Roadmap to decarbonising European cars

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Executive Summary

Transport is Europe's biggest source of carbon emissions, contributing 27% to the EU's total greenhouse gas emissions, with cars representing 44% of these. Transport is also the only sector in which emissions have grown since 1990, driving an increase in the EU's overall emissions in 2017. If the EU is to achieve the global Paris climate agreement goals of pursuing efforts to limit the global temperature rise to 1.5ºC, transport emissions must be reduced to zero by 2050 at the very latest, including emissions from passenger cars.

This paper analyses options to achieve zero emissions in the EU car segment by 2050. It is designed to feed into the Commission's current deliberations on 2050 climate scenarios. There are multiple pathways to reach zero, including the adoption of clean technologies (battery electric vehicles, hydrogen fuel cell, electrofuels). Policies to curb demand (such as modal shift to public transport, cycling and walking) reduce the amount of clean electricity and other resources required to deliver zero emission mobility. Behavioural measures are estimated to curb car use, accelerate modal shift and improve load factors, together reducing emissions from the car fleet in 2050 (compared to 2015) by 40%. This represents a 28% reduction in 2050 compared to the projected baseline emissions that incorporate the effects of the current policies including 2030 car CO_2 targets. A more aggressive demand reduction scenario was also modelled, halving CO_2 emissions compared to the 2050 baseline. Reductions on this scale will only be possible through ubiquitous adoption of shared vehicles and very aggressive policies to restrict and raise the cost of private car use. However, the analysis demonstrates that whilst demand reduction measures can play an important role in terms of emission and resource demand reduction and creating more liveable cities, on their own they cannot decarbonise personal mobility.

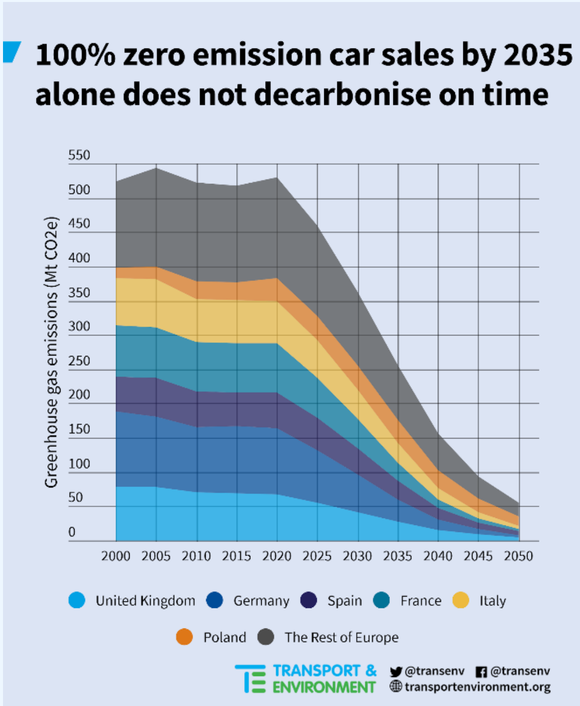
To achieve full decarbonisation a fleet of entirely zero emission vehicles (ZEVs) will be needed by 2050. This will necessitate selling 100% zero emission vehicles by the early 2030s and by 2035 at the very latest. However, this would still not be enough to achieve zero emissions in 2050 and means the use of legacy ICE vehicles sold before 2035 should be restricted and ultimately banned.

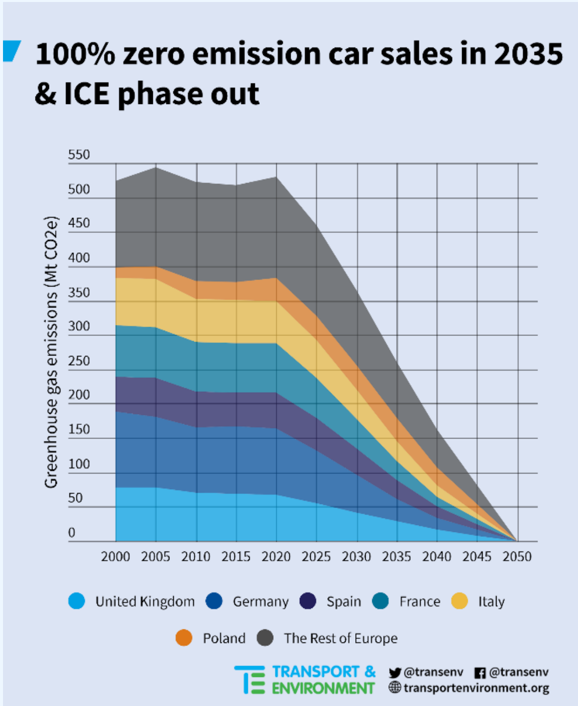
Incremental improvements to existing Internal Combustion Engine (ICE) vehicles will not achieve the required emissions reductions as there is a limit to the efficiency improvements possible and it is not possible to produce low and zero carbon fuels cost-effectively, sustainably and in the quantities required. By 2030, advanced biofuels are expected to contribute only 3% of all transport fuels (including cars, trucks, aviation) and their growth beyond this date is likely to be constrained due to land availability and competing industries. To produce sufficient synthetic fuels to power all passenger cars in 2050 in the baseline scenario would require clean electricity production equivalent to the size of the current EU electricity production, due to the inefficiency of both the production process and ICEs. Similarly, the gas industry equally cannot produce sufficient biomethane sustainably from wastes and residues to power a European car fleet, while it should be prioritised in sectors currently using fossil gas, and fossil gas is not an option if cars are to be decarbonised.

The future vehicle fleet will need to be powered with electricity. This will most probably largely be directly, through batteries, but could also be achieved through hydrogen fuel cell vehicles using zero carbon hydrogen. The electricity industry has committed to decarbonising electricity and the price of renewables is falling – electric cars could become a complement to smart, zero emissions grids. Plug-in hybrids or range extended variants are not fully zero emission and are a transition technology. The analysis shows that the optimal solution from an electricity generation, cost, and efficiency point of view for cars is battery electric vehicles (BEVs).

Fuel cell cars are an alternative but face even greater hurdles than BEVs. Specifically, a lack of commercial models, poor overall energy efficiency and high costs of both the vehicle and zero carbon hydrogen. With the performance and price of batteries allowing ever longer ranges in combination with ultrafast charging in less than 15 minutes the benefits of fuel cell over battery technology are being eroded. If around only a 20% of ZEV sales in 2050 were fuel cell cars, which would increase electricity demand to 525 TWh, or a fifth more.

Even assuming 100% ZEV sales from 2035 the CO_2 emissions are only reduced by 89.4% by 2050 compared to 2015, with around 55 Mt of remaining CO_2 stemming from the remaining ICE cars on the road. A faster phase-in the early 2030s would therefore be preferable or alternatively tackling these emissions requires measures to accelerate fleet renewal, such as time-limits to vehicle type approval and zero emission zones or ICE bans in cities or entire regions. This means that the utility and value of ICE cars decreases sharply from the 2030s onwards. If the older polluting vehicles are retired, then the EU car segment can be fully decarbonised in 2050. If all vehicles on the road in 2050 were BEVs, and the demand reduction measures were achieved, an additional 475 TWh of zero carbon electricity equivalent to 14.7% of EU electricity generation in 2015 would be required. Smart charging will significantly reduce grid upgrade costs and support higher shares of renewables.





Policy recommendations today

Back casting from where the EU needs to be in 2050 exposes the inadequacy of proposed EU 2030 car CO_2 regulations. If sales of zero emission cars are to reach 100% by 2035, significantly more than 35% of new cars should be zero emission vehicles by 2030, the current level being negotiated by the regulation. Independent analysis shows closer to 60% reduction from 2021 is needed for an optimal path to Paris compliance. In addition, there will need to be full infrastructure coverage of the EU Core and Comprehensive network no later than 2030, together with a ramp up in domestic production of sustainable batteries. Member states will also need to reform their tax systems, in particular company car systems, to speed up the uptake of electric cars and make them competitive with fossil fuel alternatives, by reducing taxes on clean models paid for with higher taxes for conventional models.

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1. Introduction

1.1. The problem

Transport is Europe's biggest source of carbon emissions, contributing 27% to the EU's total greenhouse gas emissions, with cars representing 44% of these, according to the European Environment Agency (EEA).[i] Transport is the only sector in which emissions have grown since 1990,[ii] driving an increase in the EU's overall emissions in 2017.[iii]

The 2015 global Paris Agreement commits to limiting the temperature rise to below 2ºC and to pursue efforts to go even further to 1.5ºC. If the EU is to achieve the Paris climate goals, transport emissions must be reduced to zero,[iv] much more than the 60% suggested by the European Commission in its outdated 2011 Transport White Paper.[v] The latest *Special Report on Global Warming to 1.5C* by IPCC stresses further the urgency and the need for "rapid, far-reaching and unprecedented changes in all aspects of society"[vi], including transport, which needs to be firmly on the path to net zero emissions by the mid-century.

Surface transport accounts for around three quarters of all EU transport emissions, with the rest coming largely from aviation and shipping (Figure 1). Even if feasible, fully decarbonising aviation and shipping by 2050 will be particularly challenging, which means light duty vehicles, i.e. cars and vans, will need to be entirely decarbonised by 2050 at the very latest.

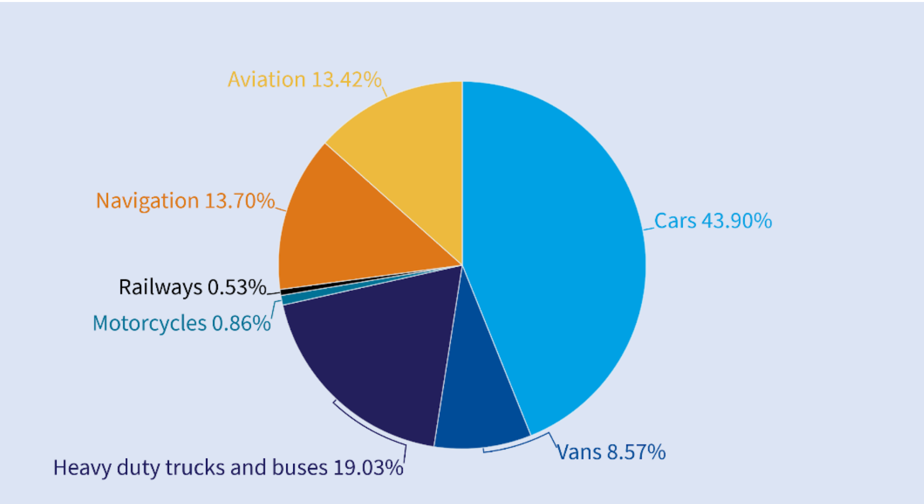

Figure 1. European transport (including bunkers) emitted 1226 Mt CO_2eq. in 2016, with more than half of the emissions coming from light duty vehicles (passenger cars and light duty trucks - vans).

