REflex

Analysis of the European energy system

# Policy Brief

## Transport trends in the context of future energy scenarios

Angelo Martino
Francesca Fermi
Davide Fiorello
TRT Trasporti e Territorio srl

Stephanie Heitel
Michael Krail
Fraunhofer ISI

Katrin Seddig
Patrick Jochem
KIT-IIP

# Bibliographical data

Angelo Martino, Francesca Fermi, Davide Fiorello
TRT Trasporti e Territorio srl

Stephanie Heitel, Michael Krail
Fraunhofer Institute for Systems and Innovation Research (ISI)

Katrin Seddig, Patrick Jochem
Karlsruhe Institute of Technology (KIT)

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| | |
|---|---|
| BEV | Battery Electric Vehicle |
| C-ITS | Collaborative Intelligent Transport Systems |
| CNG | Compressed Natural Gas |
| EU | European Union |
| FCEV | Fuel Cell Electric Vehicle |
| GDP | Gross Domestic Product |
| GHG | Greenhouse Gas |
| HDV | Heavy Duty Vehicles |
| ICE | Internal Combustion Engine |
| ICT | Information and Communication Technology |
| IWW | Inland Waterways |
| LDV | Light Duty Vehicles |
| LPG | Liquefied Petroleum Gas |
| PHEV | Plug-in Hybrid Electric Vehicle |
| PtG | Power-to-Gas |
| PtL | Power-to-Liquid |
| PtX | Power-to-X |
| PV | Photovoltaic |

# 1 Introduction

Despite the decreasing trend of all other energy demand sectors, the transport sector shows still an upwards trend in its greenhouse gas (GHG) emissions (European Environment Agency, 2018). Furthermore, there is no reversal of this trend in sight even though these emissions need to be reduced drastically – by at least 60% in 2050 relative to 1990 levels (European Commission, 2011). This minimum goal for the transport sector was affirmed in the European Strategy for Low-Emission Mobility (European Commission, 2016a). According to this strategy the reversal of the ongoing upward-trend should be approached soon and also air pollutants harming our health need to be substantially reduced. Considering also the continuous growth of passenger and freight transport demand, substantial technological developments as well as strong and timely policy instruments are required.

Today, the transport sector accounts for around 30% of the European greenhouse gas emissions. As reported by the European Environment Agency (European Commission, 2017), emissions mainly stem from road transport (73%) and from aviation (13%). Road transport emissions are mainly caused by passenger cars (61%), by heavy duty trucks and buses (26%) and by light duty vehicles (12%). Importantly, the transport sector is highly oil dependent and responsible for about 33% of overall final energy consumption in EU28 countries (European Commission 2017) but only 3% (about 60 TWh in 2015) of electricity demand.

The European Strategy for low-emission mobility sets clear guiding principles for the transition towards a low-carbon transport sector and is the basis of the policy scenarios applied in the REFLEX project. The three main strategic elements are:

1) Increasing the efficiency of the transport system by making the most of digital technologies, smart pricing and further encouraging the shift to lower emission transport modes, in particular ships, rail and public transport,
2) Speeding up the deployment of low-emission alternative energy for transport, such as advanced biofuels, electricity, hydrogen and renewable synthetic fuels and removing obstacles to the electrification of transport,
3) Moving towards zero-emission vehicles: accelerating the transition towards low- and zero-emission vehicles comprising plug-in hybrid (PHEV), battery (BEV) and fuel cell (FCEV) electric vehicles while making further improvements to the internal combustion engine (ICE).

# 2 Modelling framework

In the REFLEX project a modelling framework is used for the analysis of the European decarbonisation pathways for the transport sector and the related impacts on energy consumption and flexibility is estimated: the ASTRA (ASsessment of TRAnsport strategies) model at European scale is complemented with the TE3 (Transport, Energy, Economics, Environment) model considering the key non-European automotive markets to simulate global learning effects for new vehicle technologies. In addition, ASTRA is coupled with the models eLOAD and ELTRAMOD to simulate feedback mechanisms between electricity consumption patterns, electricity supply and prices.

**ASTRA**[1] is a system dynamics model simulating the EU transport system development in combination with the economy and the environment until the year 2050. The model is made of different modules that interact among each other with direct linkages and feed-back effects. Strategic assessment capabilities in ASTRA cover a wide range of transport measures and investments with flexible timing and levels of implementation. ASTRA consists of different modules, each related to one specific aspect such as the economy, transport demand or the vehicle fleet. The main modules cover the following aspects:

- transport, simulating generation, distribution and modal split of passenger and freight movements;
- vehicle fleet, simulating the development through the years of road vehicle fleet composition and technologies;
- population, simulating the evolution of socio-economic population groups;
- economy, which simulates the linkages of the transport sector with the whole economic system and covering the estimation of GDP, input-output matrices employment, consumption and investment;
- foreign trade, both inside EU and to countries / regions from outside EU
- environment, including the calculation of energy consumption, air pollutant emissions, GHG emissions and accidents.

