption values from the literature for all vehicles were then increased by an annual average weather penalty of 10-15% for light vehicles (Barberson, 2024; Taggart, 2017) and 5%-10% for heavy vehicles, resulting in very close matches with figures calculated through the conversion ratios.

Greenhouse gas emissions from vehicle production (GHG\_veh), excluding the battery, are assumed equal to those of an ICEV (Neugebauer et al., 2022). GHG emissions from battery production are assumed at 61-106 kg CO₂e/kWh battery capacity (Emilsson & Dahllöf, 2019).

The total vehicle cost per kilometer (C\_tot(slow), C\_tot(fast)) of operation appears in two different versions, depending on the charging method is (slow/fast). Costs in practice will be given by the mix of charging methods used.

### 4.3.3 Scalability

Estimates of the share of EU traffic that can be electric by 2035 are based on estimates of new sales and the age composition of the current vehicle stock. For pessimistic assumptions, we assume current sales trends and natural vehicle replacement, while for optimistic assumptions we further estimate the combined impact of several potentially viable additional interventions.
The BEV share of new vehicle registrations in different markets is influenced by a range of factors, including vehicle manufacturing cost, model availability in different vehicle segments, market influencing policy, battery supply and technological advancements, fuel and electricity price development, electrical grid capacity, and charging infrastructure buildout. It is beyond the scope of this report to model how changes to these factors would influence future new vehicle sales. Instead, we use sales shares forecasts from prior research, and assume that the joint constraints imposed by the underlying factors are represented in these forecasts.

This implicitly assumes that charging infrastructure can and will be made available to support the increase in new registrations, but also that it is not feasible to accelerate the uptake of vehicles significantly above the forecasts without some substantial system change. Furthermore, the currently dominant form of charging is stationary via cable, primarily at low power during overnight parking and supplemented by high-power charging via centralized public infrastructure. We note that there is an assumption, but no direct evidence, that this form of charging can be scaled within the desired timeframe to achieve 100% electric vehicle sales across the EU, and we observe that standard parking conditions differ quite substantially between vehicle owners who already have adopted electric vehicles, and those that remain. The higher-income and more sparsely populated Nordics can be expected to have better access to designated parking spaces with slow charging installations than lower-income and/or more densely populated regions of the EU.

With the present policy, an EU sales ban comes into effect in 2035 on non-zero tailpipe emission for cars and vans. As we expect no series production of hydrogen fuel cell vehicles in the light segments by this year, we equate this regulation to 100% BEV sales by the same year. The sales ratio curves, see Figure 4-1 for light vehicles used in the analysis are best-effort approximations of forecasts (BloombergNEF, 2021) for four EU regions (Nordics+, Western Europe, Southern Europe and Eastern Europe) that we believe reflect probable trajectories given the EU sales ban.

Sales forecasts for zero tailpipe emission heavy vehicles are more uncertain. Present EU regulation stipulates that average tailpipe CO\textsubscript{2} emissions from new trucks must decrease by 30% per manufacturer from 2030, vs. a 2020 reference level. The regulation will likely be revised to 45% reduction by 2030 and 65% reduction by 2035 (European Commission, n.d.). Meanwhile, battery electric heavy duty vehicles are forecasted to reach a 12.5% market share of new registrations in Sweden by 2026 (Trafikanalys, 2023) and Volvo Group aims for 50% of global truck sales to be electric by 2030 (Volvo Trucks, 2022b). Battery electric trucks are forecast to offer lower total cost of ownership than diesel trucks in all truck segments by 2035 (Tol et al., 2022). Based on these preliminary signals of market uptake, we assume new registrations of heavy vehicles will follow the same curves as for light vehicles, delayed 7-5 years per region.

To estimate the pessimistic shares of electrified light and heavy road traffic per EU region by 2035, we use the following methodology. The vehicle age distribution in the vehicle stock has been estimated per region from...
reported statistical means (ACEA, 2023), with the same distributions used for light and heavy vehicles. The means and modes (most common value) of the age distributions are 1 and 9 years for Nordics+, 5 and 10 years for Western Europe, 11 and 12 years for Southern Europe, and 16 and 14 years for Eastern Europe. The vehicle age distributions have then been multiplied by relative annual driving distance per vehicle age, estimated based on German statistics for light duty vehicles (KBA, 2024). According to this distribution, vehicles are driven twice as far in their first year as in their 20th year. The resulting assumed distributions for share of traffic by vehicle age are presented in Figure 4-2.

Figure 4-2: Traffic by vehicle age, per EU region

To estimate the optimistic share of electrified road traffic, we further evaluate the combined impact potential of different additional measures that could be taken, grouped into three types of effects.

First, we consider measures that accelerate the increase in BEV sales ratio of new vehicles. In the default scenario, the BEV share of new vehicle sales reaches 100% no later than 2035 for light vehicles and no later than 2040 for heavy vehicles. With additional (unspecified) measures, we model that 100% BEV share of new sales is reached for light vehicles by 2031 and for heavy vehicles by 2037 in all four EU regions.

Second, we consider measures that limit the maximum age of vehicles in use. Vehicles older than 20 years are assumed to be scrapped and recycled, which in Nordics+ represents approximately 6% of vehicles and 3% of vehicle km, and in Eastern Europe approximately 17% of vehicles and 11% of vehicle km.

Third, we consider measures that stimulate conversions of ICEVs in use to BEV. We assume a market for conversions takes off in the late 2020s, with 2% per region of the originally-ICEV stock converted in 2030, equally for both light and heavy vehicles. This ratio increases to 100% of the originally-ICEV fleet by 2050. As the stock of original-ICEVs shrinks naturally past the 2035 sales ban, the share of traffic by converted vehicles peaks in the early 2040s.

4.4 Battery Electric with Electric Road Systems

In this paper we assume that an ERS network is available for both light and heavy-duty vehicles, as motivated in section 2.4.4. EV Charging Alternatives Analyzed. Any longer trips include a transfer from the origin to an ERS road, travelling on that road and finally a transfer from the ERS road to the destination. Based on the reasoning in section 2.4.1, the battery capacity can be significantly limited, both in cars and trucks.

Table 4-5: Parameter values used in ERS-adapted BEV analysis. Omitted parameters have the same values as for BEV.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Light vehicles</th>
<th>Heavy vehicles</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pessimistic</td>
<td>Optimistic</td>
<td>Pessimistic</td>
</tr>
<tr>
<td>C_veh</td>
<td>€</td>
<td>42 086</td>
<td>23 850</td>
<td>234 699</td>
</tr>
<tr>
<td>C_v</td>
<td>%</td>
<td>6%</td>
<td>12%</td>
<td>7%</td>
</tr>
<tr>
<td>C_maint</td>
<td>€/km</td>
<td>0.06</td>
<td>0.031</td>
<td>0.14</td>
</tr>
<tr>
<td>C_fuel</td>
<td>€/kWh</td>
<td>0.34</td>
<td>0.16</td>
<td>0.34</td>
</tr>
<tr>
<td>F</td>
<td>kWh/km</td>
<td>0.17</td>
<td>0.17</td>
<td>0.90</td>
</tr>
<tr>
<td>GHG_veh</td>
<td>kg</td>
<td>9 822</td>
<td>4 412</td>
<td>73 601</td>
</tr>
<tr>
<td>C_v</td>
<td>€/km</td>
<td>0.44</td>
<td>0.45</td>
<td>0.77</td>
</tr>
<tr>
<td>GHG_res</td>
<td>kg</td>
<td>0.06</td>
<td>0.09</td>
<td>0.14</td>
</tr>
</tbody>
</table>

4.4.1 Cost

The vehicle cost (C_v) is modelled in the same way as for BEV’s with two differences; I) The battery is reduced in size and thus represents a lower cost, and II) the cost of the equipment that transfers the energy from the ERS to
the vehicle is added (Elonroad, 2023). The battery cost for trucks is higher for trucks than cars just like for full BEVs, see section 4.3.1.

Several studies show that, in scenarios with sufficient ERS cover, the capacity of the battery on both light and heavy vehicles can be reduced between 50 and 75% compared to equivalent scenarios with only access to static charging, without compromising the operational performance of the vehicles (Coban et al., 2022; de Saxe et al., 2022; Kany et al., 2022; Márquez-Fernández et al., 2022; Ministères Écologie Énergie Territoires, 2021; Rogstadius et al., 2023; Shoman et al., 2022). The battery capacities are therefore estimated based on vehicle energy consumption and desired reduced ranges of 150-300 km (22-64 kWh usable capacity) on a single charge for light vehicles, and 200-400 km (222-605 kWh) for heavy vehicles. We model ERS with conductive rail in the road surface, and the new ERS-specific components in the vehicle are a “pick up” (the mechatronic device that connects to the ERS in the road) and a galvanically isolated on-board DC/DC-converter. The cost of these is assumed at 1000-1500 € for light vehicles and 5000-7500 € for heavy vehicles.

The vehicle maintenance cost ($C_{\text{maint}}$) is modelled in the same way as for BEV, with addition of the estimated cost of maintaining ERS-specific systems and components. The ERS specific system components are assumed to require service at the same rate and at the same cost level (expressed as €/km) per vehicle as brake service on fossil fueled vehicles ((MECA, 2024) and Elonroad, personal communication). Trucks are assumed to wear the pickup harder than cars and are assumed to need 2x the pickup maintenance costs of cars. There is no extensive experience of ERS-pick up maintenance for road vehicles available, but we consider this assumption to be reasonably realistic.

Vehicle energy consumption ($P$) is adjusted from BEV parameters based on the difference in vehicle weight from reduced battery capacity and the addition of ERS-specific components. We use 0.06 kWh/km/ton for light vehicles (Weiss et al., 2020) and 0.1 kWh/km/ton for heavy vehicles (Nils-Gunnar Vägstedt, Scania CV, personal communication). In commercial vehicles, weight reductions would be partially absorbed by increases in cargo load, which we do not consider.