Passenger cars have been dominated by internal combustion engines (ICEs) for the last 100 years. In 2017 in the EU, only 1.4% of new vehicle registrations were plug-in cars.[vii] In order to achieve the necessary reduction in emissions, Europe, and indeed the world, cannot rely on incremental improvements to existing vehicles; there is a limit to the efficiency improvements possible with internal combustion engines. Low carbon drop-in replacement fuels for oil (either advanced biofuels or synthetic fuels) cannot, realistically, be produced sustainably in the volumes needed to power all mobility[viii,ix], as explained in later sections of this study. Instead, a transformation is needed in the way that personal mobility is delivered, notably a shift to zero emission, shared, smart and optimised mobility.

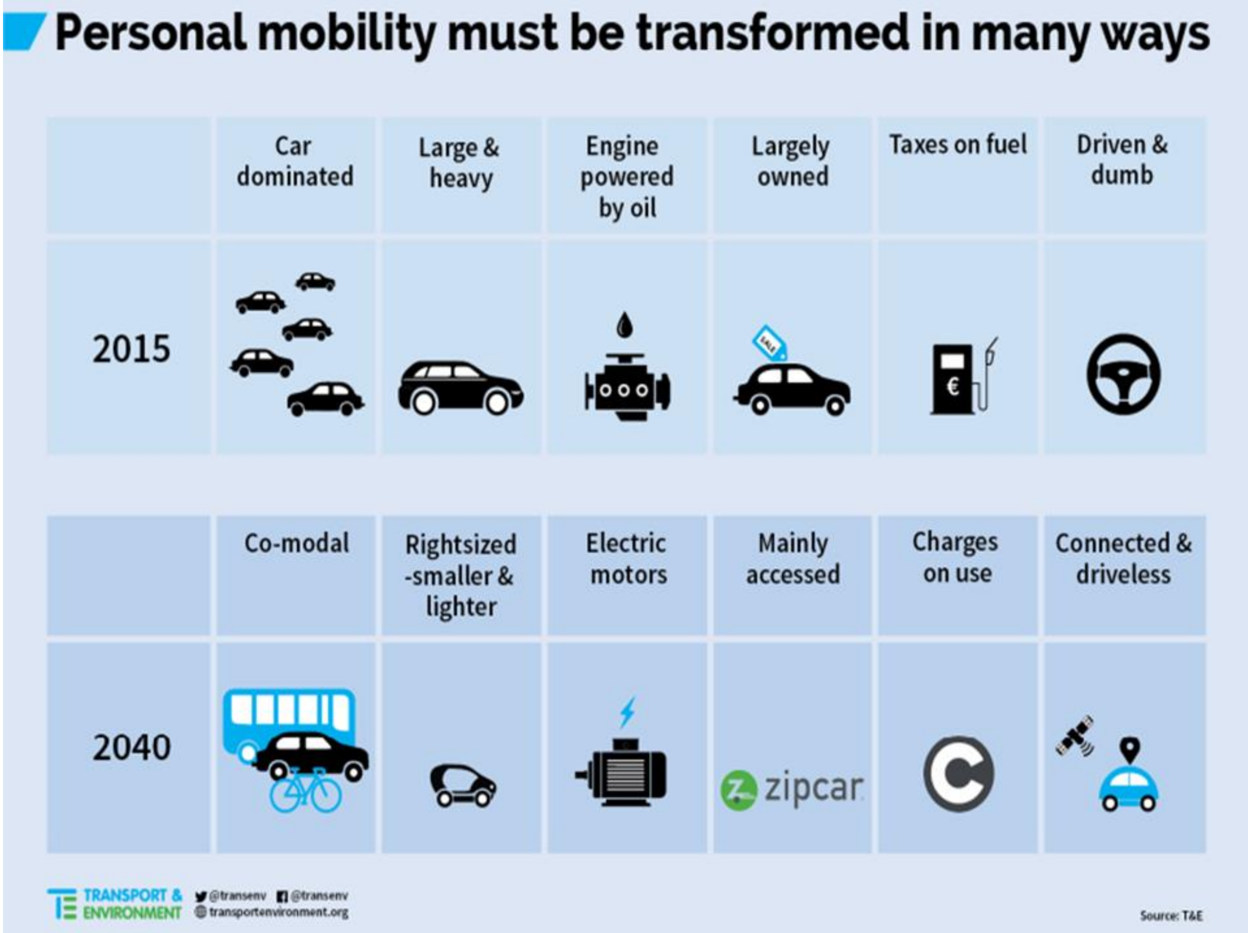

Figure 2: No single policy will be sufficient to deliver zero carbon mobility

1.2. Purpose of the report

Following the calls by the European ministers and the European Parliament, the European Commission has started work on the EU 2050 long-term climate strategy. The aim is to analyse different scenarios towards decarbonisation in line with the Paris Agreement across all sectors of the economy. With the strategy expected by the end of 2018, this report by Transport & Environment is a timely contribution designed to feed into Commission's thinking and subsequent discussions on how to reach zero emissions from the EU car fleet by 2050, and shows that fully decarbonising light-duty transport is feasible. The report focuses on passenger cars only, which represent 61% of surface transport emissions in Europe[x].

1.3. Political context

The CO_2 emissions from cars continue to grow despite the existing standards, or the 95g/km CO_2 target that all carmakers have to meet by 2021. Part of the reason are the growth of the car fleet and vehicle kilometres driven, but a large part also stems from the failure of the current regulation to deliver the emission reductions on the road due to outdated tests and test manipulation. Whilst new car CO_2 emissions measured using the obsolete laboratory test (NEDC) have fallen by 31% since 2000, on the road the reduction is a mere 11%.[xi] The gap between test and real-world performance has leapt from 9 to 42%[xii] halving the real-world stringency of the regulation, increasing CO_2 emissions and raising fuel bills for drivers.

In an attempt to reverse the trend in car CO_2 emissions, last year the Commission proposed the CO_2 standards for new cars and vans for 2025 and 2030. Based on flawed assumptions in the impact assessment[xiii], the Commission has proposed a reduction of only 15% by 2025 and an even less inadequate 30% by 2030. The Parliament has since strengthened the proposals by raising the targets to 20% and 40% respectively, and the national governments have agreed to raise the 2030 target to 35% reduction. But independent evidence[xiv] clearly shows that this is far from what is needed to put the EU on a cost-effective path to achieve the Paris goals, or indeed the EU's 2030 goals, with reductions from new cars closer to 60% needed in 2030. This means a much faster transition from ICE to zero emission technology in the next decade than is likely to be agreed in the new car CO_2 law. Zero emission cars have to account for at least half of all new car sales by 2030, from the estimated 5-7%[xv] in 2021 that's needed to meet the current regulation.

Sales of plug-in cars in Norway are already 60%[xvi] of all cars today, which shows that with right policies, making cars zero emission is feasible. But much more profound tax reform is needed to enable the market to drive a much faster shift to EV than policy makers have been willing to impose through regulation currently being discussed. Alongside the 2050 scenarios, this paper also presents analysis of what is needed in the mid-term (2030) to achieve the long-term decarbonisation target in a cost-effective and optimal manner.

2. What is in store for the passenger car?

This paper does not aim to predict the future; rather it aims to investigate the effect of policy driven changes to the transport system and quantifying their impact. This study is essentially a back cast analysis where the target is clear: all cars should be decarbonised by 2050 at the latest. And even 2050 might be too late. Previous studies by DLR (for Greenpeace)[xvii] and the Öko Institut (for Transport & Environment)[xviii] on carbon budgets show that, in order to limit global temperature rises to 1.5ºC with sufficient likelihood, transport should be decarbonised by 2040, unless we rely on unproven technologies such as carbon capture and storage. For the purpose of this paper, we explore decarbonisation by 2050 in line with the Commission's expected strategy for net-zero emissions by 2050, and compare it to available carbon budgets in the bibliography.

There are multiple pathways to reach zero, including the adoption of clean technologies (battery electric vehicles, hydrogen fuel cell, electrofuels) and policies to curb demand to reduce pressure on the road network (such as modal shift to public transport, cycling, and walking). Transport is on the cusp of a dramatic change not seen since the introduction of the car itself thanks to developments in digitalisation enabling automated driving, shared vehicles and co-mobility. Assessing these impacts is crucial for effective policy design and to ensure the whole economy, from power generation to urban planning, is ready.

2.1. Methodology

The analysis undertaken in this report was undertaken with T&E's European Transportation Roadmap Model (EUTRM[xix]). The model is a bottom up tool driven by growing transport demand. In short, in the absence of policy, as the population grows and becomes wealthier, there will be an increase in transport demand - in the case of cars, more people will take to the road. New vehicle sales replace retired vehicles and fill the remaining demand. The model captures the flow of second hand vehicles between European Member States, and is calibrated against national statistics of vehicle sales, fuel consumption (diesel and petrol) and GHG emissions.

2.2. Baseline

2.2.1. Inputs and activity projections

The baseline used for this report is a scenario in which the transport system continues to evolve based on historical trends and where no further legislative changes are made beyond the 2030 light duty vehicle standards that are expected to be agreed imminently. This will be used as the benchmark from which to compare the impact of policy decisions to achieve decarbonisation. Careful consideration of GDP projections must be taken into account as it is the key parameter to predict transport demand, as well as the implementation of legislated policies. In the EUTRM, GDP and population estimates are based on the lowest of the European Commission's 2016 Reference Scenario,[xx] OECD and IMF WEO data; oil prices are kept constant. Table 1 summarises the main inputs and projections for passenger activity, with a comparison to the EU Reference Scenario in 2050. As can be seen, there are small differences compared to the Reference Scenario passenger activity projections. This appears to be largely due to fuel price differences, which in the Reference Scenario increase, resulting in a decrease in passenger demand and transportation becoming more expensive.

Table 1: Exogenous inputs of population and GDP, resulting in transport activity. §Excluding aviation and maritime. #Includes motorcycles.

	EUTRM			EU Ref. Scenario
	2020	2035	2050	2050
Population (millions)	510	518	522	522
GDP (billion $€_{2013}$)	14 849	18 342	22 980	22 526
Passenger activity (Gpkm)§	6 530	7 736	8 477	7 824
of which car activity (Gpkm)	5 064	6 095	6 615	6 279#

Importantly, Table 1 illustrates the assumption that passenger activity increases based on historical correlations with wealth and that transport and urban planning systems remain unchanged. This essentially means that in 2050, this projected future is one where there will be *even more* privately owned cars on the road, sitting unused for 90%[xxi] of the time, being driven in a clogged and presumably expanded road network. The GDP assumptions themselves are highly uncertain; whether this growth is possible in the context of the increasing effects of climate change is beyond the scope of this report, but this is nevertheless questionable. Thus, projecting behaviour over such a long period of time without considering the likely technological advances that may occur, with or without policy, can lead to large deviations to what the future will entail. Finally, humanity appears to be on the cusp of mobility revolutions that will profoundly affect car ownership and use of vehicles; this baseline scenario effectively assumes the system continues to evolve essentially in a business as usual manner. This may very well be an unlikely outcome but the aim of the baseline scenario is not to predict the future but to first, allow a simple comparison and evaluation of the policy driven changes in the results, and second, it is in line with the Commission's modelling approach[xxii] for its 2050 strategy work. The transformation of the transport system will be analysed in depth in an upcoming study by T&E. Some insight to these transport revolutions is provided in the two information boxes in this report.