The indicators that ASTRA can produce cover a wide range of impacts; in particular transport system operation, economic, environmental and social indicators. Within REFLEX, ASTRA provides the estimation of final energy consumption for different energy carriers relevant for the transport sector. In order to support this analysis, the model has been enhanced taking into account the requested technical transition of vehicle fleets for all transport modes from fossil fuels towards renewable energy carriers as well as new mobility concepts and behaviour change towards active modes.

The diffusion of alternative drive technologies is simulated separately for different vehicle categories. These categories comprise private and commercial cars, light duty vehicles, heavy duty vehicles in four gross vehicle weight categories, urban buses and coaches. Based on the technical characteristics of available fuel options today and in the future and the heterogeneous requirements of the different users, a set of fuel options is available for each vehicle category.

New mobility concepts (such as car sharing services) are a further development in the transport system that is taken into consideration in ASTRA; furthermore, active passenger transport modes are explicitly considered in terms of walking and cycling mode in urban areas.

Transport system investments are also modelled in ASTRA. For example, deployment of filling station infrastructure is fed in via exogenous data, but can also develop dynamically in the model based on the scenario e.g. assuming a certain ratio of charging points per battery-electric vehicle. Required investments in transport infrastructure depend endogenously on

[1] http://www.astra-model.eu/

the transport activity development and are additionally increased in case of policies like an improvement of public transport.

The System Dynamics based multi-country model **TE3** provides a simplified representation of the road passenger transport system, with a focus on car travel activity and car powertrain technologies. In particular, the modelling exercise underlying TE3 can be divided into three main steps:

1) Projection of the total car stock by means of an aggregate econometric model,
2) Simulation of market shares by car technology by means of a discrete choice modelling framework and
3) Estimation of energy use and greenhouse gas emissions by means of an accounting framework.

In REFLEX, the TE3 model creates scenarios of the dynamic market penetration of alternative car technologies in the key non-European countries (China, India, Japan and US). The interaction between ASTRA and TE3 is performed with feedback loops in terms of electric vehicles (cars) sold in key non-EU markets by powertrain technology in order to assess the future prices of electric vehicle batteries and fuel cells based on the learning curve theory.

# 3 Transport scenarios

In order to deal with the complexity and uncertainty of the transformation process and to be in line with the considerations on the energy sector, two main scenarios are distinguished in REFLEX: a “reference” scenario (Mod-RES) based on observed trends and most recent projections and two “policy” scenarios (High-RES) representing a more ambitious decarbonisation pathway for Europe to 2050 according to the prevalence of centralised/decentralized technologies in electricity generation and supply.

The **Mod-RES scenario** considers (only) all policy targets and actions that are already implemented or decided at European and national level by the end of 2017.

For the more ambitious **High-RES policy scenarios**, some measures from Mod-RES are further intensified and complemented by additional regulations in order to achieve a stronger shift to more efficient modes, to low- and zero-emission vehicles and to alternative fuels.

Two measures have a major impact in both High-RES scenarios: i) the mandatory phase-out of internal combustion engine vehicles for new car registrations and light duty vehicles after 2040 and for new urban buses after 2035, in line with the current plans and strategies of several European countries and ii) the adoption of fuel cell technology for long distance road transport. The latter choice is linked to the analysis of the potential of flexibility mechanisms required in an efficient energy system with a large share of volatile renewable energy. Power-to-gas for hydrogen production via electrolysis can provide a certain flexibility potential to the energy system. In the both High-RES scenarios it is assumed that hydrogen is produced in Europe and that FCEV can also be applied for passenger cars, buses and intermediate trucks, thus increasing technological learning and enabling spill-over effects to other vehicle types.

General drivers for both High-RES scenarios are related in particular to road infrastructure pricing with the internalization of external cost for emissions, the diffusion of Collaborative Intelligent Transport Systems (C-ITS) applications, urban policies to promote sustainable mobility and measures encouraging efficiency improvements and multimodality. In addition, improved fuel efficiency is fostered by more ambitious vehicle efficiency standards for new cars, vans, buses and trucks. Furthermore, the penetration of cleaner vehicles is enforced by expanded recharging and refuelling infrastructure and by advanced research and innovation in electro mobility and fuel-cell technology. Increased fuel tax for conventional fuels and reduced fuel tax for electricity, hydrogen, and biofuels, further contribute to the utilization of low-emission energy.