The levelized cost before taxes of ERS charging ($C_{\text{fuel}}$) is modelled as the sum of (1) costs of electricity and grid fees, at 0.15-0.25 €/kWh, and (2) levelized costs of ERS-infrastructure, operation, and maintenance cost. Parameter assumptions used to derive $C_{\text{fuel}}$ are listed in Table 4-6. For pessimistic assumptions, we consider ERS used in two scenarios: I) only by heavy duty vehicles, and II) by both light and heavy duty vehicles. Optimistic assumptions always include all traffic. Physical ERS infrastructure is installed in intervals of 50% of the ERS network (e.g. 1 km out of 2 km or 10 km out of 20 km) and BEVs traverse gaps on battery power, gained on physical ERS sections. The total cost of erecting and maintaining the infrastructure, which includes grid connections, is levelized over the total electrical energy sold throughout the infrastructure lifetime. Energy sold is estimated by ramping up linearly over 20 years from no users to a set share of total electrical energy used by all vehicles, which is then held constant over the remainder of the infrastructure lifetime. The share of total electrical energy for heavy vehicles is based on cost-minimizing simulations of competitive effects between different types of charging, but we have no source for light vehicles.

We are sharing both costs and energy sold across country borders. If the same calculations were done per country, ERS costs would be lower in the densely populated countries and higher in the periphery, but we are not trying to account for such regional differences. Building an ERS must be a regional (EU) joint effort and equally expensive for all users independent of where in the region the users are.
Table 4-6: Additional input and calculated parameter values used in ERS analysis, aggregated to levelized cost per kWh.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Pessimistic</th>
<th>Optimistic</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERS network length, EU total</td>
<td>km, bidirectional</td>
<td>48 200</td>
<td>132 574</td>
<td>132 574</td>
</tr>
<tr>
<td>Cost of construction</td>
<td>€/km (excl. gaps)</td>
<td>4 000 000</td>
<td>5 000 000</td>
<td>3 500 000</td>
</tr>
<tr>
<td>ERS coverage on ERS network</td>
<td>%</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Effective cost of construction</td>
<td>€/km (incl. gaps)</td>
<td>2 000 000</td>
<td>2 500 000</td>
<td>1 750 000</td>
</tr>
<tr>
<td>Infrastructure lifetime</td>
<td>years</td>
<td>25</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>Capital interest rate</td>
<td>%/year, above inflation</td>
<td>4.0%</td>
<td>4.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Cost of capital</td>
<td>%, of investment</td>
<td>60%</td>
<td>60%</td>
<td>11%</td>
</tr>
<tr>
<td>ERS maintenance</td>
<td>%/year, of investment</td>
<td>4.0%</td>
<td>4.0%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Increase in cost of road maintenance</td>
<td>€/km-year</td>
<td>12 000</td>
<td>12 000</td>
<td>2 000</td>
</tr>
<tr>
<td>Levelized total infrastructure cost</td>
<td>€/year</td>
<td>6.7E+09</td>
<td>2.3E+10</td>
<td>5.5E+09</td>
</tr>
<tr>
<td>Ratio of truck energy, steady state</td>
<td>%, EU total</td>
<td>30%</td>
<td>50%</td>
<td>75%</td>
</tr>
<tr>
<td>Ratio of passenger car energy, steady state</td>
<td>%, EU total</td>
<td>0%</td>
<td>30%</td>
<td>70%</td>
</tr>
<tr>
<td>Lifetime average utilization, steady state</td>
<td>%, EU total</td>
<td>60%</td>
<td>60%</td>
<td>75%</td>
</tr>
<tr>
<td>Annual mean ratio of road transport energy</td>
<td>%, EU total</td>
<td>6%</td>
<td>22%</td>
<td>54%</td>
</tr>
<tr>
<td>Annual energy delivered</td>
<td>kWh/year</td>
<td>7.5E+10</td>
<td>2.6E+11</td>
<td>6.3E+11</td>
</tr>
<tr>
<td>Levelized total infrastructure cost</td>
<td>€/kWh</td>
<td>0.09</td>
<td>0.09</td>
<td>0.01</td>
</tr>
<tr>
<td>Energy + grid fees</td>
<td>€/kWh</td>
<td>0.25</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>$C_{net}$</td>
<td>€/kWh</td>
<td>0.34</td>
<td>0.34</td>
<td>0.16</td>
</tr>
</tbody>
</table>

4.4.2 Greenhouse Gas Emissions
The absolute greenhouse gas emissions of the vehicle ($GHG_{abs}$) are calculated the same way as for BEVs not adapted to ERS, with reduced battery pack capacity resulting in reduced embodied emissions. As most embodied BEV emissions are from the battery pack, a 50% reduction in pack capacity results in approximately 40% reduction in total embodied vehicle emissions. Energy consumption is reduced to compensate for reduced weight, with 0.06 kWh/km/ton for light-duty vehicles (Weiss et al., 2020) and 0.1 kWh/km/ton for heavy-duty vehicles (Nils-Gunnar Vågstedt, Scania, and John Holland, Kleanbus, personal communication). 75% of this reduction is applied to heavy-duty vehicles, with the remainder assumed to be negated by increased cargo weight. Energy consumption is then increased 3% to account for friction against the ERS (does not apply to inductive technologies) and increased aerodynamic drag (likely higher for overhead catenary technologies). We have not accounted for efficiency differences between static and dynamic charging, which result from differences in charging interface and different shares of energy taking a roundtrip via the traction battery pack.

4.4.3 Scalability
While several EU countries are exploring the potential of different ERS technologies, no country in the world has to date made a formal decision to build, let alone begun construction of, a large-scale ERS network. Thus, as for hydrogen fuel cell vehicles, we must carefully consider several factors that may restrict how extensively use of this technology can be scaled until 2035. The factors considered are I) necessary scope of buildout to achieve desired effects, II) how quickly ERS of this scope can be deployed, III) how quickly infrastructure utilization can increase once available, and IV) how late an investment can take place to still have desired effects.

Required ERS Network Scope and Density
Most potential future ERS-adapted vehicles are still assumed to get some share of their electrical energy through static charging. In comparison to a static charging infrastructure, the economics of ERS infrastructure are highly sensitive to economics of both scale (local traffic volume) and scope (geographic network extent) (Börjesson et al., 2021). Scale benefits are explained by a very high initial cost per electrified road distance, with a very low marginal cost per additional user. Scope benefits result from vehicles requiring additional components to utilize an ERS, with marginal reductions in total cost of vehicle ownership from battery-related cost reductions as the network.
expands. ERS network utility will be higher for vehicles based near the center of the network than on the periphery and adoption is only likely to take place if marginal utility is greater than marginal cost. The effect is that expansion of a small ERS network, e.g. in and around Berlin, to a greater region, e.g. Germany, will lead to increased utilization of the original infrastructure that was built prior to the expansion. Expansion can take place into regions that previously lacked ERS, to join disconnected ERS networks, or to densify the network in regions that already have some coverage.

Traffic is very unevenly distributed on the EU road network and as the ERS network expands, a point comes when no more sufficiently densely trafficked roads remain to be electrified. At this point, the cost of further infrastructure construction is greater than the sum of marginal increase in utility and expansion should stop. The road distance at which point this threshold is reached depends on the share of traffic that draws power from the infrastructure while driving on ERS-equipped roads. If the infrastructure only supports or is only sufficiently attractive to a subset of all traffic, total energy that can be delivered decreases and the optimal network size shrinks.

Based on geographically comprehensive road census data from 2005 (UNECE, n.d.) and simulation results that account for competition with diesel and other charging infrastructure types (Rogstadius et al., 2023), regions that can be ruled out from inclusion in an ERS network directly based on lack of traffic are limited to the northern parts of the Nordic countries and possibly some parts of Eastern Europe. We therefore assume a European ERS network would include major (TEN-T) roads in all countries. ERS-adapted vehicles are assumed to rely on static charging alone when operating far outside of the ERS network, or for regional trips where no major roads are utilized.

Several independent studies have analyzed hypothetical ERS introduction at national scale (e.g., France (Perdu et al., 2023), UK (Ainalis et al., 2022), Germany (Hacker et al., 2022), Sweden (Rogstadius et al., 2023), Denmark (Domingues-Olavarria et al., 2018), Turkey (Coban & Lewicki, 2022)), but we are not aware of any studies that have investigated a complete European network. Studies generally either assume as input or recommend from output ERS on road networks comparable in density and total length to either the national subsets of the TEN-T Core or Comprehensive networks (but not necessarily the same roads). These networks are shown in Figure 2-1, with total lengths of 48200 km (Core, excluding UK) and 132574 km (Comprehensive, excluding UK) (The EU Core Road Network: Shorter Travel Times but Network Not yet Fully Functional, n.d.). Studies that consider ERS for light vehicles generally assume denser ERS networks than studies that evaluate ERS only for heavy vehicles.

As we wish to evaluate ERS as a charging option for daily use, we also believe a dense ERS network is needed if the infrastructure is to contribute to electrification of substantial shares of all driven vehicle kilometers. Based on this, we model ERS for only heavy vehicles with the total road network length of the TEN-T Core network, and ERS for both light and heavy vehicles with the total length of the TEN-T Comprehensive network.

**Earliest Year of Availability**

The current absence of Electric Road Systems (ERS) in the Alternative Fuels Infrastructure Regulation (AFIR) poses significant challenges for their deployment in decarbonizing road traffic. Without ERS inclusion, member states implementing ERS must still establish additional static charging infrastructure, despite potential lack of demand. This could lead to inefficiencies and redundant infrastructure. Moreover, early adopters of ERS face the risk of adopting standards that may not align with future, broader networks, potentially affecting utilization rates. Therefore, ERS integration into AFIR seems essential for EU-wide implementation, with the earliest potential for formal decision-making being 2027, following AFIR’s planned revision in 2026.