The baseline is intended to be illustrative of a future where nothing changes[1], however it is assumed that *at least* the European Commission proposal of the post 2020 passenger car standards are met (30% reduction in *real-world* CO_2 emissions for the new vehicles fleet in 2030). No rebound effect is assumed to occur based on the improved vehicle efficiency of internal combustion engine vehicles. Many studies cite a 10% rebound; in the short term, this will have a negligible impact on demand, owing to the relatively slow turnover of the vehicle stock.

The vehicles themselves are not the only way the sector may change. The recently updated renewable energy directive (RED)[xxiii] has a specific mandate for advanced biofuels in 2030 of 3.5%. At least in terms of CO_2 accounting, biofuels are zero-counted at the tailpipe, despite that many feedstocks are significantly worse than the fossil they are replacing on a well-to-wheel basis[xxiv]. For first generation biofuels, there are significant differences between Member States on the current and projected uptake of these fuels. Therefore, it is assumed that crop based biofuels remain constant at 2016 levels. It is assumed that all Member States will reach the 3.5% 2030 advanced biofuel target. Finally, it is assumed that first generation biofuels will be phased out for sustainability reasons, and advanced biofuel production will shift to kerosene

[1] The only exception to this, is that it is assumed that diesel sales continue to reduce following Dieselgate, but still achieve 25% EU wide sales in 2050

production owing to significant demand from aviation[xxv], by 2040. More details and discussion on the role of biofuels in road transport are given in Section 4.1.2.

2.2.2. Projected CO_2 emissions

The trajectory of emissions in the baseline in 2050 are projected to be 431 Mt CO_2eq., or 16.8% less than 2015 emissions. Cumulatively, 2016 to 2050 emissions will amount to 17.0 Gt CO_2eq. Figure 3 shows the evolution of resulting GHG emissions based on the six largest emitting countries in the EU in 2050 and the rest of the bloc. These projections indicate that transport emissions start decreasing in 2020, largely driven by the existing 2021 standards for cars, despite these standards delivering much less on the road due to extensive lab test optimisations. The key take-away from these results is that doing nothing will not decarbonise the sector: ambitious short and medium term policies are required to ensure a trajectory to full decarbonisation is possible by the midcentury. These measures are the subject of the next section of this report.

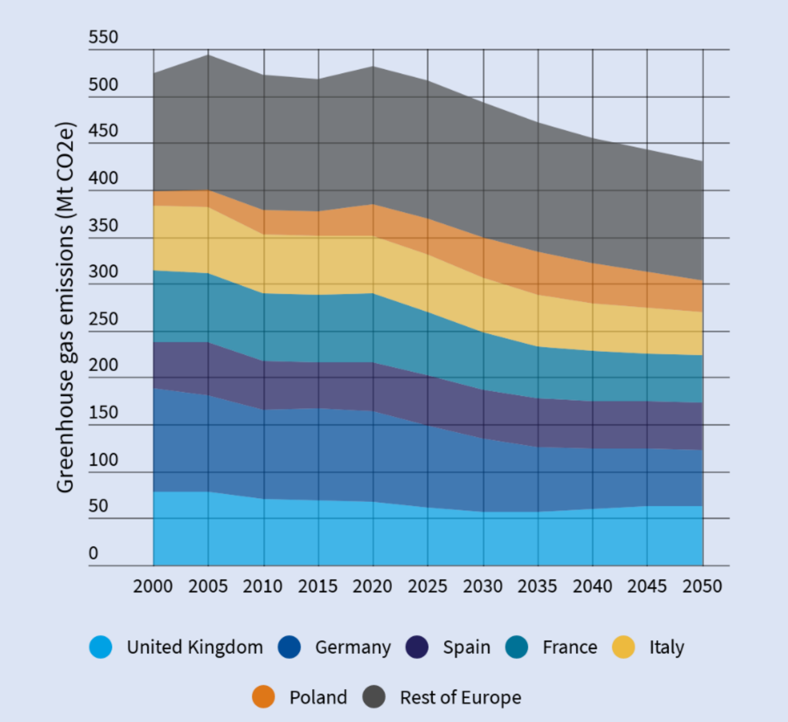

Figure 3: CO_2 emissions in the baseline scenario, assuming a wealthier Europe, increasing transport demand, and 30% CO_2 2030 standards are met in the real-world, showing the six largest polluters in 2050 and the remaining EU28.

BOX 1: Automated Vehicles - how will they change the system?

Fully automated vehicles (AVs) are already driving in Europe[xxvi], albeit for very limited applications. The question is no longer of *if*, but *when* these vehicles will be widely available. Some estimates (including those of some carmakers[xxvii]) suggest AVs will dominate urban transport completely by 2030[xxviii]; while other analysts expect a much slower transition[xxix,xxx].

An AV revolution will require fully autonomous vehicles that can operate within the scope of normal driving operational domains (on paved, well-mapped out roads). Automated vehicles have a compelling safety benefit, as they could eliminate a large proportion of the road fatalities attributable to human error.[2] They are also attractive to transport providers, who could offer much cheaper services without having to pay the salary of the driver. However, it would result in significant job losses with around 4.8 million professional

[2] European Commission, DG Mobility and Transport: https://ec.europa.eu/transport/themes/its/road_en

drivers in Europe, of whom 2.1 million are employed for passenger transport (i.e. taxi, bus, and minivan drivers)[xxxi].

Safety aside, an AV revolution will have a profound effect on mobility. Whether this will benefit society at large or not will largely depend on regulation and planning.

In a worst case scenario, automated vehicles would still be privately owned and powered by fossil fuels. Owners of these vehicles would be able to utilise their time in these vehicles productively (so would not mind being stuck in traffic jams or longer journeys), and could send the vehicle on errands such as parcel pick-ups, or rather than pay for parking at their destination, send the vehicle home and summon it for a ride back when needed.

Even if part of the vehicle fleet was for ride hailing as seen today (i.e. a taxi-like service), the affordability of this mode of transport (which could be up to 10 times cheaper to operate per kilometre[xxxii]) could move passengers away from public transport and accelerate passenger demand considerably. Congestion aside, in terms of energy demand and GHG emissions, this default, do-nothing, 'hell' scenario would be a disaster in terms of both congestion and emissions system[xxxiii]. Initial results show that energy demand from passenger cars could result in CO_2 emissions increasing by up to 74% in 2050 compared to 2015, or to 915 Mt CO_2 eq. in 2050. More details and a more in-depth analysis will be contained in an upcoming T&E study, and their impact is not included in this analysis.

3. Measures to cut fuel and passenger demand

Many different measures can be implemented to increase the number of people travelling in each car and to switch the number of trips by car to other more efficient modes of transport, such as public transit, walking and cycling. Most of these measures are the remit of national, regional and local authorities. This section provides a qualitative description of some of those measures that can increase load factors and promote modal shift, resulting in reduced transport demand for passenger cars.

The policies described are interconnected, resulting in direct and indirect effects on car use, public transport, and active modes of transport. A relatively simple measure (in terms of implementation) such as increasing fuel taxes may have a direct effect of increasing the operating cost of cars, but whether that results in forfeited travel, the purchase of a more fuel efficient or smaller car in order to maintain the transport activity, or a shift to a cheaper mode is unclear, and likely a combination of these outcomes. Therefore, in quantifying these policy measures, studies are used where possible to support the demand reduction; conversely, these measures could be used as a best practice guideline for countries to ensure a transition to equitable, efficient, clean mobility for their citizens, where the quantified shifts could be viewed as minimum targets to achieve.

If all of the below measures are implemented to their potential, the joint transport demand reduction is assumed as follows (note that these figures will vary significantly between countries and for regions within countries):

- 22% reduction in car use by 2050 compared to the baseline, through combined effects of fuel taxes, road charging, and policies to induce modal shift.
- 10% increase in the number of passengers per vehicle from carpooling and sharing.
- 5% reduction in in-use consumption of vehicles from measures such as eco driving behaviour and cooperative intelligent transport systems.

More information on the assumptions is in Appendix 2, and detailed discussion of each measure and the resultant reduction in GHG emissions are provided in the remainder of this section. Furthermore, a scenario where these measures are ramped up to achieve even greater demand reduction is detailed at the end of this section.

3.1. Fuel taxes

Fuel taxation is not only a means to earn money for the state, it helps internalise the externalities of transport (societal costs of infrastructure, congestion, health problems related to pollution, injuries and loss of life due to accidents) and more significantly, it influences the long term behaviour and choices of passengers. With a long term elasticity[3] of -0.3 to -0.5 for car use, an increase on petrol, diesel and natural gas fuel taxes to increase the final price of the fuel by 10%, would decrease demand (passenger activity) by 3-5%. However, increases in price may have other effects such as increasing carpooling or modal shift to bus or train.

3.2. Road charging

As with fuel taxes, road charging can also contribute to increasing car costs, promoting smarter passenger demand and modal shift to cleaner transport modes. Through its use in low and zero emission zones, it can help the uptake of cleaner, more fuel efficient vehicles and ZEVs. Cars spend a lot of time in cities, but a disproportionate amount of that time is spent parked. A duration based charging system, whereby users pay per hour of city access, can reduce the amount of cars in city centres. Such a system encourages collective mobility (i.e. train, bus, or carpooling) and allows for more space to become available for better cycling, walking infrastructure, bus lanes, or parks. This charge could be further differentiated to promote the use of cleaner vehicles, through higher charges for more polluting vehicles. Finally, time based road charging is AV proof (cars that won't need to park), and also covers journeys with private parking that would otherwise not be affected by time based parking charges (despite those drivers contributing to congestion). The London congestion zone could be used as a model for city resident, who pay 10% of the daily charge.

3.3. Speed limits

Reducing speed limits and having them properly enforced, particularly on highways, can reduce fuel consumption of passenger cars. A report that modern cars could reduce their CO_2 emissions per kilometer by up to 12% (in line with findings from Ricardo[xxxiv]), but in a more realistic scenario, it would more likely be 3%[xxxv]. Reducing speed limits in cities would improve pedestrian and cyclist safety with less severe injuries and smaller probability of fatalities[xxxvi]. However, the CO_2 savings will generally not be as significant.

3.4. Public transit and active transport modes

In 2016, 81.3% of passenger land transport activity (measured in pkm) was done by car (statistics exclude cycling and walking)[xxxvii]. Even if modal shares between cars, buses, trains, trams and metros have remained relatively stable the last 20 years, there is space for improvement. At typical occupancy rates, cars are the least efficient form of land transport[xxxviii], so shifting passengers to rapid transit or active modes enables lower carbon intensive transport.

In cities, in order to shift car passengers to public transport, an essential component is appropriate infrastructure for walking and cycling. While a journey by car is typically characterised by door to door transport, a public transport journey is often part of a multimodal trip, and typically involve walking or cycling to mass transit stations. Although walking in itself will not be able to offer the same transport activity as cars in terms of sheer numbers, it is an integral element of facilitating the journey. Cycling enables short distance trips to be completely replaced, especially with the current uptake of electric bikes[xxxix], making cycling a transport solution for more people. The most successful cities and countries (such as the Netherlands and Copenhagen) have high cycling rates owing to extensive infrastructure that is separate from the road and gives cyclists priority over cars. The reduction in CO_2 could be significant: in Germany 28% of all car trips are less than 15 km while in Austria 43% are under 5 km[xl]. However this is highly dependent on the case, and attention must be given to the CO_2 reduction of the whole system. Despite the

[3] Elasticity is the measure of how one variable (here, car use) changes with another variable (here, fuel price). In the most general case, as a something becomes more expensive, demand for it reduces.

success of Copenhagen as a cyclist city, Denmark has one of the highest high CO_2 emissions per capita from cars[xli]. Alongside cycling and walking, the public transport itself must also be reliable and affordable.