The two High-RES transport scenarios differ for some aspects related to the deployment of the energy system. While renewable power generation mainly takes place in large wind parks in the centralized High-RES scenario, renewable power generation is more locally distributed using for example rooftop photovoltaic and distributed onshore wind plants in the decentralized case.

Two factors are expected to lead to a faster diffusion of electric vehicles in the decentralized High-RES compared to the centralized scenario:

- The number of households with rooftop photovoltaic, that strongly increases over time in the decentralized scenario, have a higher probability to purchase a BEV or PHEV vehicle; such purchasing behaviour is also triggered by financial incentives due to own generation of the electricity for charging the batteries and by higher technical affinity or familiarity.
- As people are more familiar with demand-side management and digitalized monitoring and control, a higher acceptance of multi-modal transport is assumed including more use of car sharing as well as more walking and cycling and reduced car ownership.

Further factors that differ between the two High-RES scenarios can influence the diffusion of FCEV trucks. These factors comprise the production and distribution of hydrogen and conditions with an impact on financial incentives and perceived reliability. While electrolysis to hydrogen and its compression will be operated directly at the filling station in the decentralized scenario, hydrogen is produced in larger plants and transported to the filling stations by combining trailers and pipelines in the centralized scenario. In the centralized system, joint and clear decisions for infrastructure deployment and announcements for a favourable and stable hydrogen price lead to higher perceived reliability and thus to slightly faster diffusion. In contrast, a decentralized energy system with more diverse actors and more need for coordination activities could lead to a slower penetration that varies more widely between countries.

# 4 Main results

## 4.1 Transport activity

Transport demand is another key variable for the analysis of the impacts on the energy system. As transport avoidance strategies were not successful during the last decades, only modal shifts to more efficient modes, technical improvements or less emission intensive cars may lead to a reduction of GHG emissions in transport (cf. Schipper et al., 2000). As mentioned above, transport demand is expected to increase over time until the time horizon of 2050, mainly caused by economic and population growth expected in the future decades (e.g. ITF, 2012). Passenger transport demand is expected to increase by 34% and freight transport by 60% until 2050 with respect to 2015 level. More specifically, road transport will experience a reduced growth rate in the High-RES scenarios with respect to Mod-RES scenario, thanks to policies discouraging the use of private vehicles for passengers (availability of shared mobility, better public transport, partially also higher travel cost due to higher energy taxes) and improved alternatives for freight (enhancement of railways, logistic policies etc.). This impact is especially visible when looking at the modal split for passenger total transport demand, at 2050 the modal share for cars is estimated to decrease with respect to 2015 by 2.4% in Mod-RES and about 4.7% and 5.6% respectively in High-RES decentralized and centralized scenario, mostly in favour of rail and air transport. Air transport is also estimated to gain some 3% modal share by 2050, although energy taxes on aviation fuels like kerosene may limit part of the long-term expansion of air traffic.