Planning, procurement, and preliminary design of a full-scale Swedish ERS network has been estimated to take 7-10 years, as current capacity constraints make it difficult to complete construction. (Kenneth Natanaelsson, Swedish Transport Administration, private communication). Under normal administrative processes, we therefore consider that a comprehensive EU ERS network is unlikely before 2035, preventing any near-term contribution to GHG emission reductions. However, expedited procedures, akin to those during the global COVID-19 pandemic response, could increase overall administrative capacity and allow preparatory work to be initiated before ERS's inclusion in AFIR. With such measures, we estimate construction could begin as early as 2028. An ERS-specific amendment into AFIR, before the full revision, would significantly reduce project risk but may not translate into an earlier start date for construction.

ERS production in a small (500 m²) factory in Sweden is considered able to produce ERS tracks at a rate of at least 300 km/year, fully automated (Elonroad personal communication). A big factory (5000 m²) of the same type would thus be able to manufacture 3000 km ERS/year. If the TEN-T comprehensive network of 132574 km was to be covered within a period of five years (26500 km/year), it would require less than 10 such factories across EU to produce the ERS hardware. Thus, manufacturing capability is not likely to prevent a full TEN-T comprehensive network ERS deployment in five years.

Estimating the physical construction time for a European ERS is challenging, given the lack of large-scale precedents. Assuming that the TEN-T comprehensive network of 132574 km is maintained every 30 years, that
corresponds to 4400km/year. This indicates that installation of ERS on that network would require an effort in the order of four times the normal 30-year interval road maintenance.

It is unclear if raw materials and parts manufacturing will be available in sufficient quantities to not create a bottleneck for deployment. Electrical grid capacity may be a constraint but would only need to be upgraded at the rate of increased BEV traffic. The required increase of grid capacity for ERS and a fast-charging system are similar in the sense that they both must provide the energy needed for long distance road transport.

**Adoption Rate Once Available**

For both the pessimistic and optimistic transition curves for BEVs, approximately 50% of the light BEVs and 80% of the heavy BEVs in use in the EU by 2035 will have entered operation in 2030 or later (further discussed in section 6). Regional shares are lower in Nordic+ and Western Europe and higher in Southern and Eastern Europe, as more BEVs are sold in primary vehicle markets before 2030. If ERS is available from 2030, these are the upper bounds for utilization, unless BEVs sold before ERS construction are also retrofitted with ERS-specific components to be compatible with the new infrastructure. BEVs that are not ERS compatible would not be affected by the new infrastructure.

When estimating levelized ERS cost, we have assumed that utilization increases from zero to its maximum level over 20 years, i.e., from 2030 to 2050, to then remain at maximum level for the remaining assumed lifetime.

Steady-state (maximum) utilization is based on findings from simulations in (Rogstadius et al., 2023). These simulations considered interaction effects between static and dynamic charging in competition, with dynamic pricing based on use and charging behavior determined through agent-based cost-minimization. In analyzed scenarios that included ERS, approximately 50-75% of all energy consumed by BEVs (including non-ERS-compatible vehicles and non-ERS roads) was delivered via ERS. The simulations included only heavy vehicles.

No comparable sources have been identified for light-duty vehicles, forcing us to speculate. In the simulations for heavy-duty vehicles, charging at depots remained attractive even with ERS. The reason ERS charging reached such dominant shares was that cost-motivated battery capacity reductions also reduced the maximum energy that could be charged nightly at the depot. As passenger cars drive shorter daily distances than trucks, day-time charging is not required to the same extent if night-time charging is available. We therefore assume lower shares of ERS charging for light-duty than heavy-duty vehicles. As ERS charging emerges as a cost-competitive charging solution, and as night-time charging has proven to be challenging to provide in some neighborhoods, we still assume significant shares of total energy from ERS, should this infrastructure be built.

### 4.5 Hydrogen

**Table 4-7: Parameter values used in FCEV analysis. Omitted parameters have the same values as for BEV.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Pessimistic</th>
<th>Optimistic</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>km</td>
<td>900 000</td>
<td>1 300 000</td>
<td>Same as ICEV (Marcinkoski et al., 2019)</td>
</tr>
<tr>
<td>$C_{veh}$</td>
<td>€</td>
<td>200 000</td>
<td>140 000</td>
<td>See text</td>
</tr>
<tr>
<td>$C_{res}$</td>
<td>%</td>
<td>6%</td>
<td>12%</td>
<td>See text</td>
</tr>
<tr>
<td>$C_{init}$</td>
<td>€/km</td>
<td>0.25</td>
<td>0.13</td>
<td>See text</td>
</tr>
<tr>
<td>$C_{fu}$</td>
<td>€/kg</td>
<td>44.5</td>
<td>7.5</td>
<td>See text</td>
</tr>
<tr>
<td>$GHG_{fuel}$</td>
<td>kg/kg</td>
<td>7.4</td>
<td>1.3</td>
<td>See text</td>
</tr>
<tr>
<td>$F$</td>
<td>kg/km</td>
<td>0.07</td>
<td>0.05</td>
<td>(Basma et al., 2022; NPM, 2020)</td>
</tr>
<tr>
<td>$GHG_{veh}$</td>
<td>kg</td>
<td>177 010</td>
<td>48 100</td>
<td>See text</td>
</tr>
<tr>
<td>$C_{tot}$</td>
<td>€/km</td>
<td>1.69</td>
<td>0.64</td>
<td>Eq. 1</td>
</tr>
<tr>
<td>$GHG_{tot}$</td>
<td>kg/km</td>
<td>0.66</td>
<td>0.10</td>
<td>Eq. 2</td>
</tr>
<tr>
<td>Scalability</td>
<td>%</td>
<td>0%</td>
<td>6%</td>
<td>See text</td>
</tr>
</tbody>
</table>

Hydrogen in road transport is stored in vehicles and can be used for propulsion in I) hydrogen combustion engines or II) converted to electricity in a fuel cell and the electricity powers the electric drive system like in a BEV. Fuel cell vehicles are equipped with a battery to be able to recuperate energy from braking, and to support the fuel cell with additional power when required. The storage capacity of the battery is assumed to be lower than in a battery-electric vehicle.
In this analysis, we only model heavy-duty fuel cell electric trucks (FCET), as several manufacturers of heavy-duty vehicles are investing in such technology, with announcements of series production by the end of the 2020s (NOW GmbH, 2023). All parameter values represent possible means for the stock of rolling FCETs in 2035, of which we assume a majority will have been manufactured after 2030. Light-duty fuel cell electric vehicles are assumed to not contribute meaningfully to GHG emission reductions from EU road traffic by 2035, based on lack of consumer interest in available vehicle models, lack of interest among most vehicle manufacturers (NOW GmbH, 2023), and a recent international trend of shut-downs of hydrogen refueling stations for light vehicles. Light-duty fuel cell electric vehicles are therefore considered out of scope.

Today, hydrogen is produced almost exclusively via steam reformation from fossil methane, locally at the site where demand for the gas exists, e.g., in oil refineries and chemical plants. We assume so-called green hydrogen in this analysis, i.e., production using renewable electricity and a sustainable source of water.

### 4.5.1 Cost

Upfront vehicle costs for hydrogen fuel cell trucks are in several studies expected to decrease rapidly from €310 000-350 000 for a heavy-duty long-haul truck in 2021 (Noll et al., 2022), to €158 000-240 000 in 2030 (Basma et al., 2022; Burke et al., 2023; NPM, 2020). These forecasts have been extrapolated to assume further vehicle cost decreases by 2035, but actual prices are highly uncertain and high-volume production would be required for such cost reductions to materialize. High-volume production is only realistic if the total levelized cost, including fuel and maintenance, is competitive versus other available options. This does not appear to be the case, suggesting that we may be underestimating vehicle costs.

Several prior studies, e.g. (Basma et al., 2022; NPM, 2020), have assumed that maintenance costs of FCETs will be equal to or marginally higher than those of battery electric trucks. However, these figures appear to be based on originally weak assumptions that have become accepted in the scientific literature primarily through a chain of citations. In contrast, 20 years of trials of fuel cell buses and trains suggest maintenance costs have been approximately twice those of diesel vehicles and that costs have not decreased over time (Barnard, 2024b). In this study, we use U.S. Department of Energy assumptions on maintenance of interim diesel-electric hybrid technology at 25% above ICET levels (Marcinkowski et al., 2019), representing a substantial improvement over historical data from FCET trials but still accounting for the much greater powertrain complexity than in BETs.

Daimler Trucks achieved a fuel consumption of 7 kg H2/100 km with a prototype truck loaded to 40 tons in 2023 (Volker Hasenberg, personal communication). We believe the cited sources correspond to a reasonable improvement below this level.

Cost assumptions for green hydrogen sold at truck refueling stations are highly uncertain, reflected in a wide spread of estimates in the scientific literature. When searching for sources to use, we have strived to use only those that are transparent with their assumptions and calculations, and which together cover the full set of cost components contributing to the final refueling price. Different sources cover different cost subsets, which forces us to combine values from multiple studies in ways that may introduce errors.

In (Collis & Schomäcker, 2022), the authors estimate the combined cost of producing hydrogen at various locations around the world and transporting it using a range of options to a set of major cities on each continent. The lowest cost option for hydrogen delivered to Cologne, Germany, is determined to be by pipeline from electrolysis plants in southern France, at 7.6 €/kg. Excluding pipelines, which are not in place today and which are partially planned to be in place by 2030, the lower cost option is hydrogen produced in Egypt and delivered as liquid organic hydrogen compounds (LOHCs) by ship and road to Cologne, at 9.4 €/kg. Similar costs are seen for most of North Africa, South Europe and the area directly around Cologne. The study notes that resulting costs are in the upper range of prior work, and list what cost components they have included that each prior study did not account for (table 4), showing that the results are largely in agreement with prior work for the overlapping cost subsets. The study does not look at the cost of transporting hydrogen from the central point of import to refueling stations, or the stations themselves.