3.5. Car sharing

The transport system is on the verge of a paradigm shift from the tradition of private car ownership to usage models around sharing and mobility as a service (MaaS). This has largely been through a revolution in digitalisation and application based services (Blablacar, Uber), and business models that facilitate infrastructure sharing (Car2go, DriveNow). Evidence [xlii] shows that these developments can lead to a significant reduction of single occupancy private car use and an increase of public transport use, leading to a strong reduction in congestion, local air pollution and CO_2 emissions. The French environment and energy management agency (ADEME) found that each shared car replaces on average 5 to 6 private vehicles, while freeing up at least 2 parking places[xliii].

These benefits will occur when more vehicles are shared and private car ownership is reduced; when these shared vehicles are electric, the benefits are even greater. Modelling has shown ride-sharing services could make public transport more efficient and thus end congestion, reduce traffic emissions by one third, and decrease required parking space [xliv]. Surveys by the Pew research centre [xlv] and work by the Union Internationale des Transports Publics (UITP) [xlvi] indicate that car and ride sharing complement public transport, but do not replace it. This has positive implications for modal shift, as citizens abandon their cars and opt for shared resources, more active forms of transport (walking and cycling) become attractive as streets are cleared of congestion and cars, liberating space for appropriate footpaths and cycling paths.

The technology behind these applications can enable more passengers per car, as pooling services are enabled. This can be reinforced with favourable conditions for cars with multiple (more than 2) occupants on key city roads, such as occupancy-based charges. While the development of shared mobility seems unstoppable, whether the transition from ownership models to sharing will lead to short term increase in congestion because of induced demand will largely vary from city to city.[xlvii] Local measures such as high occupancy lanes can also accelerate this transition.

3.6. Eco-driving

Eco-driving is a driving behaviour that can reduce CO_2 emissions from cars and other vehicles by training drivers to reduce speeds, anticipate traffic situations to maintain more constant speeds, and reduce the severity of accelerations or braking. One industry-led report[xlviii] has shown that the benefits of eco-driving are highly variable: in congested roads, eco-driving has a maximum benefit of 4% if all drivers adopted and use eco-driving practices, while in free flowing traffic, the benefit ranges from a 4% to 15% depending on how many drivers drive economically. However, the JRC[xlix] and others[l] found that the impacts of eco-driving tends to decrease over time. This implies that the benefits would require extensive and repetitive training programs of all drivers to see appreciable benefit. Although this may be feasible for professional drivers where the burden may fall on transport companies, such a broad program for all drivers would be an unlikely policy measure.

3.7. Connected cars

Connected cars make use of the internet to optimise their operation and maintenance, the convenience of their occupants, as well as communication to other road vehicles and infrastructure. Better connectivity offers many opportunities to optimise the use of road infrastructure and space, e.g. by avoiding long traffic jams or driving around the city in search of parking. Connected vehicle technology can play a role in making transport more efficient. The flow of real time information regarding traffic and congestion is underutilised today. Internet applications that are being developed and increasingly used can help reduce congestion and CO_2 emissions.

An example is the cooperative intelligent transport systems (C-ITS) technology, which allows for interoperable cross-border exchange of information between vehicles, and between vehicles and the road infrastructure. Both Ricardo 2016 [lii] and the European Commission [liii] state that widespread and rapid deployment of C-ITS can deliver reduce the fleet emissions from cars, albeit by a modest 1.0%.

The impact of connectivity on long-term carbon emissions from cars is difficult to predict with certainty. On the one hand, more efficient flows of traffic and optimal speeds will help reduce fuel consumption and emissions. On the other hand, the increased use of in-vehicle digital applications can in itself result in increased fuel consumption, whereas easier vehicle navigation and rebound effects from fuel savings can bring more vehicle km. Given the inherent uncertainties, the pros and cons of connectivity on long-term car emissions are assumed to cancel each other out for the purposes of this paper.

BOX 2: Connected, Automated, Shared, and Electric Vehicles - Transport Heaven?

Shared vehicles in an integrated transport system, where transportation as we know it is transformed to a customer-centric, multimodal, on-demand mobility paradigm [mobility as a service (MaaS)], could be the most important development in passenger transport. This is a system where rather than privately owned, automated ICE vehicles, personal mobility is provided by a range of on-demand mobility options including shared, electric, right-sized vehicles that are integrated to suit and complement the current public transit infrastructure and services of a city. These vehicles would need to be ubiquitous enough to offer an efficient service to citizens who live in small towns or poorly connected suburbs of cities. They would complement existing infrastructure such as mass transit rail, tram, and bus networks, combining the flexibility of a taxi service - especially for the first and last mile - but the efficiency of mass transit networks. In this system, a passenger would use a single app to plan their journey, and the most (cost[4])-efficient journey would be chosen, combining perhaps an automated minibus to a metro or train station, and at the other end a shared bike to the final destination. With less cars on the road, trams and buses would be faster, and cycle lanes could be integrated into the spare road lanes.

There are several studies that have quantified the effects that such a transformation could have. The International Transport Forum have used a bottom-up agent based modelling approach for a number of European cities[liii] and their results have shown a significant reduction in the number of cars is possible (up to 94%) to complete all the journeys in a city. UC Davis on the other hand had a global, top-down approach, showing how energy demand and CO_2 emissions could be reduced[liv]. T&E will be looking at integrating both of these approaches for a European context, with the aim to show specifically what it could mean for energy, CO_2, congestion, for each Member State in an upcoming study. This is beyond the purpose of this report.

A transport heaven scenario is, however, far from inevitable (see Box 1). The passenger transport system described here is indeed something that Europe should strive for; whether it eventuates will depend largely on adequate pricing mechanisms to manage demand, coordinated policy between all European countries, collaboration between public and private mobility providers, and common approaches for cities and towns. The transition to such a system may also cause huge disruptions, another subject of investigation for the upcoming T&E study.

3.8. CO_2 emissions after applying demand reduction measures

The measures above have an impact on improving modal shares and load factors thus reducing demand for transport. For a detailed description on what assumptions were included, see Appendix 2. Figure 4 shows

[4] Some shared mobility providers, such as ridesharing company Uber, apply flexible pricing mechanisms whereby at constant supply level, prices increase with demand.

the results of applying these measures, highlighting the importance they can have in reducing emissions. Compared to 2015, emissions in 2030 are 21% lower, and by 2050 they are 40% lower. These emissions represent a 28% reduction in 2050 compared to the projected baseline emissions. Although these measures will not achieve zero emissions by themselves, the reduction in energy demand is proportional to the reduction in CO_2 emissions. Aside from reducing emissions and energy demand, reducing vehicle kilometres is necessary for liveable cities, and will reduce noise and congestion. Finally, reduced demand in transport makes the change in vehicle technology to zero-emissions vehicles much easier, where new sources of energy (namely, clean electricity) must replace the incumbent fossil fuels.

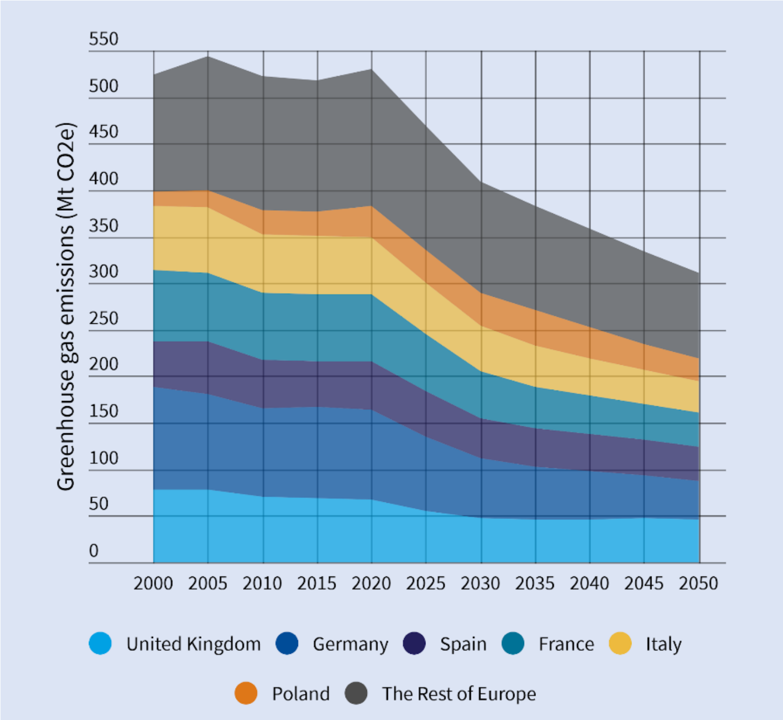

Figure 4: Projected emissions with demand reduction strategies, and vehicle standards to 2030.

3.9. Ramp up of demand limitation

Figure 4 showed that despite ambitious demand reduction measures, the emissions in 2050 are still projected to be over 300 Gt CO_2eq. This section investigates what would happen if these measures were more than doubled, with a combined effect of cutting demand by a quarter in 2030 and halving it in 2050, compared to the baseline. Even with such drastic demand reduction the resulting CO_2 emissions would still be half of those compared to the baseline in 2050, with technology needed to decarbonise the remaining car stock. This would represent a 58% reduction compared to 2015. This reduction in demand would have positive consequences such as reducing resource requirements (less cars and their associated materials e.g. for batteries) and could free up more space in cities to enable public transit and active modes of mobility. However, it is unclear whether public transport and active modes of transport could maintain the level of total passenger activity. This would imply a significant reduction in overall mobility, as well necessitating significant additional investment into public transport infrastructure.

4. Options to cover remaining car activity demand

4.1. Different technologies

4.1.1. Hydrogen fuel cells

Fuel cell electric vehicles (FCEV) that run on compressed hydrogen are considered zero emission vehicles in EU legislation, only emitting water. Fuel cells convert hydrogen to electricity, which in turn powers an electric motor. FCEV have longer range than battery electric cars on the road today (with ranges similar to conventional cars) and require less frequent re-filling making them more suitable for long-distance applications.

There remains a limited choice of fuel cell cars in Europe. The first commercially available hydrogen fuel cell car was the Toyota Mirai, released in 2015. Aside from that vehicle, the only other models available to date is the Hyundai Nexo and Mercedes-Benz GLC. In terms of models available or announced, available infrastructure, and technology maturity, hydrogen cars have several hurdles to overcome to see the same level of adoption as their battery electric counterparts have.