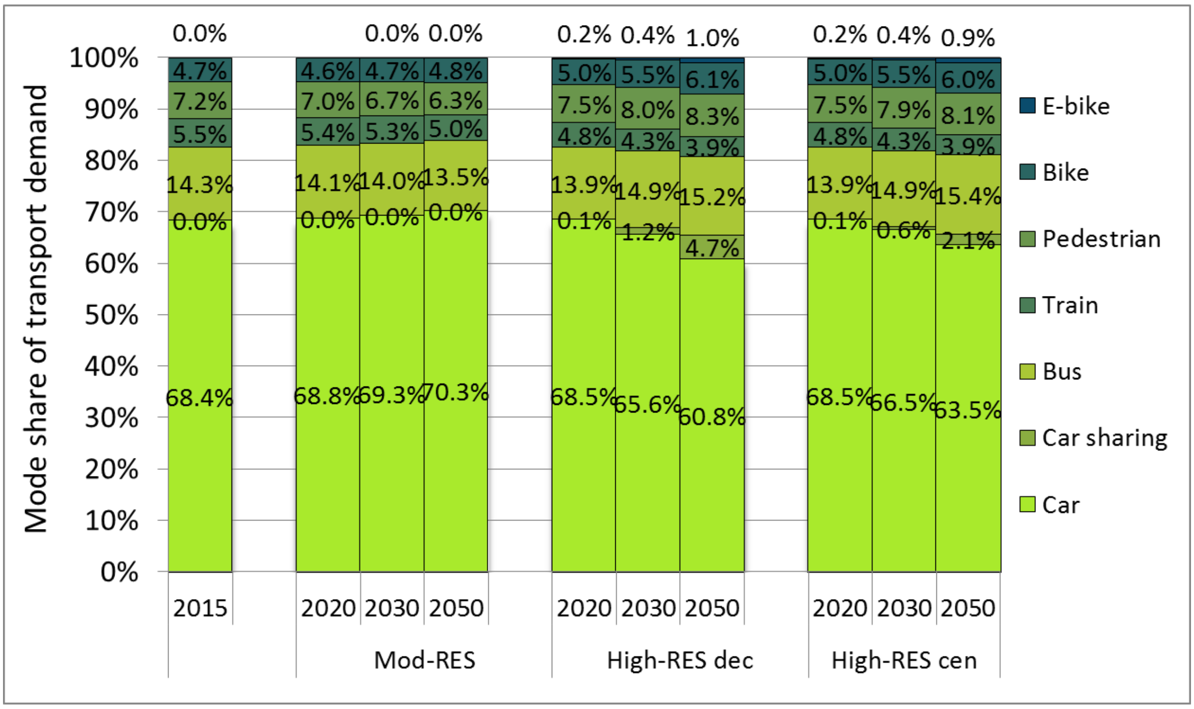


**Figure 1: EU28 countries – passenger-km modal split of local transport demand (trips < 50 km)**

Interesting results can be observed when looking at short-distance transport demand (i.e. below 50 km) presented in Figure 1. Here modal shift from private cars to more sustainable modes is in fact more pronounced: in the two High-RES policy scenarios, the private car share is estimated to decrease by 7.6% and 4.8% in the decentralized and centralized scenario respectively, although part of the demand is shifted to car sharing service (increasing to 4.7% and 2.1% in terms of mode share at 2050). An increased share at 2050 is observed for High-RES scenarios also in terms of active modes (bike, e-bike and pedestrian) used for about 15% of demand. The use of buses is also encouraged and slightly increased in these scenarios by about 1% with respect to 2015. These results suggest that the combination of policy measures such as rail infrastructure investments, improved public transport services, coupled with relevant technological developments (shared transport, ITS, demand management etc.), can make a significant contribution in reducing car use locally.

## 4.2 Road transport fleet composition

As expected, some differences exist between the two High-RES scenarios in terms of a larger share of battery electric passenger vehicles in the decentralized scenario compared to the centralized High-RES (see Figure 2), due to the assumption that in a decentralized world the number of BEV grows faster thanks to an increasing number of households generating electricity. It's interesting to note that in road freight transport, the energy transition process towards low-emission technologies is more delayed than in the passenger segment (compare Figure 2 and Figure 3).