Several of the higher quality studies we have found indicate that electrolysis in or near the Iberian Peninsula offers the lowest total cost of delivered hydrogen. For electrolysis in Europe, Boston Consulting Group (Burchardt et al., 2023) estimates the cost to be 5-8 €/kg, a substantial increase from 3 €/kg in a prior BCG analysis from 2021. Researchers at the European Joint Research Center (Ortiz Cebolla et al., 2022) estimate the cost of transportation from an electrolysis plant to a network of refueling stations at approximately 2.5-3.5 €/kg (range of best alternatives), excluding equipment and energy at the refueling station. Together, these studies indicate a wholesale cost of hydrogen delivered at a central distribution hub at approximately 7.5-11.5 €/kg, which closely agrees with (Collis & Schomäcker, 2022).

Finally, in (Zhou & Searle, 2022), ICCT estimated the levelized cost of gaseous hydrogen refueling stations for heavy-duty trucks in Europe in 2030 to be approximately -3 €/kg, excluding the cost of the sold product. After consultation with an industry expert (Volker Hasenberg, personal communication), we reduce this to 1.5-3 €/kg.
under optimistic and pessimistic assumptions for 2035. Liquid hydrogen refueling may achieve lower station costs, but the cost of liquefaction must be added.

Adding up these figures, we arrive at a total cost of hydrogen refueling at approximately 9 to 14.5 €/kg, of which the higher value is our pessimistic assumption for \( C_{\text{fuel}} \). Gaseous green hydrogen sold today at refueling stations in Germany falls within this range, though it is subject to various subsidies.

A thorough analysis of the levelized cost of on-site hydrogen electrolysis at a refueling station with a grid-connected PV plant in Italy (Minutillo et al., 2021) arrived at total costs of 9.3-11.5 €/kg, for stations with 50-200 kg/day capacity. Extrapolating the cost estimates to 800 kg/day average sales yields a levelized cost of hydrogen around 7.5 €/kg, which is our optimistic assumption for \( C_{\text{fuel}} \). Hydrogen refueling stations mandated by AFIR must have a capacity of at least one ton per day, but it is unclear to us if this capacity takes daily and annual demand curves into account, or if it is nameplate capacity as for wind farms.

A member of our reference group has raised concerns that the JRC study underestimates the maintenance costs of a pipeline system for long-distance hydrogen transportation, and that the ICCT study greatly underestimates the maintenance costs of hydrogen refueling stations (Barnard, 2024a). While it appears to be correct that the studies assume far lower costs than have been seen in real installation in the past two decades, we have been unable to ascertain how maintenance costs will develop in the future and we have therefore not adjusted the figures assumed in the cited studies. Another reference group member has recommended we use costs in the 5-8 €/kg range for hydrogen sold at refueling stations. While many studies assume similar or even lower values, we deem the cited sources to be the most credible and complete among those we have been able to go through. A potential source of error is that several cited sources estimate costs in 2030, rather than 2035. While this suggests some opportunities for cost reductions due to technical advancement are possible, levelized costs in the cited studies depend primarily on estimated production and sales volumes, rather than calendar year. Assumptions in these studies are in the order of magnitude of 100 kiloton per year for production and delivery using non-pipeline pathways, 1000 kiloton per year for delivery via pipeline, and 300 ton per year sold at a single refueling station.

### 4.5.2 Greenhouse Gas Emissions

Embodied GHG emissions from vehicle production have been estimated for the fuel cell stack, hydrogen tanks, battery, and remaining vehicle. Values used are: 200-300 kW fuel cell power at 24-34 kg CO₂-eq/kWh (Yeow et al., 2022); 1000-1500 km range on hydrogen, resulting in 50-105 kg tank capacity, at 277-1002 kg CO₂-eq/kg capacity (Yeow et al., 2022); 150-350 kWh battery capacity, at the same emissions levels as for battery-electric vehicles. For the remaining vehicle, the same base emissions are used as for combustion engine vehicles.

We account for three sources of GHG emissions from hydrogen use: electricity input for electrolysis, energy input for transportation, and leakage. Electrolysis is assumed to use sustainable energy production from solar and wind, complemented by local energy storage or a small share of grid energy, with an electricity consumption of 51-64 kWh/kg hydrogen. This is based on a lower heating value for hydrogen of 33-33 kWh/kg and 5% efficiency improvements above 2018 state of the art nominal system efficiencies for AEL (51-60%) and PEMEL (46-60%) electrolysis plants, and excluding annual efficiency degradation (Buttler & Spletichoff, 2018). Lacking better sources, we use a range based on the CO₂ intensity of the Swedish electricity mix at 26 g CO₂-eq/kWh (Energimyndigheten, 2023), as less than 10% of this mix is from combustion sources, mostly biofuels and household waste. This assumption is aligned with our assumptions on the cost and scalability of green hydrogen, detailed above and below. If a much greater supply of hydrogen was assumed, we would also need to increase emissions to include production from less sustainable pathways.

No transportation related GHG emissions are assumed for local hydrogen production at the refueling station. In the pessimistic case, CO₂ emissions equivalent to 0.4 kWh of EU electricity mix are added for every kWh (LHV) of imported hydrogen. This is based on findings that the total required energy input throughout the different possible distribution chains is 40-160 MJ/kg, to be compared with the lower heating value of hydrogen at 120 MJ/kg (Ortiz Cebolla et al., 2022). As a significant amount of this energy needs to be supplied within Europe (assuming transportation by pipelines and/or trucks), the energy can be taken from the hydrogen being imported or from EU electricity production. We assume EU grid mix is used, as this results in lower total emissions than if the energy is taken from the imported hydrogen. A noteworthy implication of this is that hydrogen imports via pipeline do not substantially reduce Europe’s need to produce or import electricity.

Hydrogen is not a direct greenhouse gas, but its chemical reactions change the abundances of the greenhouse gases methane, ozone, and stratospheric water vapor, as well as aerosols, with a global warming potential over 100 years of 9–14 times that of CO₂ (Sand et al., 2023). Reviews of different studies that have studied leakage rates for different steps in the hydrogen value chain, from electrolysis, via pipeline, ships or trucks, to refueling stations and use in heavy duty vehicles, have identified a wide spread of leakage rates for different pathways. We assume an optimistic 3% total leakage rate for on-site electrolysis at the refueling station and sales of gaseous hydrogen, and a pessimistic 10% for long-distance imports of gaseous hydrogen via pipeline, and local distribution to refueling.

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stations via truck (Fan et al., 2022). Liquid hydrogen pathways appear to have potential for leakage rates up to 20%, due to difficulties containing boil-off (Esquivel-Elizondo et al., 2023).

4.5.3 Scalability
The EU hydrogen economy is still in its infancy and the capacity to generate, distribute and consume hydrogen in road transport applications is virtually non-existent today. Thus, as for Electric Road Systems, we must carefully consider several factors that may restrict how extensively of this technology can be scaled until 2035.

The EU’s Alternative Fuels Infrastructure Regulation (AFIR) stipulates in Article 6 that one gaseous hydrogen refueling station (HRS) every 200 km on the TEN-T core network by the end of 2030, as well as one HRS in every of 424 urban nodes. The stations shall have a daily minimum supply capacity of one ton of hydrogen for both light and heavy vehicles (AFIR, 2023). Many stations in urban nodes should also count towards the distance-based requirement. With approximately 500 stations and 55% average daily utilization rate, this corresponds to a total refueling capacity of 100 kilotons of hydrogen per year, which is also our pessimistic assumption for scalability. Our optimistic assumption is that refueling capacity has grown tenfold from 2030 to 2035, to 1 Mt (million tons) per year.

The EU has a stated ambition to produce 10 Mt of renewable hydrogen and import 10 Mt by 2030 (European Commission, 2022). Reaching this ambition would require electrolysis capacity both inside the EU and in exporting countries to grow significantly quicker than solar PV installations have ever done historically (Odenweller et al., 2022). There are few signs the target quantities will be reached before 2035. Five percent of this total supply is thus assumed to get to road transport, plus some share for hydrogen used in e-fuels.

According to version 5 of the Hydrogen Ladder (Liebreich, 2023), uses of green hydrogen with greater merit than long-haul trucks include fertilizer, hydrogenation, hydrocracking, desulphurization, methanol, e-fuels for shipping and jet aviation, steel, chemical feedstocks, long-duration grid balancing, biogas upgrading, and non-road mobile machinery. How much hydrogen could be used in these sectors by 2035? The industrial use of hydrogen today is approximately 10 Mt/y [3], which includes fertilizer, oil refining, methanol production and chemical feedstocks. Virtually all hydrogen today is manufactured onsite from fossil fuels. According to the EU Renewable Energy Directive [26], 60% of industrial hydrogen use must be green hydrogen by 2035. Other uses are in addition to current demand. The EU produces steel at ~150 Mt/year and 1 ton steel requires 50 kg hydrogen [8], for a total potential of 7.5 Mt/y. EU shipping and aviation use approximately 80 MTOE (million tons of oil equivalent) per year (Eurostat, 2023a). With 42 GJ per TOE, 120 MJ per kg hydrogen and 60% conversion efficiency to e-fuels, shipping and aviation has a demand potential of 46 Mt/y of hydrogen. Energy storage for grid balancing has unknown demand potential, but if we assume 20 Mt/y, the total demand potential excluding road traffic is around 75 Mt/y, which clearly surpasses supply by 2035. Assuming a greater than 1 Mt/y supply for road transport seems unsupported, when options with both lower emissions and cost are available for road transport but not the other listed sectors.