There are several reasons why more manufacturers have not been pursuing this technology. First, the technology remains prohibitively expensive despite decades of investment. With only a few models available (notably by Toyota and Hyundai), the price is currently over €60,000; in contrast, a 2018 Nissan Leaf or VW e-Golf is half that. Limited choice and persisting safety concerns mean that it is unlikely to drop significantly - even in 2030 FCEV will remain the most expensive car to own, even if purchase prices come down.[lv] Second, producing hydrogen by electrolysis and then converting it back into electricity in the fuel cell requires large amounts of energy, making the technology inefficient, and comparatively expensive. As shown in Figure 5, FCEVs requires 2 to 3 times more energy to run when compared to battery electric cars that use electricity from the mains to power the highly efficient battery directly. Finally, hydrogen today largely comes from fossil fuel processes, derived either via steam methane reforming or coal gasification. Making “green” hydrogen from renewables is possible by water electrolysis (using electricity to split water into hydrogen and oxygen) but only 4% of hydrogen is produced this way - largely because it is much more expensive.[lvi] Although battery electric cars also rely on the grid to charge (still resulting in a reduction in CO_2 emissions of 50% over the life of the vehicle on *today's* power mix[lvii]), the additional electricity required for hydrogen could slow down the decarbonisation of the grid because of the higher demand.

4.1.2. Sustainable advanced biofuels

Biofuels according to the current EU legislation are “liquid or gaseous fuels produced from biomass”[lviii]. A biofuel can be ethanol, methanol, fatty acid methyl ester (FAME), hydrotreated vegetable oil (HVO) or biomethane (either compressed or liquefied). These biofuels can also be split into generations of biofuels, first generation (or conventional) being produced from sugars, starch crops, or vegetable oils, and advanced biofuels that are produced from wastes, residues or novel feedstocks such as algae. Biofuels were first introduced in the hope of reducing carbon intensity of fuel, as in a simplistic sense the CO_2 generated by combustion has been absorbed by the growth of the biomass used to make it. Biofuels are usually blended into fossil fuels in low proportions without the need to modify engine technology.

For passenger cars the drop-in options that can be blended to fossil fuels in current vehicles are different types of bioethanol and biodiesel. Biomethane can be used to substitute in compressed natural gas (CNG) cars. First generation vegetable oil based biodiesel is not a decarbonisation option for the transport sector as when both direct and indirect emissions are taken into account, all biodiesels have higher greenhouse gases than fossil derived diesel[lix]. This is due to indirect land-use change (ILUC) emissions[5]. Palm oil, for instance, is the second largest feedstock for biodiesel in the EU (31%)[lx], and has significant ILUC emissions due to tropical deforestation and peatland drainage. Starch and sugar crops (e.g. maize or sugar beet) are typically grown on agricultural land for the production of bioethanol or biomethane, also resulting in ILUC.

The Renewable Energy Directive (RED)[lxi] established a policy for the production and promotion of energy from renewable sources in the EU. The relevance for transport is that all EU countries must ensure that at least 10% of the energy used in transport (via biofuels or renewable electricity) come from renewable sources by 2020. Although the RED is not specifically a climate law, its goals include combatting climate change. The REDII, which formally ended negotiations in June 2018, is the revision of the RED and will apply from 2021 to 2030. The REDII sets a binding target for advanced renewable fuels of 7%, which include advanced biofuels, renewable electricity, hydrogen, etc., in an attempt to promote the use of sustainable and cleaner forms of transport. In addition, the EU is slowly moving away from food-based biofuels that are unsustainable and have negative impacts on climate and environment, by eliminating a binding target for food-based biofuels and limiting their use.

In T&E's 2050 series, sustainable advanced biofuels based on wastes and residues were analysed in more detail, but their potential contribution is finite as the sustainable feedstocks are limited. The maximum potential of advanced biofuels in road transport is also very much dependant on the other sectors potentially using the same raw materials or fuels.

For the purpose of this report, which has a long-term decarbonisation perspective, we assumed that REDII targets would be achieved by 2030. However, afterwards all sustainable advanced biofuels would be diverted to aviation[lxii]. Regarding biomethane, it would be used in sectors where currently fossil gas is used: industry and heating mostly.[lxiii]

4.1.3. Electrofuels: Synthetic diesel and petrol

Electrofuels, also known as power-to-liquid or power-to-gas, are electricity based gaseous or liquid fuels which can be used in internal combustion engines, such as passenger cars, in the form of synthetic petrol or synthetic diesel. They would only have meaningful climate benefits[lxiv] if strict sustainability criteria are observed throughout the production process. The key factors determining the sustainability of electrofuels are the source of electricity (it must be renewable and additional), the source of CO_2 (it should be air capture) as well as impacts on land and water.

Electrofuels are not a credible or cost-effective solution to decarbonise road transport. This is because the production of electrofuels is inefficient and costly. To fuel Europe's car fleet after applying the demand reduction with electrofuels would require adding 2619 TWh to EU electricity generation (equivalent to 81% of generation in 2015) and all of this additional electricity would have to be zero carbon. This means electrofuel production cannot realistically be scaled up the levels needed to fuel the European, let alone, the global vehicle fleet. Where better alternatives exist - i.e. in cars - electrofuels have no role to play.

Some car manufacturers are starting to produce e-diesel[lxv]. However, our vision is that all synthetic fuels produced in the future will be used to fuel the sector which currently has no alternatives: aviation[lxvi]. The difference between directly using the electricity to fuel battery electric vehicles or to use it in complicated processes to capture carbon dioxide from the air and hydrolyse water, to then burn it in an inefficient

[5] Direct emissions for crop based biofuels result from land clearing to make space for the crops, in addition to the harvesting and production itself. Indirect land use change emissions are a result of new land being cleared for food crops, as they have been converted to energy crops. More information found: https://www.transportenvironment.org/what-we-do/biofuels

internal combustion engine, is several orders of magnitude. This is further explained in the section below about efficiency first.

4.1.4. Battery electric

Battery electric cars (BEV) have seen major technology improvement and cost reduction in recent years, recording a 37.4% increase in sales across Europe in the latest 2018 quarter alone.[lxvii] BEVs are today the most promising and optimal zero emission technology to decarbonise Europe's car fleet: it has zero tailpipe GHG, air pollutant or noise emissions, is the most efficient option considering the power needed to directly charge the battery, and is already cost-competitive in some markets on the total cost of ownership bases given its low running and maintenance costs, expected to reach parity in all Europe in early 2020s[lxviii].

The largest part of BEV life-cycle CO_2 emissions comes from charging BEV, i.e. its use phase, which will improve as the EU electricity sector decarbonises. The EU power sector has committed to full decarbonisation by 2050. But already today BEV are considerably cleaner than a comparable diesel car over its lifetime, even in the member states with carbon intensive grids.[lxix]

Batteries account for the largest cost component of BEVs, with battery pack costs having come down from \$1000/kWh in 2010 to industry averages around \$200/kWh in 2017[lxx], and are likely to continue decreasing in the next years as investment and production capacity increase. If costs reach \$100/kWh - predicted between 2020 and 2025 - the upfront cost of an electric car would be below an ICE car. Battery improvement coupled with growing number of fast chargers means range anxiety associated with BEVs is disappearing: as battery densities increase, EVs have a longer range with models such as the Jaguar i-pace, the Audi e-tron or the Tesla model 3 reaching ca. 400-500 km. In the next decade they are likely to have a similar range to ICEs.

Charging issues (lack of charging infrastructure, range anxiety) will be resolved as the number of BEVs on the road increase and business case for infrastructure providers improves. Current users do not and will not require fast charging regularly, as most charging happens at home or at the office.[lxxi] For more widespread adoption, particularly where dwellings do not have private parking, roadside charging will also need to be extensively rolled out. Some innovative solutions are beginning to crop up, for example in London with street light posts being converted to chargers[lxxii]. However, fast charging is important for long interurban trips and to deal with range anxiety. Fast charging networks of up to 350 kW are already being developed across Europe today[lxxiii], which means that a BEV with a 100 kWh battery (range of more than 500 km) could be fully charged in around 15 minutes. The impact on the EU grid from the increasing BEV fleet is also manageable: different studies[lxxiv] have shown that, if managed properly, electric cars are not a burden on the electricity grid. If smart charging and vehicle-to-grid technology is rolled-out, BEVs can actually provide flexibility services and an opportunity to incorporate more renewables and avoid clean electricity curtailment.

Concerns have also been raised around environmental and ethical considerations stemming from mining the materials needed for batteries, given that most resources such as cobalt and lithium today are sourced from developing countries such as the Democratic Republic of Congo. The issues here are similar to those faced by consumer electronics such as smartphones or laptops. One answer to this is better transparency and accountability in global supply chains, being made possible with international measures underpinned by new IT traceability tools (e.g. Blockchain). The key will however be development in the mining countries. Another is innovation in battery manufacturing: battery chemistries are constantly evolving, and using less cobalt (3% is current state of the art) or moving to cobalt-free solid-state batteries in the future will help reduce reliance on unstable and socially questionable supply of materials. Crucially, repurposing and recycling of batteries will increase availability of secondary materials and improve CO_2 balance of battery manufacturing.

4.1.5. Piecemeal options

There are also various transitional and combined solutions available to decarbonise the car fleet. Plug-in hybrids (PHEV) are widely regarded as the main transition technology from ICE to full EV; they have a small battery with a limited electric range, most current models driving electrically for about 40 km[lxxv], and an internal combustion engine. On the road most PHEVs have relatively high average emissions of around 120g/km[lxxvi], but as the electric range and battery capacity increase, evidence suggests the real world emissions fall sharply.[lxxvii] The main reason for their popularity among policy-makers in Europe is the fact that they do not disrupt the automotive supply chain to the same degree as a complete transition to battery electric vehicles and require around 20%[lxxviii] more people to build each vehicle. However, plug-in hybrid technology where the ICE is running on fossil fuels will never be zero emission and the emissions per kilometer largely depend on drivers charging behaviour. Having two different powertrains in the one vehicle tends to result in a higher purchase price than either a full ICE of BEV. Thus, PHEVs may have a brief role to play as a transitional technology, but they are ultimately unable to deliver zero emission mobility and cannot be relied upon for longer term decarbonisation.

Dual fuel cell-battery vehicles are another piecemeal approach (even though most fuel cell cars already have an auxiliary battery). In this case, the BEV would have larger battery giving greater autonomy, and use an onboard hydrogen fuel cell as a range extender. Similar to the arguments listed above for PHEVs, combining two drivetrains in one vehicle increases the cost. With positive developments in battery density, costs, and lifetime, and because of the aforementioned limitations of hydrogen fuel cell technology, this solution does not at this time appear to be economically viable. Finally, a PHEV could be run on synthetic fuel (or power-to-liquid, PtL). The inhibitive costs and inefficiencies aside (see following section), PHEVs operating on PtL would *still* emit pollutants (NOx and PM) at the tailpipe. Therefore, no piecemeal option can realistically be considered an optimal solution.

4.2. Efficiency first

As explained above, there are different decarbonisation pathways for cars. For instance, cars can be decarbonised by using battery electric, hydrogen, synthetic fuels, or even a combination of them in different types of hybrid vehicles. In all cases, renewable electricity will fuel the cars, either directly or indirectly.