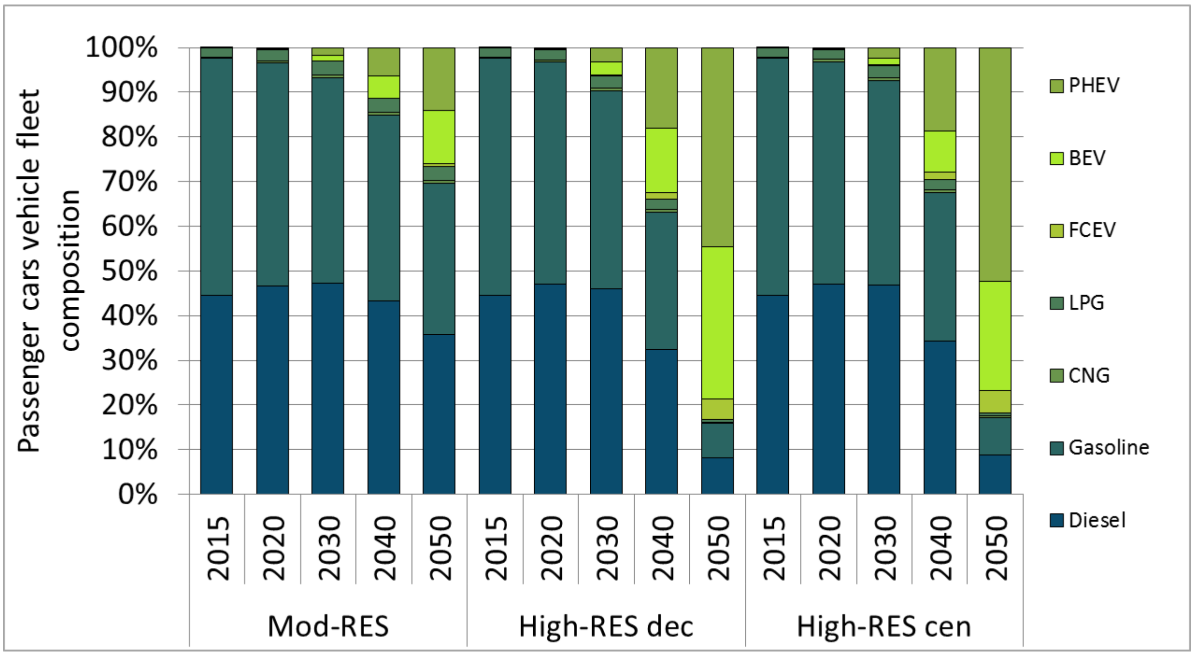


**Figure 2: Development of the car fleet composition from the transport sector for EU28**

These results indicate that in the mid-term, low-emission technologies do not seem to be an option for long-distance trucks, due to their higher costs, limited range and technical issues (e.g. fuelling infrastructure, powertrain weight and dimension leading to negative impacts on load factors). As shown in Figure 3, the change happens after the year 2030 with the penetration of alternative technologies – notably hydrogen powered trucks – supported by investments in infrastructure and R&D, tax incentives and tighter fuel efficiency standard that contribute to make alternative fuels more cost competitive and attractive compared to diesel vehicles. The ASTRA model results show that in the High-RES scenarios low-emission vehicles are estimated to reach a share of 48% to 58% in 2050, where about 13% are electric and plug-in hybrid trucks that belong to the lower weight category of trucks while the remaining part is fuel cell trucks. Additional technology change toward the use of biofuels in other carbon-intensive modes (e.g. biokerosene in the aviation sector) leads to further $CO_2$ reduction, up to 96% of reduction target at 2050.

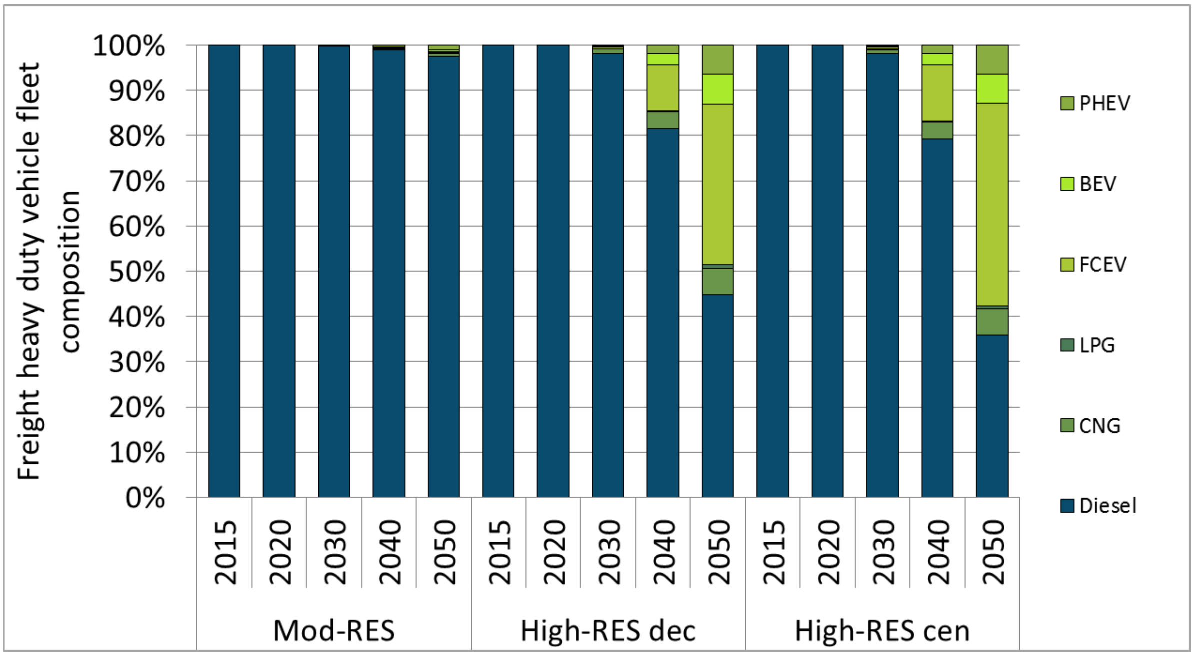


**Figure 3: Development of the truck fleet composition from the transport sector for EU28**

## 4.3 Energy demand

As a result of the electrification of passenger road transport in 2050, electricity demand by transport will be ten times higher compared to the level of 2015: more specifically, annual final electricity demand is expected to reach 200 TWh by 2050 in the Mod-RES scenario, while it grows up respectively to 647 TWh and 600 TWh in both High-RES scenarios (see Figure 4). At the same time, driven by the uptake of fuel cell trucks in road freight transport, which will request about 80% of the hydrogen consumption of the transport sector, final hydrogen demand is estimated to range between 380 TWh and 418 TWh by 2050 in the centralized and the decentralized High-RES scenarios (see Figure 5).