At 5-7 kg/100 km and our estimated total annual 336 billion km for heavy road transport, 1 Mt/y corresponds to 4-6% of all heavy road traffic by distance. The AFIR targets correspond to approximately 0.5%. We assume public hydrogen refueling stations will deliver the bulk of all hydrogen to road vehicles, and that private refueling capacity will be limited by 2035.

4.6 RFNBO

Table 4-8: Parameter values used in RFNBOs (e-fuels) analysis.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Light vehicles</th>
<th>Heavy vehicles</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{fuel} )</td>
<td>€/liter</td>
<td>Pessimistic</td>
<td>Optimistic</td>
<td>Pessimistic</td>
</tr>
<tr>
<td>( C_{fuel} )</td>
<td>kg/liter</td>
<td>1.8</td>
<td>1.2</td>
<td>1.8</td>
</tr>
<tr>
<td>( C_{fuel} )</td>
<td>€/km</td>
<td>0.77</td>
<td>0.35</td>
<td>1.94</td>
</tr>
<tr>
<td>( GHG_{fuel} )</td>
<td>kg/km</td>
<td>0.14</td>
<td>0.08</td>
<td>0.52</td>
</tr>
<tr>
<td>Scalability</td>
<td>%</td>
<td>0%</td>
<td>1%</td>
<td>0%</td>
</tr>
</tbody>
</table>

Renewable fuels of non-biological origin (RFNBO), also known as electro-fuels, or e-fuels, are fuels synthesized using renewable sources of hydrogen and carbon. Within the scope of road transport, the primary e-fuel is synthetic diesel, which can be used as a drop-in fuel in the existing vehicle stock.

(Herz et al., 2021) estimate a production cost of RFNBOs from Fischer-Tropsch synthesis using two different methods at 0.43 and 0.46 €/kWh\textsubscript{LHV} in 2020, forecast to decrease to 0.26 and 0.20 €/kWh\textsubscript{LHV} and 0.20-0.26 in 2050. We assume 0.34 €/kWh\textsubscript{LHV} in 2035, add 20% for inflation to 2023 monetary value, add
10% for distribution and profit, multiply by 10 kWh/liter, and finally add a 10% spread around the mean to get an optimistic and pessimistic range.

Emissions intensities for lifecycle RFNBO production, distribution and use are taken from (Zang et al., 2021).

Concerning availability and scalability of RFNBOs, similar arguments apply as for hydrogen. Sustainable RFNBO production requires as input sustainable sources of hydrogen, competing with direct hydrogen use, and carbon (e.g., CO₂, CO, or ethanol). Global production capacity of hydrocarbons produced from green hydrogen can per definition not surpass global production of green hydrogen, and substantial additional investments are required in refinement infrastructure and supply chains for sustainable carbon. One advantage compared to hydrogen is that existing infrastructure for import of liquid fuels to Europe can be reused. We assume the same pessimistic and optimistic scalability of RFNBOs as for hydrogen, but with supply spread over all vehicle segments rather than only heavy vehicles. Scalability is not constrained by distribution infrastructure in the same way that hydrogen is, but the same concerns apply regarding the merit of using green hydrogen in road transport.

4.7 Estimate of Vehicle Kilometers in 2035

To estimate future total GHG emissions from EU road traffic, we need both emissions per method of propulsion, the share of traffic per propulsion method, as well as total annual driven distance. We have been unable to find direct sources for annual driven distance per EU country. We have therefore derived total driven distance for light and heavy vehicles per EU-country from Eurostat’s compiled 2021 national statistics on CO₂ emissions from road traffic, in turn estimated based on national sales of combustion fuels. Estimating distance based on CO₂ emissions has the advantage of ensuring that total GHG emissions in our model correspond to real-world totals.

Annual emissions data per country were provided for cars, light-duty trucks and heavy-duty trucks and buses. Data for motorcycles were discarded. Data were complete except for Finland, for which total emissions were imputed based on assuming the share of each vehicle groups is the same as for Sweden. Conversion from CO₂ to km was performed using the figures in Table 4-9. CO₂ per liter in 2021 are weighted estimates based on shares of petrol and diesel vehicles in each segment and biofuel use. Liter per km in 2035 is estimated based on 2021 fuel efficiencies and 1% reduction per year. Because homogeneous national figures for total annual distance statistics could not be found, we have compared estimated national distances to official figures on either total distance driven on the national road network, or total distance driven by vehicles registered in the country, in weight groupings that may not perfectly align with those we use. The figures appear to be within 10% of correct values for light traffic. We marginally underestimate heavy traffic intensities, as we assume all traffic consists of heavy-duty trucks, which have higher fuel consumption than medium-duty trucks. As we draw conclusions based on total CO₂ and not total distance driven, this should not introduce errors in our analysis.

Table 4-9: Conversion factors from CO₂ to driven distance.

<table>
<thead>
<tr>
<th></th>
<th>Cars</th>
<th>Light-duty trucks</th>
<th>Heavy-duty trucks and buses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil CO₂ kg/km 2021</td>
<td>0.15</td>
<td>0.20</td>
<td>0.75</td>
</tr>
<tr>
<td>Fossil CO₂ kg/liter</td>
<td>2.35</td>
<td>2.50</td>
<td>2.54</td>
</tr>
<tr>
<td>Liter/km 2021</td>
<td>0.064</td>
<td>0.080</td>
<td>0.295</td>
</tr>
</tbody>
</table>

Relative change in total driven distance between 2021 and 2035 was assumed to be equal in all countries, and using trends from (European Commission, 2024a), were set to 10% total increase for light vehicle traffic and 20% total increase for heavy vehicle traffic. Final estimated annual distances per vehicle category and EU region are listed in Table 4-10.
Table 4-10: Estimated total driven distance in 2035 per vehicle group and EU region, in billion km per year.

<table>
<thead>
<tr>
<th></th>
<th>2021</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heavy duty</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nordics+</td>
<td>23</td>
<td>28</td>
</tr>
<tr>
<td>Western Europe</td>
<td>126</td>
<td>152</td>
</tr>
<tr>
<td>Southern Europe</td>
<td>57</td>
<td>68</td>
</tr>
<tr>
<td>Eastern Europe</td>
<td>74</td>
<td>89</td>
</tr>
<tr>
<td><strong>EU-27</strong></td>
<td><strong>280</strong></td>
<td><strong>336</strong></td>
</tr>
<tr>
<td><strong>Light duty</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nordics+</td>
<td>293</td>
<td>322</td>
</tr>
<tr>
<td>Western Europe</td>
<td>1,408</td>
<td>1,548</td>
</tr>
<tr>
<td>Southern Europe</td>
<td>918</td>
<td>1,010</td>
</tr>
<tr>
<td>Eastern Europe</td>
<td>735</td>
<td>808</td>
</tr>
<tr>
<td><strong>EU-27</strong></td>
<td><strong>3,353</strong></td>
<td><strong>3,688</strong></td>
</tr>
</tbody>
</table>
5 Technology Comparison

We expect market forces to gradually push for a transition towards lower-cost technologies. This section provides a comparison of the per-technology levelized costs and GHG intensities identified in the previous section. Combinations of technologies, such as blending biofuels or e-fuels with fossil fuels, or using combinations of different charging methods, will result in costs between those we present, at ratios proportional to the combinations used.

There is an important distinction between cost and price. Prices may differ from costs when market competition either permits greater than assumed margins, or when losses are accepted for strategic reasons. Prices are also affected by subsidies and other forms of price-altering policy instruments. Prices are what ultimately affect demand.

5.1 Light-Duty Vehicle and Energy Costs

By the early 2030s, light vehicle ICEVs and BEVs are expected to have similar purchase costs. However, because we consider the risk that policy incentives will bring about a reduction in lifetime distance for ICEVs, our pessimistic assumption for levelized vehicle cost is higher for ICEVs than BEVs. Maintenance costs are expected to be substantially lower for BEVs than ICEVs, in particular in older vehicles for which maintenance costs are higher than in new vehicles (and value depreciation lower). The wide ranges of vehicle costs in Figure 5-1 primarily capture the cost differences of owning vehicles in the premium versus budget segments.

For all evaluated technology pathways for light vehicles, the levelized lifecycle transport cost is on average dominated by the cost of the vehicle itself, with maintenance and fuel costs of less significance (the only exception being RFNBOs). Budget-segment vehicles are expected to fall near the bottom of the ranges for vehicle and maintenance costs, resulting in energy or fuel costs making up a larger share of the total cost of ownership.

Fuel and energy consumption is largely dependent on vehicle weight, while ICEV fuel costs are primarily dependent on CO2 valuation and global oil prices. Unlike liquid fuels, charging costs for BEVs are expected to exhibit significant variations within regions and at different times of day. Charging cost increases with lower charger utilization rates, higher electricity prices at the time of charging, and site-specific factors such as low prior electrical grid capacity and high land value and costs of digging.

Due to our higher-than-present assumed 2035 CO2 cost of 100–250 €/ton, we arrive at similar costs of biofuels and fossil fuels. Of the 0.06–0.14 €/km energy cost of fossil fuels, 0.02–0.05 €/km is the cost of carbon. Electrofuels (RFNBOs) are not expected to reach a competitive price point by 2035.

We find no significant difference in vehicle-related costs for statically and dynamically charged BEVs. This is despite our assumption that battery capacity is approximately half for ERS-equipped vehicles. The reason is that additional ERS-related components required to charge dynamically partially cancel out the reduction in upfront vehicle cost, and that vehicle maintenance cost is increased due to wear and tear on the ERS pickup. We have modeled the costs of road-bound conductive ERS technology.