However, different pathways imply very different amounts of renewable electricity needed. This is significant since transport is not the only sector that will need to move from fossil fuels (either liquid or gas) to renewable electricity, either as an energy carrier or a raw material to produce fuels. Industry or heating would require growing amount of renewables. And whilst there has been a revolution in solar and wind technology deployment and cost reduction, we are still far removed from a 100% clean grid. Given the growing demand from all sectors of EU economy, ensuring zero emission electricity is used optimally and efficiently becomes paramount to avoid costly investments.

So until business models are developed that allow the rapid and cheap roll out of enormous amounts of additional zero emission electricity generation, the most sensible strategy would be to minimise the amount of additional electricity needed. The difference between the pathways can be several orders of magnitude. Figure 5 shows the efficiencies of using renewable electricity in passenger vehicles, using optimistic values as they reflect a long-term perspective. Further below we quantified the amount of renewables that different pathways would imply.

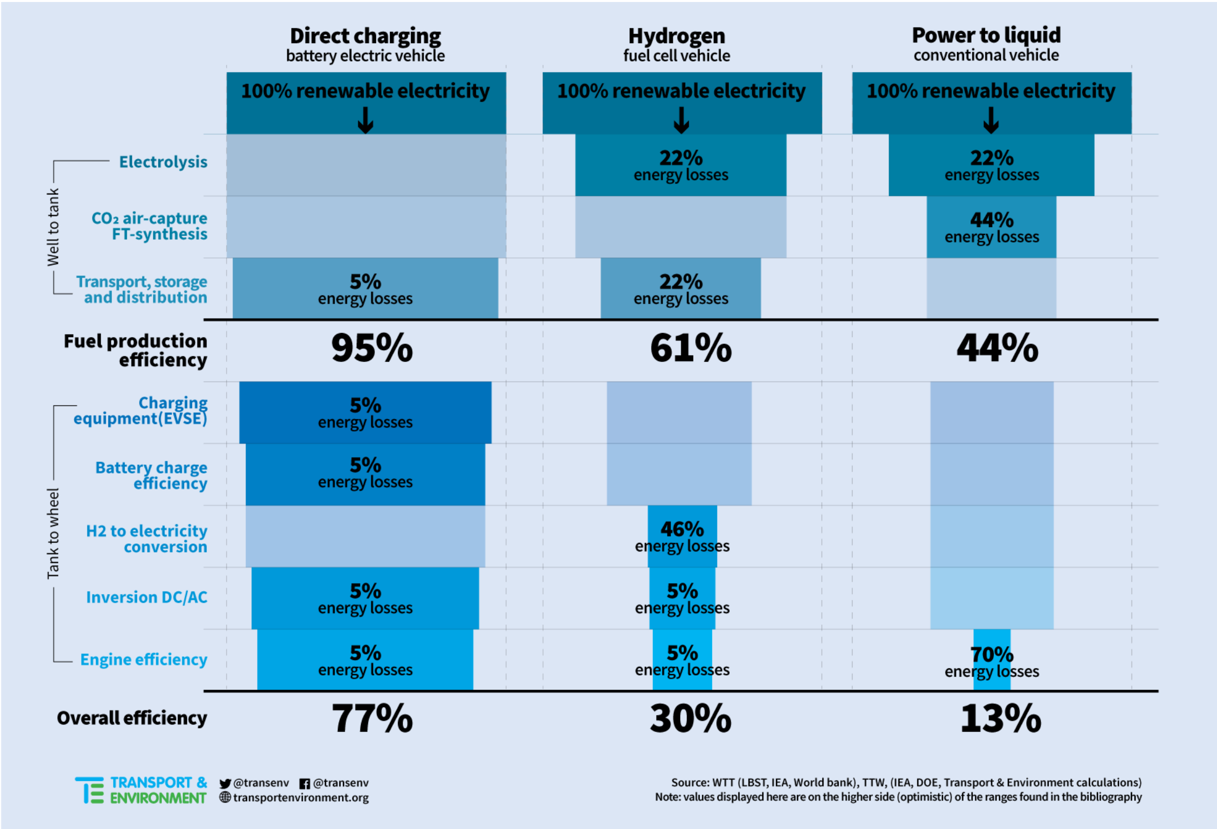

Figure 5: Efficiency of different passenger cars technology pathways based on renewable electricity. Details of assumptions to produce this graph in Appendix 3.

4.3. Conclusion: BEVs optimal for decarbonisation

Sales of light duty vehicles with engines must end by 2035 to ensure that by 2050 the fleet is fully decarbonised. Such a radical change cannot be achieved through incremental improvements to existing ICE vehicles. There is a limit to the efficiency improvements possible with internal combustion engines and zero carbon fuels.

By 2030, advanced biofuels are legislated to contribute about 3.5% of transport fuels and their growth beyond this date is likely to be constrained due to land availability. To produce sufficient synthetic fuels to power all passenger cars in 2050 in the baseline scenario would require renewable electricity production equivalent to the size of the current EU-grid, due to its inefficiency[6]. The gas industry equally cannot produce nearly enough biomethane sustainably from wastes and residues to power a European car fleet, and fossil gas is not an option if cars are to be decarbonised.

In contrast, the price and performance of batteries will improve dramatically between 2010 and the early 2020s. The range of new cars is increasing rapidly to 500 km or more and, with ultrafast charging, cars will be recharged in minutes. The electricity industry is bound by the EU ETS to decarbonise and the price of renewables is falling – electric cars will become a complement to smart, renewable grids.

In summary, the most efficient and promising technology to decarbonise cars is already here and appears to be battery electric. Fuel cell cars are also a zero emission option but are less commercialised today. T&E modelling below (Table 2) shows how much electricity will be needed to power the European car fleet with those zero emission technologies in 2050.

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[6] In the baseline scenario, energy demand is projected to be 5471 PJ, or 1520 TWh. With the conversion efficiency of 44% for producing the fuel, this would imply 3454 TWh of zero-carbon electricity. In 2015, the EU electricity generation was 3234 TWh (EU energy in Figures 2017 [link])

4.4. Results on CO_2 emissions

In order to put the emissions from the remaining passenger cars (after reduced demand) on a trajectory to zero by 2050, an ambitious uptake of ZEVs is required. Figure 6 (left) shows the new vehicle sales that would be required, and technologically possible to make this transition. In 2025, 15% sales of ZEVs and 10% of PHEVs would be aligned with the European Parliament position on the 2025 CO_2 standards, assuming 0.5 credits for PHEVs to reach 20% ZLEV sales. In 2023, the 2030 targets are likely to be revised. As the progress to more EVs on the road will have already begun in earnest, the 2030 target may be ratchetted up to ensure policy, and fiscal at national level, support is provided so that EVs will be on an optimal pathway to achieving 100% ZEV sales in 2035. Although the car CO_2 regulation would already be met on paper by achieving these ZEV shares, it is also technically possible for ICEs to continue to improve. It is assumed that there is only 5% fuel efficiency improvement of ICEs in 2025, but after the 2023 review, it is further assumed OEMs are required to improve by 20% by 2030 (compared to 2021). From 2035 onwards, only ZEVs are sold

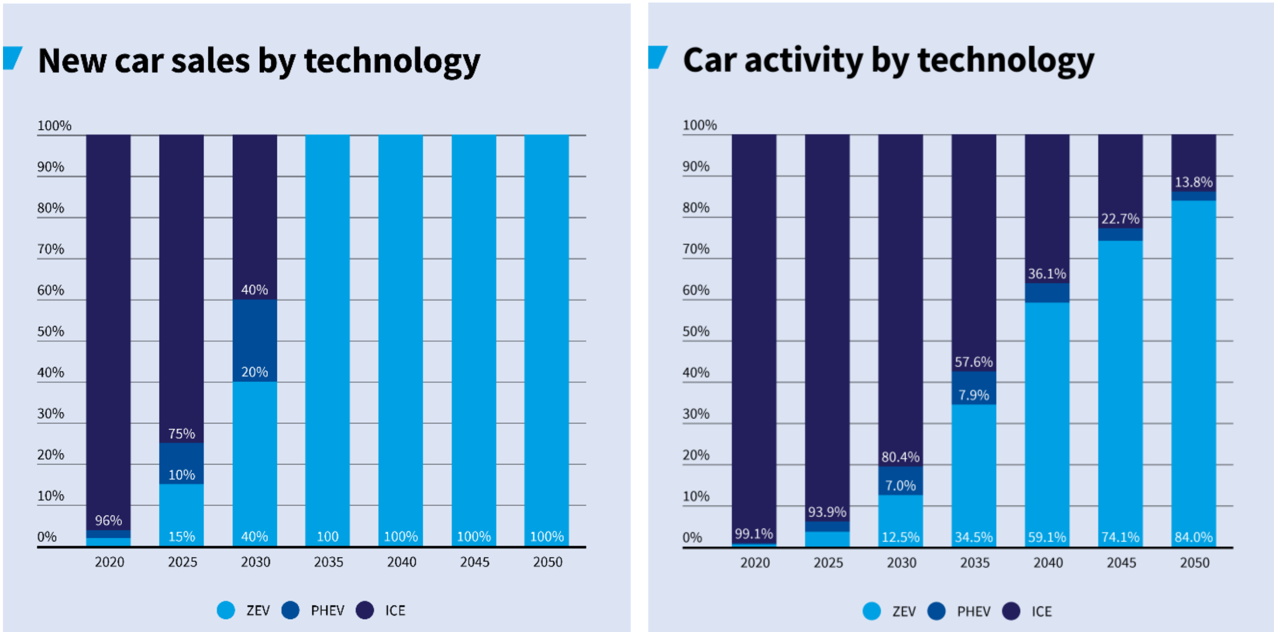

Figure 6: Passenger car sales (left) and vehicle activity in vkm (right) by technology type.

Figure 6 (right) displays the evolution of the vehicle kilometres (vkm) by drivetrain. Although the last ICEs will have been sold in 2034, there may still represent a significant vehicle activity in 2050. These cars will be disproportionately circulating around Central and Eastern Europe; much in the same way as diesel vehicles from Western Europe flood the second hand markets in the East[lxxix], with no targeted policy measures to restrict their use, this will also be the case for ICEs.

Figure 7 shows the reduction in GHG emissions based on ambitious short and midterm policy to push electrification, in combination with demand reduction measures described in section 3. By 2050, emissions are reduced by 89.4% compared to 2015 levels, to 54.7 Mt CO_2 eq. Between 2016 to 2050, the cumulative emissions would be 10.3 Gt CO_2eq. Close inspection of the GHG emissions of cars in Poland makes it go from the 6th largest European emitter in 2015 to the largest in 2050, owing to a reduction in emissions of only -48.3% compared to the projected reduction in Germany of -96.5%. Although there is a significant reduction in GHG emissions based on the combined measures of demand reduction and full electrification of new car sales from mid-2030s, the emissions are still not at zero.