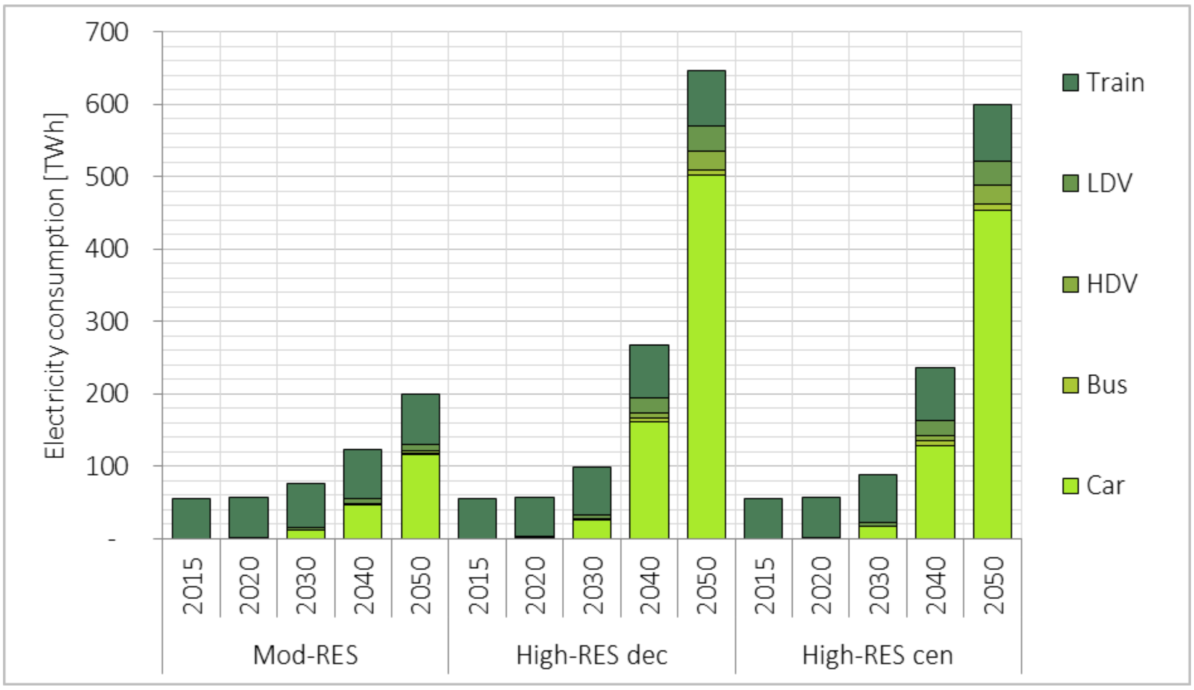


Figure 4: Development of final electricity demand of the transport sector for EU28