Energy-related costs differ significantly between the BEV charging alternatives. While ERS appears to have potential to offer the lowest charging cost, we emphasize that this is under the assumptions of deployment on a road network of length equivalent to the full TEN-T Comprehensive network (approximately 130,000 km), as well as using a simplified method of cost leveling in which both costs and delivered energy are summed across Europe. Calculations performed on national road networks may arrive at other levelized costs, with higher costs expected for ERS networks that receive revenue only from traffic in countries with below-average population density. ERS charging costs are not expected to decrease further for regions with high population density, as grid and energy costs dominate at high rates of utilization.

In relative terms, the charging cost differences become much more pronounced for owners of used low-cost vehicles than new premium vehicles. However, it is difficult to speculate if the magnitude of cost differences is large enough to influence behavior, as we are not aware of any research into how EV owners respond behaviorally to differences in charging costs. We are also not aware of any research into the extent to which ERS on urban main roads could functionally replace near-home night-time charging of passenger cars, or for which population groups this could be an attractive option. We see no obvious reason why either of the two alternatives should be preferable in the general case, given equal pricing.
Figure 5-1: Distance-levelized lifecycle costs of light-duty vehicles. Total cost is dominated by depreciation of vehicle value. Cost variability is dominated by vehicle price segment.

5.2 Heavy-Duty Vehicle and Energy Costs

In contrast to light-duty vehicles, the cost picture for heavy-duty vehicle operation is dominated by energy-related costs, which are for most technologies greater than the sum of levelized vehicle cost and maintenance. Both energy/fuel and total levelized costs for statically charged battery electric trucks are approximately 15% below their ICE counterparts (excluding e-fuels). Charging costs with dynamic charging via ERS are expected to be a further 20% below static charging, resulting in 13% reduction in total levelized costs compared with static charging. Given that haulier profit margins are typically below 5%, the relative cost reductions from ICEV to BEV and BEV to ERS-BEV are large enough that they should drive very rapid adoption of the new technologies in regions where they become logistically viable options.

As for light-duty vehicles, savings on vehicle cost from battery capacity reduction are cancelled out by the cost of additional ERS-specific parts and increased cost of vehicle maintenance. A slight reduction in fuel consumption due to reduced vehicle weight does however contribute to reduced charging costs.

Green hydrogen is not expected to constitute a cost-competitive alternative for heavy-duty trucks by 2035, with all the assessed pathways from hydrogen production to vehicle resulting in prohibitively high costs in the absence of subsidies. Total levelized costs for operating fuel-cell electric trucks in 2035 are expected to be double those of battery electric trucks, entirely due to the high cost of getting green hydrogen to the trucks. With a mix of battery charging from the grid and hydrogen refueling, total costs would fall somewhere in between the estimates for the two modes. The hydrogen fueling costs we present are significantly higher than estimates presented in several other recent studies (e.g., (Basma & Rodríguez, 2023; Bracci et al., 2024; NPM, 2020)). This is explained by that different sets of primary sources of parameter values have been used in the different studies. We believe the cost estimates presented here are representative of the full cost picture and we refer to section 4.5 for details.

As for light-duty traffic, e-fuels (RFNBOs) are not expected to reach a competitive price point by 2035.
5.3 Vehicle Conversions

Conversions of ICEVs to BEVs involve removing parts related to the ICE powertrain, and installing the corresponding electric powertrain parts including a battery. In the next section that discusses the extent to which different technologies may enable decarbonization of EU road traffic, we will discuss the emissions reduction potential of such conversions.

A vehicle conversion requires an investment in new parts and labor to perform the conversion, and replacement of parts results in a change of the vehicle’s weight. For the conversion to be technically feasible, the weight of the added parts cannot differ too much from the weight of the removed parts. For the conversion to be economically feasible, the investment cost should not be greater than the expected savings resulting from the conversion over the vehicle’s remaining useful life. The cost of the conversion should also be competitive compared to purchasing a new electric vehicle.

It is not within the scope of this study to provide an in-depth evaluation of the viability of vehicle conversions. However, we provide a starting point for future research with Table 5-1 listing estimated costs of new vehicles, estimated costs of powertrains (including batteries) used in conversions, and the differences between expected ICE and BEV energy and maintenance costs, summed over half the vehicle’s expected lifetime distance. The energy consumption of converted BEVs is assumed to be 25% greater than for new BEVs, based on personal communication with Nils-Gunnar Vågstedt (Scania). The listed values are for year 2035 and do not include other conversion costs than powertrain parts and batteries. The table also assumes that powertrains installed in converted vehicles have the same costs as powertrains in new vehicles. As the distribution of ICE powertrain maintenance expenses are heavily skewed towards the second half of the vehicle lifetime, these costs have been increased by 25% over the assumed lifetime average values.

The figures in the table suggest that in the scenario with only static charging, the cumulative reductions in included operating expenses (OPEX) over half the vehicle’s lifetime distance would not fully pay for a new electric powertrain (including battery). Vehicle weights increase, but it is unclear if the increases are acceptable or too large. In the scenario with ERS, OPEX savings are 60-80% of powertrain costs for light-duty vehicles and 130-180% for heavy-duty vehicles. While the figures are very uncertain, the results suggest that an attractive business case is easier to achieve with ERS than without, and easier for heavy-duty vehicles than light. Concerns about weight changes are likely fully addressed.
The vehicle cost and weight savings follow from a well-established conclusion in the scientific literature that ubiquitous access to dynamic charging via ERS leads to a reduction in installed battery capacity per vehicle by approximately 50%.

While the EU largely relies on importing battery cells or precursors today, 0.7 TWh of EU annual battery cell production is likely to be in place by 2030, with potential for a further 0.6 TWh by the same year (Transport & Environment, 2023). The EU is also expected to source 50% of domestic demand for refined lithium from domestic suppliers by 2030 (Transport & Environment, 2023). At 100% BEV ratio of new sales, EU road transport will require annual battery production of approximately 1.3 TWh installed capacity (estimated based on annual new vehicle registrations and model assumptions of per-vehicle battery capacity). If vehicle conversion industry takes off with 4% of the EU vehicle stock converted annually, annual battery demand would double during the transition period. An annual demand of 2.6 TWh installed battery capacity by 2035 would be very challenging from a battery supply perspective. Reducing the battery capacity per vehicle by approximately half would make vehicle conversions much more viable also from a battery supply perspective.

5.4 Levelized GHG Emissions

Light vehicles operated on pure biofuels achieve approximately the same lifetime emissions as battery-electric vehicles. However, as biofuels are supply-limited, a vehicle owner that switches from biofuels to BEV still contributes to lower total GHG emissions, as the biofuels will be used by others to displace remaining consumption of fossil fuels. Any use of fossil fuels or hydrogen, in fuel cells or as e-fuels, will generate much greater GHG emissions than if the vehicle is battery electric. Even if emissions-free electricity is used for hydrogen production and grid electricity is used for charging, hydrogen leakage alone is expected to contribute substantially to global warming. Leakage is only assumed to be acceptably low for on-site electrolysis at refueling stations selling compressed gaseous hydrogen and for gaseous hydrogen transported directly between production and retail via pipeline.

For both light-duty and heavy-duty BEVs, embodied emissions from vehicle production are greater than lifetime emissions from consumed electricity, and if all of EU road traffic was electric, remaining lifecycle emissions would be dominated by embodied emissions from production of light vehicles. Most of emissions from vehicle manufacturing are related to the battery pack production, despite assumptions of reduced production emissions over the coming decade. As ERS contributes to battery pack capacity reductions per vehicle, the technology also contributes to reduced lifetime emissions from individual BEVs. However, to achieve net neutrality for the road transport sector, emissions from steel and battery supply chains must be urgently addressed.

Hydrogen can substantially contribute to reduction of road transport GHG emissions if it is used as a range extender that enables vehicles that would otherwise be running on combustion fuels to switch most operation to direct electrification. The same holds true for electric vehicles with combustion engine range extenders. Given the very limited supply of low-emissions hydrogen, using the fuel for more than a minority share of a vehicle’s operations is not advised, as greater shares would be better spent displacing use of grey or black hydrogen in other sectors of the economy.
We see little reason to doubt BEVs will fully replace ICEVs among newly sold heavy-duty vehicles, due to very substantial cost savings, and the speed of the transition depends largely on the time required to ensure comprehensive coverage of charging infrastructure (Rogstadius et al., 2023). As FCEV costs still remain uncompetitive in 2035, any substantial growth in market share for FCEVs would take place beyond 2035, meaning that costs and GHG emissions from FCEVs should be compared to the baseline of BEVs, rather than ICEVs. A replacement of BEVs with ICEVs would be a highly undesirable development due to the substantial increase in GHG emissions this would result in.

RFNBOs, or e-fuels, offer a reduction in GHG emissions if used as a drop-in fuel for existing ICEVs. However, given the high cost, both use and investments in RFNBO production seem unlikely at scales that would meaningfully contribute to decarbonization of road traffic.

![Figure 5-3: Distance-levelized lifecycle fossil GHG emissions per technology for light-duty (top) and heavy-duty (bottom) vehicles. 100% on the vertical axes correspond to 0.21 kg/km for light-duty vehicles and 0.88 kg/km for heavy-duty vehicles. Note that expected relative emissions reductions from electrification are significantly greater for heavy-duty than light-duty vehicles. Note also that all green hydrogen used in road transport, directly or as e-fuels, could instead have been used to displace fossil fuels or fossil hydrogen in other sectors where electricity is not a viable replacement. This means that the GHG reduction levels indicated here for hydrogen and e-fuels are overestimates from an expanded system perspective.](image-url)
6 Potential for Sectoral GHG Emissions Reductions

At the onset of this study, the authors assumed multiple pathways were available for the EU to reduce emissions from road traffic. This turned out not to be the case. All the assessed technologies together still cannot displace all fossil fuel use in the EU by 2035. Among the technologies, BEV is the only decarbonization pathway that emerges as scalable to significant shares of traffic within the critical coming decade. We therefore only present two future scenarios: with Default BEV uptake, and with Increased BEV uptake. These scenarios were defined in sections 4.3.3 and 4.4.3 and are summarized here.