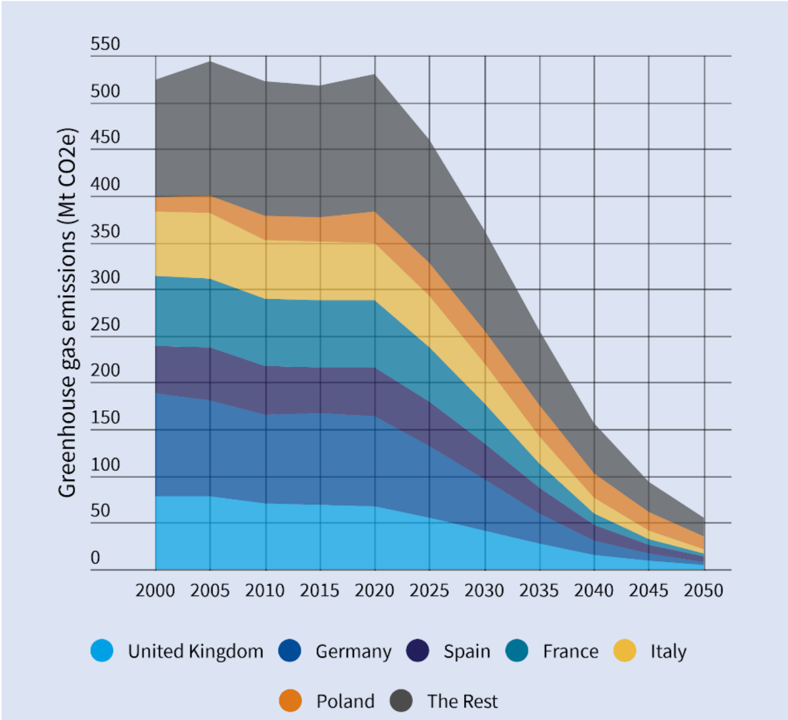

Figure 7: Projected emissions with strong electrification and demand reduction measures.

4.5. Not enough, additional action needed

This analysis shows that even with very ambitious strategy of demand reduction and full electrification of the new fleet, it is not feasible to achieve full decarbonisation of the car segment by 2050. With only ZEVs sold from 2035, cars are still responsible for around 55 Mt of CO_2 due to the activity of the residual ICEs in the fleet. This means additional measures are needed to target the existing fleet and ensure its fast retirement.

There are a number of measures available to speed up fleet renewal across Europe, notably:

- EU vehicle type approval can be made limited in time, e.g. if the last ICE is sold in 2035, it permit has to be limited to 15 years (or longer if the last ICE is sold earlier) unless the car meets the latest emission standards (e.g. plug-in) or can be retrofitted. This would ensure the older polluting vehicles are removed from circulation by 2050.
- Member states can also put in programs targeting faster fleet renewal nationally and get drivers to buy ZEV sooner. Particular support is needed in Central and Eastern European countries where the average age of cars on the road is high and most sales are second-hand.
- Locally, zero emission zones in cities is an effective tool to encourage drivers switch away from older polluting cars in favour of ZEVs. By 2050, 80% of the EU population is projected to live in urban areas[lxxx], so zero emission city centres will impact driver behaviour beyond city borders and incentivise large proportion of the EU drivers to replace their ICE cars.

Figure 8 shows the result of these measures in removing all ICEs from the fleet by 2050, where no GHG emissions are emitted by any light duty vehicle. The passenger activity performed by those retired vehicles would instead be carried out by EVs. This would require 475 TWh of renewable electricity, or 14.7% of the total generated in the EU. The cumulative emissions from 2016 to 2050 would be 10.5 Gt CO_2eq. It also shows the difference between powertrains, where a fleet of battery electric cars would require a factor of between 3 to 5 times less than hydrogen fuel cell or e-fuel powered cars, respectively.

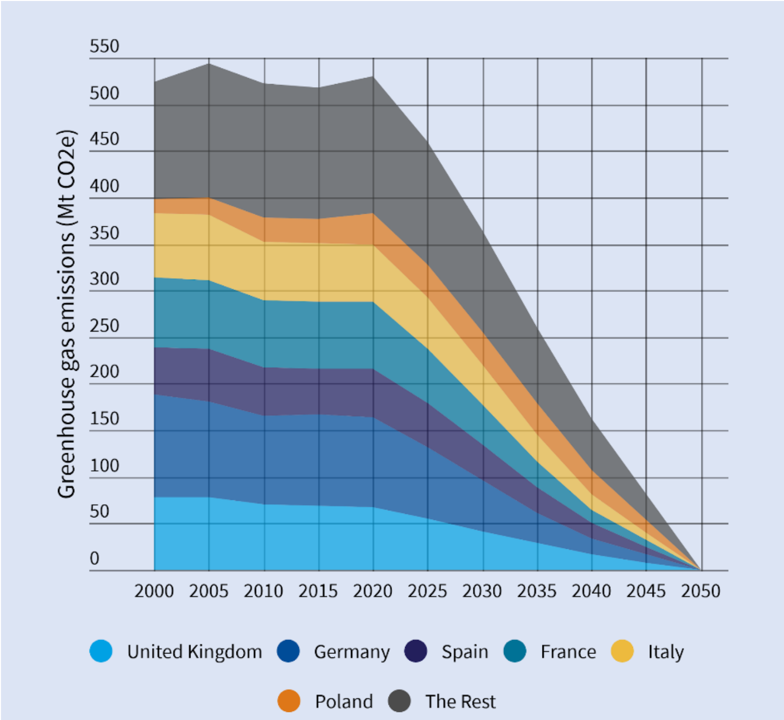

Figure 8: Projected emissions with strong electrification and demand reduction measures with limit on type approval for ICEs.

4.6. Additional electricity demand

In the scenario of 100% of the remaining car demand met by battery electric cars, and with average transmission losses over the electricity grid across Europe of 5%[7], the amount of *additional* clean electricity required to power the fleet of cars in Europe in 2050 is 475 TWh, or 14.7% of the electricity generated in the EU in 2015. There is significantly less energy compared to an equivalent ICE fleet: EVs are around 2.7 times more efficient than ICEs on a Tank-to-Wheel (TTW) basis today, a ratio projected to reduce to 2.2 owing to ICE improvements.

To see what the effect of FCEV vehicles, rather than purely BEV, would be on electricity demand, it is assumed that 10% of vehicle activity was from these vehicles in 2050 (sales ramping up linearly from 0% in 2030 to 20% in 2050). Taking into account the efficiency of well to wheel results shown in Figure 5, electricity demand would be 551 TWh, or around 15% more than in pure BEV scenario. If FC vehicle activity was doubled to 20% in 2050, this would create a demand of 627 TWh of additional, renewable electricity to produce and then use hydrogen from electrolysis. Table 2 shows the additional electricity required depending on the full adoption of each zero emission technology pathway shown in Figure 8. The Table shows the results with and without demand reduction, clearly highlighting the role that it plays in reducing final electricity demand, regardless of the powertrain.

Table 2: Electricity demand requirements for full decarbonisation. In brackets is comparison with electricity generation in the EU in 2015 (3234 TWh)

	Battery electric	Hydrogen fuel cell	E-Fuels
100% of fleet in 2050 with baseline passenger demand	589 TWh (18%)	1534 TWh (47%)	3455 TWh (107%)
100% of fleet in 2050 after demand reduction measure and ICE phase out	475 TWh (15%)	1236 TWh (38%)	2187 TWh (68%)

[7] According to the World Bank, in 2014 transmission and distribution losses in the EU were 6.4% in 2014. Based on the downward trajectory, it is assumed that today this is 5%. [link]

4.7. Implications for the carbon budget

From the results described in this report, the cumulative emissions from 2016 to 2050 can be compared to calculations of the carbon budget. At the time of writing, the global carbon budget is 384 Gt CO_2 eq.[lxxxi], taking into the account the IPCC Special Report on Global Warming of 1.5°C[lxxxii]. From this report, it is recommended that global CO_2 emissions *would need to fall by about 45 percent from 2010 levels by 2030, reaching 'net zero' around 2050*. This paper shows passenger cars reaching zero by 2050, however the reduction by 2030 is only 30% compared to 2010. The assumption here, however, is one of grandfathering the share of emissions of today, into the future. This is arguably not the most equitable calculation of the remaining carbon budgets, as rich countries such as those found in Europe have benefitted vastly from fossil fuels, particularly in the form of burning refined oil products in passenger cars.

As previously mentioned, DLR[lxxxiii] and the Öko Institut[lxxxiv] calculated carbon budgets for passenger cars in Europe and the non-ETS sectors in Europe, respectively. Although pre-dating the IPCC special report, and using a grandfathering calculation[8], the reports provide specific budgets for 1.5°C and 2°C that can be used as comparison. With a base year of 2015, the DLR study gives a 3.6 Gt CO_2 budget for passenger cars to limit warming to 1.5°C with a 66% statistical likelihood, and 6.0 Gt CO_2 with a 50% likelihood. Based on these budgets, the final scenario presented in this report would exceed the threshold for limiting warming to 1.5°C with a 50% probability. From the Öko paper, there is a 850 Gt CO_2 budget with 66% probability to limit warming to 2°C; applying a similar grandfathering methodology to this limit as per DLR would mean that the budget for European cars would be 11.3 Gt CO_2. In this case, only the rapid electrification of the fleet resulting in decarbonisation by 2050 would mean that the European car sector would have a chance at a fair contribution to limit climate warming to 2°C. To stay within the 1.5°c carbon budget even more aggressive action would need to be taken and the entire EU 2030 climate and energy framework and in particular its light duty provisions would need to be overhauled.

5. Policy recommendations

To achieve the full decarbonisation of the car fleet by 2050 at the latest, a transformation is needed in the way that personal mobility is delivered, including a rapid demand reduction, shift to zero emission and shared mobility, and a significant modal shift to public transport and co-mobility solutions. This analysis shows that even with a very drastic reduction in car use, the demand for cars and therefore zero emission technology will remain the same (but will need less clean electricity and resources). In any case, to make zero emission mobility a reality in Europe a bigger and faster commitment from the industry to invest and sell ZEVs is urgently required. Electric cars will be bought if there is good choice, if they are available in showrooms to buy with a respectable lead time, and if they are actively marketed and priced competitively. At present just 20 battery models are presently available compared to over 400 with internal combustion engines.[lxxxv] Marketing spend is typically 1-2% of total spend[lxxxvi] – well below the level needed to promote a new technology. The preferred business for the car industry in Europe today is to continue to sell diesel to recover past erroneous investments. This is why regulation is essential to kick start the market and go beyond the expected sales of plug-in cars of 5-7% in 2021 needed to meet the EU 2021 95g/km CO_2 standard.[lxxxvii]

To go beyond those levels and leapfrog to the EV shares closer to countries like Norway, the EU should without delay agree ambitious CO_2 standards for 2025/30 and put in place other supporting legislation, i.e. on charging infrastructure and sustainable batteries. The current 2030 car CO_2 standards as proposed by the Commission fall considerably short of putting the EU on the track to cost-effective and optimal long-term decarbonisation. Instead of the inadequate 30 or 35% reduction, targets closer to 60% reduction is

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[8] In the grandfathering approach the remaining budget/share of the annual pathway is divided based on current emission share (Idem.)

needed by 2030 – double what is proposed. National tax reform is also needed since it will be not feasible - or indeed desirable - continue support the purchase of ZEVs via grants as their numbers rapidly increase.