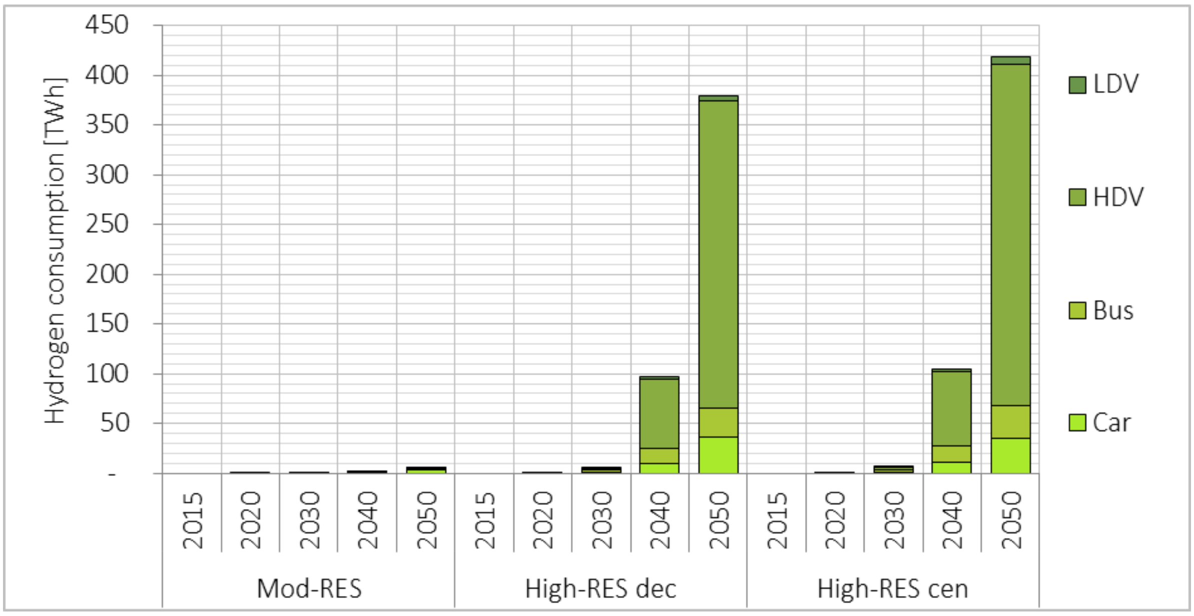


Figure 5: Development of final hydrogen demand of the transport sector for EU28

The demand for biofuels is also estimated to grow significantly, almost triplicating from 2015 to 2050 in the High-RES scenarios with about 42 Mtoe requested at 2050. Compared to the electrification of the vehicle fleet, biofuels make a smaller but still important contribution to decrease future transport GHG emissions. For example, biokerosene used in air transport is estimated to reach almost 19 Mtoe by 2050, helping to reduce the high carbon footprint of the aviation sector.

## 4.4 Tank-to-wheel $CO_2$ emissions

Both High-RES scenarios confirm the achievement of the $CO_2$ emission target reduction at 2050, with a decrease of -60% with respect to 1990 level and about 340 Mt-$CO_2$ /year. The largest $CO_2$ reduction at 2050 with respect to 2015 is obtained in the road sector achieving approximately -90% for LDV, -80% for car and bus and -65% for HDV (see figure 6).

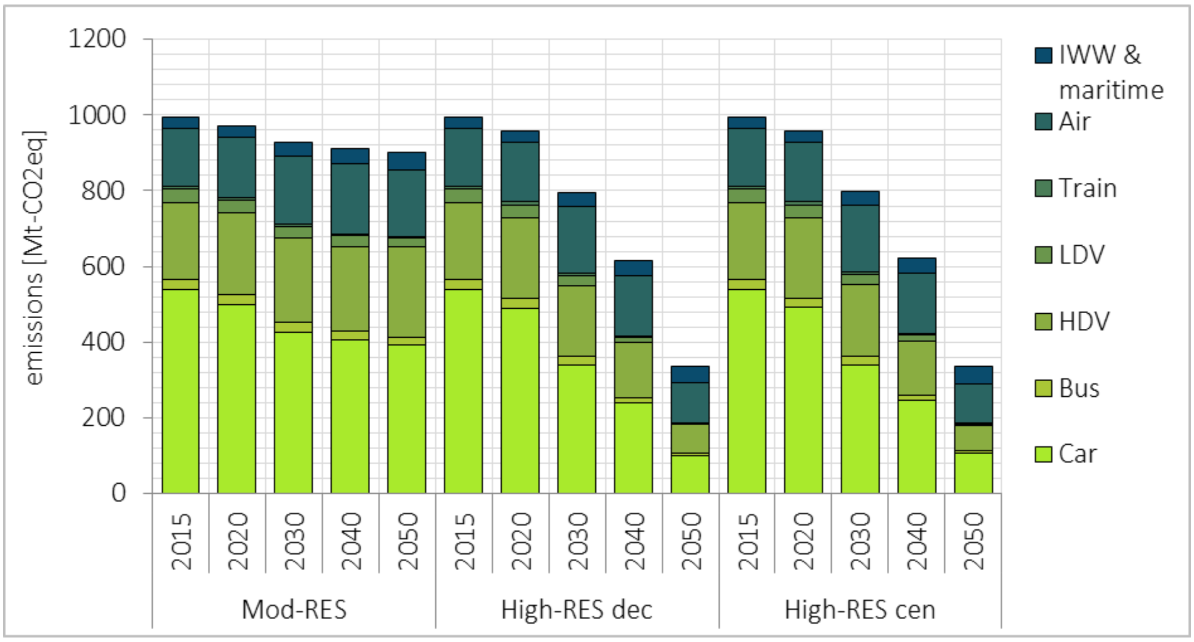


**Figure 6: Development of tank-to-wheel $CO_2$ emissions from the transport sector for EU28**

The substantial technological change in the car passenger vehicle fleet, moving from conventional powertrains to low-emission technologies (also thanks to the ban of ICE vehicles after 2035 and 2040) is the key driver for the transport sector decarbonisation: the ASTRA model estimates that by 2050 BEV, PHEV and FCEV, from their current negligible share in the base year 2015, will have a share of over 80% of the total passenger car stock in the High-RES scenarios compared to 27% in the Mod-RES scenario. In absolute values, the rail sector contributes only marginally to tank-to-wheel $CO_2$ emissions, although a reduction of about -80% is observed with respect to 2015. The -30% $CO_2$ emissions reduction in the air passenger sector is significant in the light of the constant increase in overall transport demand for this mode of transport.