In the Default BEV uptake scenario, electric vehicles enter the vehicle stock through sales of new vehicles. The BEV share of new light-duty vehicle reaches 100% between 2031 and 2035 in the different EU regions. The BEV share of new heavy-duty vehicles reaches 100% by approximately year 2040. This scenario does not include electric road systems (ERS).

The Increased BEV uptake scenario assumes 100% BEV share of new sales is reached two to four years earlier. The scenario also includes conversion of used ICEVs to BEVs, starting from 2030. The scenario includes a pan-European ERS network from year 2030 and vehicles are assumed to be ERS adapted if they enter the vehicle stock between 2030 and 2035. This includes both new sales and conversions and results in shares presented in Figure 6-1. Retrofitting existing BEVs with equipment to charge from ERS could potentially improve cost of operation but would likely not affect GHG emissions in any meaningful way.

The emissions calculations presented in this section are not specific to ERS, but the authors are not aware of any other pathway with equivalent expected effects. The feasibility of establishing an EU-wide ERS network by 2030 is discussed in the next section.

Biofuels, e-fuels and hydrogen are all used at their full scalability potential. Means of optimistic and pessimistic estimates are used for scalability and levelized GHG emissions. Use of biofuels and e-fuels is distributed based on ICEV use, but this distribution does not affect total EU emissions. Hydrogen is distributed evenly across the regions. Remaining traffic not covered by any of the decarbonization options is assigned to fossil fuels.

![Maximum ERS-adapted share of 2035 BEV traffic](image)

**Figure 6-1:** Assumed shares of ERS-adapted BEV traffic in the accelerated BEV scenario. These are optimistic shares based on that all BEVs entering operation from ERS start of operation are ERS adapted. If an ERS network is built, but start of operation is later than 2030, shares in 2035 will be significantly lower.

Resulting shares of traffic for each technology in each EU region 2035 are presented in Figure 6-2 (left). The difference between the scenarios with default and increased BEV uptake is indicated by grey bars (BEV potential), with this share allocated to fossil fuels in the default scenario. With default BEV uptake, high sales shares have resulted in 60—73% electrified light-duty traffic in the Nordics and West Europe. Heavy-duty traffic is still mostly combustion engine driven across Europe. Only 17% of light-duty traffic and 4% of heavy-duty traffic in East Europe has transitioned to BEV, as these markets are dominated by used vehicles.

Three main effects are assumed in the increased BEV uptake scenario with an EU-wide ERS network deployed in 2030: 1) new vehicle sales are expected to reach 100% BEV a few years earlier (i.e. 2030), 2) conversion of the rolling stock of ICEVs to BEVs begins in 2030, and 3) the levelized lifecycle GHG intensity of BEVs is reduced. All three effects follow from an ERS-enabled reduction of installed battery capacity per electric vehicle by approximately 50%, and all three contribute GHG emissions reductions of similar magnitude. See section 5.3 for a discussion about how ERS facilitates vehicle conversions by resolving cost, weight and battery supply barriers. BEV adoption is furthermore facilitated by more total charging infrastructure getting built than if only static charging is deployed. These effects together result in greater marginal benefits from ERS availability for late than early adopters of BEVs (Rogstadius et al., 2023).
While Figure 6-2 does indicate that a 2030 EU-wide ERS network would rapidly accelerate the transition to BEVs in all regions, in particular those with a limited inflow of new vehicles, fossil fuels still power 50% of traffic in East Europe by 2035 even if an ERS network is built.

Figure 6-2: Left: Estimated shares of EU road traffic (vehicle kilometers) per method of propulsion in 2035. Right: Resulting GHG emissions when compensating for total distance driven vehicles in each EU region. Emissions estimates represent levelized lifecycle emissions. With the default assumption about BEV uptake, the sum of emissions from fossil fuel use equals the sum of Fossil fuels, BEV potential and Avoidable. In our optimistic scenario for BEV uptake, 100% BEV share of new vehicle sales has been reached earlier, and vehicle conversions have been enabled by EU-wide ERS buildout. The marginal increase in BEV emissions is indicated by BEV potential and resulting emissions reductions are indicated by Avoidable.

Figure 6-3: Annual and remaining cumulative GHG emissions based on European Environment Agency estimates and our analysis. Yellow bars indicate means between pessimistic and optimistic estimates, with ranges indicated by black error bars. See caveats about cumulative emissions estimates after 2035 in the main text. Thick black bars indicate approximate ranges of scientifically advised maximum GHG emissions to keep global warming below 1.5 degrees.

Resulting annual and cumulative GHG emissions in the Default BEV uptake and Increased BEV uptake scenarios are indicated in Figure 6-3. For reference, the figure also includes road transport GHG estimates from EEA (European Environment Agency, 2023a), with ranges indicating the spread between existing and additional policy measures. The model estimate for 2021 equals the EEA value, as total annual distance and fuel consumption rates were derived from 2021 emissions data. EEA forecasts indicate that annual tailpipe GHG emissions from road transport by 2050 will still be 36-59% of 1990 levels, suggesting that an early phase-out of fossil fuels is not expected by the EEA.

As EEA only reports estimated tailpipe emissions, an attempt was made to convert these to lifecycle emissions using conversion ratios calculated from the model used in this study. Conversion ratios for light and heavy traffic were combined as total GHG-weighted averages. Pessimistic 2035 parameter values were used in place of data for 2021. Assumed BEV shares of 25% and 5% were used when converting 2035 estimates. At total vehicle stock level,
embodied fossil GHG emissions were estimated to be 39% above tailpipe emissions in 2021, 41% above tailpipe emissions in 2035 with a lower BEV shares assumed for the EEA forecast, and 60-80% greater than tailpipe emissions with model-estimated BEV shares without and with ERS.

Under Default assumptions about BEV uptake, our forecast is that total annual GHG emissions from manufacturing and use of EU road vehicles will have decreased by 17±18% from the 1990 level by 2035. The forecast decreases to 36±16% below the 1990 level if an EU-wide ERS network becomes operational by 2030. The ESABCC recommends that GHG emissions from the entire EU economy are reduced by 77-87% below 1990 levels by 2035 (European Scientific Advisory Board on Climate Change, 2023). We cannot see any way to achieve this magnitude of reduction through adoption of available technological options.

Cumulative emissions 2021-2035 were estimated based on assumed linear decline. Remaining cumulative emissions after 2035 for the two BEV scenarios were estimated by sampling total BEV uptake from the model for intermediary years until 2045, re-calculating total resulting emissions (without altering technology parameters or tailpipe to lifecycle scale factors), and extrapolating the resulting GHG reduction trends to find the year when zero is reached. See Figure 6-4. Linear extrapolation was used, to make results comparable with EEA forecasts. The long-term cumulative estimates should be considered indicative only, as the data collected during the literature review is insufficient to properly estimate when zero embodied fossil GHG emissions from vehicle production can be reached. Still, these estimates implicitly account for that earlier elimination of fossil fuels and reduced total demand for vehicle batteries will both make it easier to reach net zero.

Based on the EEA forecast for 2035, remaining GHG emissions until 2050 from EU road transport are approximately 23±1 Gt CO₂eq. As noted, the EEA forecasts further emissions beyond 2050. Remaining cumulative fossil GHG emissions in our Default BEV uptake and Increased BEV uptake scenarios are 22±2 and 17±2 Gt CO₂eq, respectively. Zero fossil tailpipe emissions is assumed to be reached when around 90% of traffic is BEV, with the remainder covered by other sustainable fuels. Only the increased BEV scenario reaches 100% BEV share of traffic by 2050. As the GHG footprint of BEVs predominantly consists of embodied emissions from vehicle manufacturing, cumulative emissions with high BEV uptake depend primarily on the rate at which steel, battery and electricity production can be decarbonized.

Estimated cumulative remaining GHG emissions from EU road transport should be compared to the EU remaining carbon budget from 2020 onwards of between -10 and +27 Gt CO₂eq. Regardless of how the global budget is allocated and how sectoral boundaries are drawn, we conclude that it is highly unlikely that EU road transport will not overshoot its fair share by a wide margin.

The only way to bring remaining cumulative fossil emissions down near the budget is to reduce annual lifecycle emissions to near the ESABCC recommended level by 2035. Drastic reductions would be required in both the size of the passenger car stock and total transport demand (both passenger and freight), as emissions come from both vehicle production and use. Our literature review concluded that such reductions are very unlikely unless costs of both vehicle ownership and use are raised substantially through policy measures, perhaps 100-200%. We also reiterate that we see no way for e-fuels or hydrogen to contribute meaningfully to GHG reductions within this timeframe. Biofuels are already in use and their use should continue, but supply is unlikely to increase significantly beyond current quantities. Retrofitting of combustion engine vehicles with electric powertrains will be required to achieve emissions reductions in South and East Europe and our analysis suggests that very rapid buildout of a pan-European ERS network is required for this to be feasible from a technical, economic and battery supply perspective. We estimate that an EU-wide ERS network entering operation in 2030 would reduce remaining cumulative GHG emissions by approximately 5 Gt CO₂eq.
6.1 Costs in Perspective

Today, the EU imports petroleum oils for use in road traffic at an annual cost of between 100 and 150 billion euro (Eurostat, 2023a, 2023b). After sending this money out of the economy, the products are burnt to generate GHG emissions and air pollutants, with no opportunity for value recovery. At a social cost of carbon of 200 €/ton, the fossil fuels used in road transport (tailpipe emissions only) generate an additional 150 billion € per year of damages from GHG emissions. On top of that, there are significant health and environmental costs from air pollutants.