T&E is therefore putting forward the following policy recommendations:

1. Without delay, in a 2023 review at the latest, align the 2030 CO_2 standards for cars with the Paris-compliant trajectory, i.e. at least 50-60% in 2030
2. Set an indicative target of zero emission for all new cars sold after 2035 at the latest to indicate a clear direction to the industry and provide enough lead time
3. Governments must reform national vehicle taxation policies to speed up transition and create the required total cost of ownership parity by means of purchase taxes to raise the costs of ICE's and lower those of ZEVs
4. Update the current Alternative Fuels Infrastructure Directive to set mandatory charging infrastructure targets for member states and ensure full coverage and interoperability of the EU's Core and Comprehensive road network by 2030
5. Via an enabling framework support a timely development of EV supply chain in Europe, including competitive manufacturing of safe and sustainable batteries (the EU Battery Labelling and Battery Directive review)

However, even with 100% ZEV sales after 2035, the remaining fleet of fossil cars will continue to emit close to 60Mt of CO_2 in 2050, even more if demand is not reduced, so additional measures are needed to speed up fleet renewal. Limits to EU vehicle circulation length (via type approval), national support to retire old cars and zero emission zones in cities will all help drivers retire their old polluting cars faster and enable the EU to achieve full decarbonisation of the entire car segment in 2050.

Appendix 1 - Will the market alone decarbonise cars in Europe?

The baseline scenario assumes no changes to the fleet beyond 2030, an appropriate measure from which to compare the implementation of effective decarbonising policies. The aim of this section is to understand what may happen to car emissions in Europe based on global market trends, which are pointing towards an electrified or hydrogen future.

The Global EV Outlook of the International Energy Agency puts the number of EVs on the road globally between 125 and 220 million in 2030[lxxxviii] (compared to around 950 million passenger cars in use[lxxxix], this would equate to up to 23%), while the Bloomberg New Energy Finance predicts that by 2040 at least 55% of all car sales will be plug-in[xc]. As regards 2050, a recent study[xci] by some carmakers, trade unions and NGOs expects all car sales to be plug-in by then, including 71% battery electric, 26% fuel cell and the remaining 3% plug-in hybrid.

Taking these various studies into account, we assume a gradual uptake of low-emission vehicles (LEVs), where no further policy measures (such as zero emission vehicle mandates, low emission zones, ICE bans etc.) are envisaged, but these vehicles gradually increase in popularity and uptake based on the market developments discussed above. Battery electric cars will likely to be a cost comparison by mid 2020s[xcii]. But even if there is a rapid market uptake of plug-in cars in the coming decades, without strong EU policy and domestic incentives the cars will likely be supplied from China (or Japan and South Korea if the shift is towards fuel cell), which would have grave economic and employment consequences for Europe. The inputs for these scenarios are shown in Table 3.

Table 3: Assumed sales in LEVs with gradual, market driven uptake. This compares to a baseline scenario where nothing changes after 2030.

Year	PHEV sales	ZEV sales
2030	10%	10%
2040	20%	25%
2050	30%	40%

With a gradual ingress of PHEVs and BEVs in the 2020s and 2040s, that eventually come to dominate the market, emissions in 2050 are projected to be 323 Mt CO_2eq., or 37.6% less than 2015 emissions (Figure 9)[9]. From 2016, these emissions would cumulatively amount to 16.0 Gt CO_2eq, growing the total cumulative emissions every year as they are far from zero. The projected emissions in 2050 are far from reaching the Paris Agreement compliant target of zero emissions by 2050 at the latest. Linearly projecting these emissions beyond 2050 would indicate decarbonisation in the 2070s, more than 20 years later than necessary. These projections demonstrate the imperativeness of effective policy that legislates to meet these targets. With these assumptions, the market alone will not deliver passenger cars that are Paris compliant.

[9] This does not include demand reduction measures

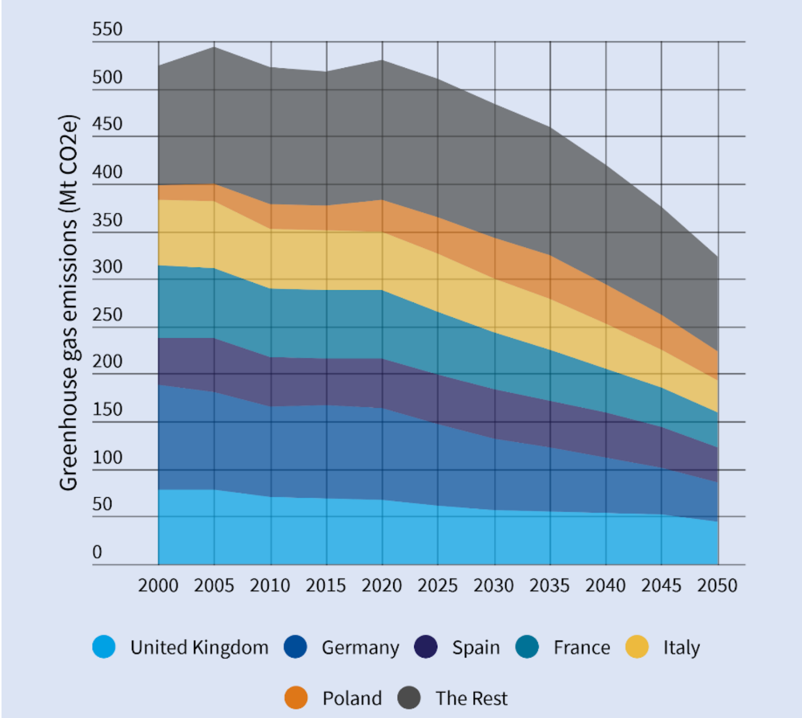

Figure 9: Modelling market penetration alone will not decarbonise cars in Europe by 2050.

Appendix 2 - Model inputs for demand reduction

Section 3 described and quantified, where possible, the potential impacts of policy on transport demand, modal shift to cleaner transport, and policies to increase the efficiency of the transport system. These policies can have complex interactions and do not necessarily result in accumulative benefits. Therefore, these inputs are based on careful consideration of each measure so as not to overstate the potential of any given measure or combination of measures. On the other hand, these measures could be seen as targets that Member States of the European Union would need to achieve in order to meet its long term decarbonisation targets while designing policy. For example, to ensure car passengers are shifted to walking and cycling by the amount stated below, impact assessments should investigate how to achieve this, and what type of policy and investment is required to get there. In Table 4, the inputs to the model are detailed along with a brief justification and the policy levers required. Note that rebound effects of more efficient vehicles and lower fuel costs for electric vehicles (where reduced costs induce more demand), are not considered, as the combination of other measures are assumed to be designed to negate this effect.

Table 4: Model input assumptions for demand side measures in Section 3: Behavioural measures to cut fuel demand.

Policy Lever	Measure	Change by 2030	Change by 2050	Main policy interactions and justification for assumption	Implication of measure
1	SHARE OF CAR ACTIVITY SHIFTED TO BUS	2.0%	4.0%	Fuel tax normalisation between petrol and diesel with a general increase in excise duty; new electric buses being able to offer cheaper services; congestion zones disincentivising car ownership and use; coach market expansion; bus lane expansion.	4% of 2050 passenger activity in cars is 57% of 2016 bus activity. Since 2000, bus activity has not changed.
2	SHARE OF CAR ACTIVITY SHIFTED TO RAIL	2.0%	4.0%	This represents a significant increase of current tram, metro and train ridership. This will be facilitated from fuel taxes, TEN-T network implementation (long distance), intermodality, train pricing and improved punctuality, competition offering new and more attractive services.	4% implies an increase of 70% of passenger rail activity. Since 2000, rail activity has increased 21%.
3	MODE SHIFT FROM CAR TO WALK/ BIKE	2.0%	4.0%	As part of a city infrastructure investment (cycle- and footpaths), congestion charges that reduce traffic in order to reclaim space, more people willing to take public transport. Increased availability of shared e-Scooters.	Walking and cycling activity is usually expressed as a number of trips, and typically represent short distances.

4	LDV LOAD FACTOR INCREASE (PASSENGERS/VEHICLE)	5.0%	10.0%	Car sharing phone applications; incentives and/or priority access to carpooling cars (e.g. high congestion charges for single occupancy vehicles); higher vehicle registration taxes; low emission zones; higher fuel taxes.	The EU average car occupancy is on average ~1.6 person per car, this would be ~1.8 with a 10% increase.
5	LDV ACTIVITY - REDUCTION FROM BASE CASE	5.0%	10.0%	Combination of fuel tax harmonisation and increase, low emission zones, congestion zones, toll roads and distance based charging. Other forms of reduction in demand has been through modal shift (policy levers 1,2,3)	N/A
6	REDUCTION IN IN-USE FUEL CONSUMPTION OF ON-ROAD VEHICLES	5.0%	5.0%	C-ITS, eco-driving, congestion relief through time based charging, reduced and heavily enforced speed limits.	N/A

Appendix 3 - Assumptions on drivetrain efficiencies

The efficiency pathways for different drivetrains are derived from a number of sources. This Appendix details the assumptions used and their sources. The values taken are assumed to be optimistic or expected values for the near future (up to 2030).

Table 5: Assumptions and sources for energy efficiency graph (Figure 5). #Applicable to battery electric and hydrogen fuel cell drivetrains. §Applicable to both e-fuel and hydrogen fuel cell

Drivetrain	Process	Losses	Source
Battery Electric	Transport, storage and distribution	95%	The value in 2014 was 6.44%; we assume it improves over time to 5%. Source: https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?locations=1W-EU
	Charging equipment (EVSE)	95%	Poliscanova, 2018. Grid-to-motor efficiency comparison of a fuel cell and a battery electric vehicle
	Battery charge efficiency	95%	Poliscanova, 2018. Grid-to-motor efficiency comparison of a fuel cell and a battery electric vehicle
	Inversion DC/AC#	95%	https://matter2energy.wordpress.com/2013/02/22/wells-to-wheels-electric-car-efficiency/
	Engine efficiency#	95%	Pellegrino G., Vagati, A., Boazzo, B., Guglielmi, P. (2012) Comparison of Induction and PM Synchronous Motor Drives for EV Application Including Design Examples. Available: https://ieeexplore.ieee.org/document/6352905
Hydrogen Fuel Cell	Electrolysis§	78%	Poliscanova, 2018. Grid-to-motor efficiency comparison of a fuel cell and a battery electric vehicle. (PEM electrolyser). Higher but same order as quoted by IEA: https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHydrogenandFuelCells.pdf (today)
	Transport, storage and distribution	78%	IEA states 15% losses at 35MPa, 30% losses at 70MPa: https://iea-etsap.org/E-TechDS/PDF/P12_H2_Feb2014_FINAL%203_CRES-2a-GS%20Mz%20GSOK.pdf
	H2 to Electricity conversion	54%	IEA value for 2030: https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapHydrogenandFuelCells.pdf
E-Fuels used in internal combustion engine	CO_2 air-capture, FT-synthesis	56%	Calculated, based on stated efficiency of 44%: http://www.lbst.de/news/2016_docs/FVV_H1086_Renewables-in-Transport-2050-Kraftstoffstudie_II.pdf.
	Engine efficiency	30%	Engine losses stated in combined driving of 68% to 72%: https://fueleconomy.gov/feg/atv.shtml

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