We believe the annual expenditure on fossil fuels is a good frame of reference against which to interpret the costs involved with a transition to zero tailpipe emission vehicles. The numbers presented here are ballpark estimates.

We can estimate the full cost of infrastructure required to deliver all electricity used by a fully electrified stock of EU road vehicles. Using a levelized infrastructure cost that includes upgrades to the electrical grid of 0.033 €/kWh (Rogstadius, 2021), a 15 year infrastructure lifetime, and a total annual energy consumption of 1000 TWh for all EU road transport, we get a total investment of 450 billion euro.

If ERS infrastructure is installed on 130,000 km of roads (e.g., the TEN-T Comprehensive network), that infrastructure would be expected to deliver approximately half of all electrical energy used by electric road vehicles. At approximately 2 million € per km, the initial investment would be approximately 250 billion €, with an infrastructure lifetime of 25-40 years. If built, the infrastructure is expected to deliver more than half of all energy used by electric vehicles. If ERS availability at this scale reduces total annual battery consumption in the EU by a quarter, the cumulative value of battery savings over the infrastructure’s lifetime should be more than double the cost of building the infrastructure. The required raw materials for the infrastructure are common metals like aluminium, copper, and steel, which can be recycled at the end of the lifespan.

If 4% of 250 million EU cars require a new 60 kWh battery every year (i.e., 25-year lifespan), the EU needs an annual battery supply of 625 GWh. At a price to customers of 80 €/kWh, this is 50 billion € per year. Of this cost, approximately 40 €/kWh (50%) is the market value of raw materials ((Schmidt, 2023), 2010-2020 average market prices), which at the end of the battery lifetime enter the EU battery recycling stream. The remaining cost adds value in the EU economy if battery production is domestic.

Unlike import of petroleum oils, battery manufacturing and infrastructure construction creates jobs and brings new raw materials into circulation within the EU. The investments also reduce GHG emissions and air pollution.

Using the full levelized costs of fossil fuel and BEV operation and multiplying with total annual distance, we can get a sense for the total economic value of the transition. Using 2035 costs and traffic, shifting all EU road traffic from fossil fueled ICEV to statically charged BEV would generate savings of approximately 400 billion euro per year. If fossil fuels are imported and vehicles, batteries, charging infrastructure, electricity production and electrical grid upgrades are considered to originate from within the European economy (some may be imports), electrification of EU road traffic can generate annual savings for the EU of approximately 600 billion euro. Delaying this transition is unwise, for both economic and environmental reasons.
7 Conclusions

Despite the significant attention given by the EU today to biofuels, hydrogen, and e-fuels, we find that these technologies are unlikely to contribute meaningfully to reduced greenhouse gas (GHG) emissions from EU road transport before 2035, relative to 2021. While biofuels are in use today and while we recommend their continued use, scaling up supply to provide more than 10% of the final energy to vehicles seems infeasible. This is because proposed additional raw material streams that don’t compete with global food supply would raise costs significantly. If sustainable biofuel supply can be increased without significantly raising costs, this is a positive development.

Green hydrogen is not recommended as a fuel for road transport. The costs are too high, the time to market too long and the environmental benefit too small. In fact, due to the long time to market, hydrogen fuel cell vehicles would compete primarily with battery electric vehicles, substantially raising both costs and GHG emissions. E-fuels face similar challenges, only greater.

Battery electric vehicles (BEVs) emerge as the most viable strategy for achieving zero tailpipe emissions at scale, due to a combination of attractive cost and greatly reduced environmental footprint compared to ICEVs. Further reductions in fossil GHG emissions associated with the use phase of BEVs will result from continued decarbonization of EU electricity generation.

By 2035, the lifecycle environmental footprint of BEVs will be dominated by embodied emissions from light-duty vehicle production, in particular battery packs. These emissions are significant, and it is important that both mining and production facilities throughout the supply chain transition to sustainable sources of energy as early as possible. It is also important that taxation of embodied BEV emissions, e.g., through the EU’s carbon border adjustment scheme, is not greater than taxation of (well-to-wheel) emissions from fossil fuels, as this would be counterproductive.

The scalability of direct electrification as a decarbonization strategy is dependent on the rate at which the stock of vehicles can be electrified. As the BEV share of new light-duty vehicle sales is expected to reach 100% by 2035 (a limit imposed by legislation), there is limited potential for accelerating the uptake through increased new sales. However, there is substantial potential to expedite the adoption of new heavy-duty BEVs. This appears to be feasible, as the relative cost savings from electrification of road freight are by 2035 are three times typical profit margins in the industry.

Due to the identified non-existence of scalable and cost effective sustainable drop-in fuels, retrofitting of reasonably old vehicles with electric powertrains becomes a necessary component in the EU’s strategy to decarbonize road transport. Challenges associated with retrofits include insufficient battery supply, weight constraints and potentially poor economic return on investment. It is of critical importance that these issues are urgently addressed.

For BEVs to be an attractive choice across the EU, continued and accelerated expansion of charging infrastructure is required, in particular in regions where BEV adoption is low day. It is also crucial that charging infrastructure can eventually be made available with sufficient density and capacity for the entire EU vehicle stock to be electric. We are concerned that evidence is lacking that static plug-in charging can be scaled in this way and see potential risks that this form of charging may become increasingly costly to expand as the most attractive locations are all used up. Keeping up with the rate of increase in charging demand may also prove challenging with both 100% of new sales being electric and a similar number of vehicles being retrofitted each year.

Electric Road Systems (ERS) appear to present a solution to multiple challenges associated with the electrification of road transport. We conclude, in line with prior research, that ERS infrastructure installed along most of the TEN-T Comprehensive network (~130 000 km) would be a more cost-effective way than only static charging to transmit electricity to a fully electrified transport system. A comprehensive ERS network would furthermore offer low-cost charging to all road users, improving equity and leveling the playing field between freight operators who may otherwise get access to charging at very different costs. As with BEV uptake, rapid adoption of ERS would be driven by significant cost savings.

From an environmental perspective, an important effect is that dynamic charging enables reductions in installed battery capacity per vehicle by approximately half, without compromising operational flexibility. Reduced battery capacity reduces embodied emissions, frees up battery supply, resolves weight constraints for vehicle conversions, and greatly improves the economic return on investment from converting ICE vehicles to electric. Our modelling indicates that a pan-European ERS network with start of operation in 2030 would reduce remaining EU GHG emissions by approximately 5 Gt CO₂eq, with most coming from light-duty vehicles. The GHG reductions from vehicle conversions alone surpass the combined reduction potential of biofuels, e-fuels and hydrogen.

The primary barriers to getting an ERS network in place by 2030 are identified to be political will and bureaucratic inertia. Achieving a start of operation by 2030 is plausible only if an international agreement, preferably at the EU
level, is established by 2026 to commence such a project. An early decision not only contributes to accelerated GHG emissions reductions, but also reduces financial risk for investors in other charging infrastructure, in particular public fast charging (Rogstadius et al., 2023). An international decision would quickly need to be followed by an agreement on a technical standard for dynamic charging. The full environmental benefits can only be realized if both light-duty and heavy-duty traffic can utilize the infrastructure, and if the infrastructure is deployed across the entire EU from the start. Gradual extensions of the ERS network should focus on increasing its density rather than its scope. Overcoming national-level bureaucratic delays and streamlining planning and tender processes are also crucial, as these processes alone can otherwise delay an introduction by a decade. Several ERS technologies are deemed sufficiently mature that remaining engineering problems could be resolved before start of construction. Manufacturing of ERS parts and physical installation are not identified to be bottlenecks for a buildout.

Future work is needed to explore how policy development can contribute to the rapid establishment of a European industry for vehicle conversions. Topics to explore include type approvals, safety standards, testing and certification for converted vehicles, new economic incentives to stimulate the conversion market, and workforce training programs. Secondary vehicle markets have a unique opportunity to stimulate conversions, by restricting imports of combustion engine vehicles and by providing charging infrastructure that makes cheap and light battery packs logistically viable. Additionally, policy opportunities should be explored to for limiting the environmental footprint of both new and converted vehicles, for instance by encouraging low-emissions batteries, reduced vehicle weights, or reduced physical footprints.

Despite identifying several opportunities for substantial GHG emissions reductions, we see no pathway along which a technological transition ensures that the EU road transport sector does not greatly exceed its fair share of both global and EU fossil GHG emissions. While the scientific advice for the EU is to reduce 2035 economy wide GHG emissions by 77–87% below the 1990 reference level, we forecast reductions of only 17±18% without ERS and 36±16% with ERS.

We also find no indications in the literature that demand for road transport will decrease by 2035, even when assuming policy to encourage modal shift and investments in city planning and public transport. There is evidence in the literature that soft interventions of many types can lead to reductions in car use, but this literature is not yet sufficiently mature to offer reproducible templates for how to reduce car use in cities. We find evidence in the literature that policy that greatly reduces the cost of vehicle ownership and use would also reduce transport demand, primarily by reducing travel and disproportionally among economically disadvantaged groups. This also suggests that the cost reduction potential that drives much of the transition to electric vehicles is likely to lead to an overall increase in road transport. Raising costs on fossil fuels will not be sufficient to reduce total transport work. Solutions to rapidly decarbonize road transport further are desperately needed, but it is difficult to see what options remain on the table other than those we have explored.

Although rapid decarbonization of EU road transport is extremely challenging, the economic value is significant. The EU's annual expenditure on petroleum oils for road traffic amounts to 100-150 billion euros in direct import costs, 150 billion euros in annual social costs of carbon, and additional societal costs from air and environmental pollutants. Transitioning to zero tailpipe emission vehicles and electrifying EU road transport, while requiring significant initial investment in infrastructure and battery supply, is projected to generate annual savings of approximately 600 billion euros, underscoring the high financial and ecological opportunity costs of delaying electrification efforts.
8 References


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