Looking more specifically at the contribution of each policy category, it can be said that alone the fleet technology composition and related policies can contribute to achieve a reduction of -26% (2050 vs 1990 $CO_2$ emissions). By adding of tighter fuel efficiency standard for new vehicles to the fleet technology assumptions, a reduction of -44% can be achieved, while the contribution of additional technology change toward the use of biofuels in other carbon-intensive modes (e.g. bio-kerosene in the aviation sector) leads up to -58% (i.e. almost achieving the reduction target of -60% at 2050). The final bit is then provided by the measures aimed at sustain modal shift for passenger transport in urban areas.

# 5 Comparison with other studies

This section compares the REFLEX project results with the European Commission (2016b) staff working document, which explores a range of policy scenarios and transport decarbonisation pathways based on the PRIMES model, and with a recent study from Cambridge Econometrics (2018) investigating the impact of low-carbon vehicle uptake on EU energy demand and emissions. For a consistent comparison of the REFLEX policy scenarios results, the central policy scenarios from both these studies have been considered, hereafter abbreviated as EUCO and CAMECON.

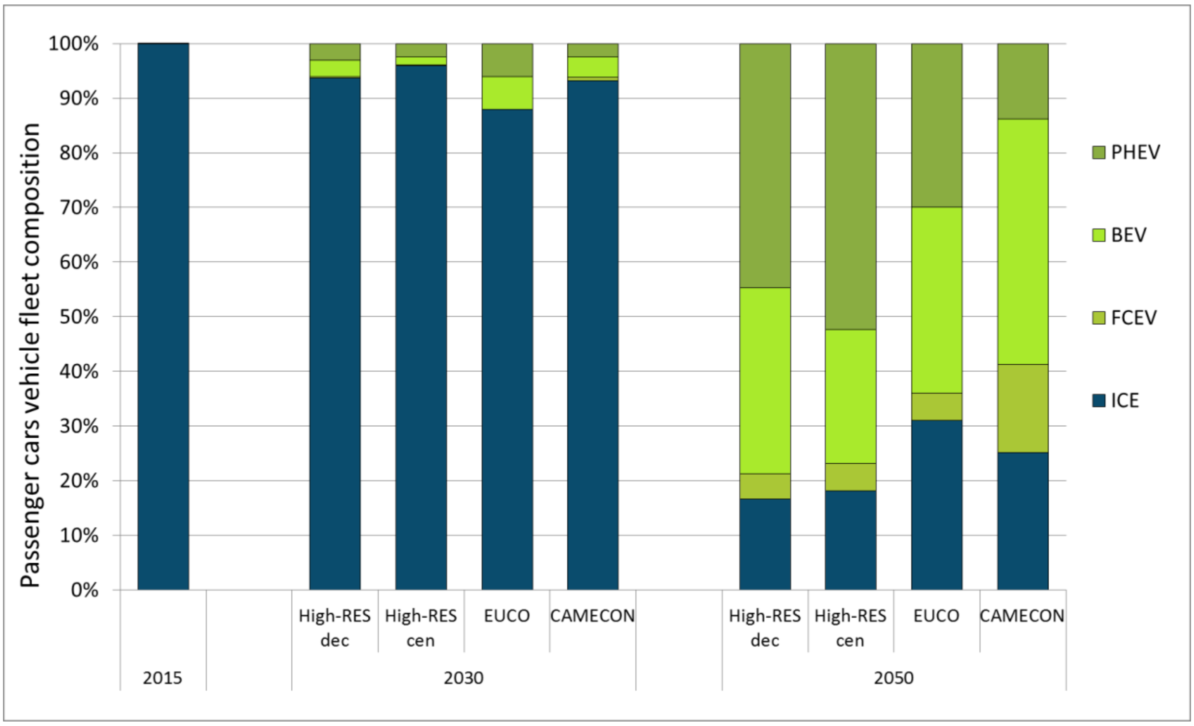


**Figure 7: Results comparison on car passenger vehicle fleet composition for EU28**

Concerning the evolution of passenger car fleet composition, the REFLEX projections are in line with those from the two studies (see Figure 7). All studies predict a general shift from conventional ICE vehicles towards zero-emission technologies, particularly after 2030. REFLEX assumes ICE vehicle sales to end by 2040 and CAMECON by 2035, making the diffusion of Zero Emission Vehicles more pronounced in subsequent years compared to the EUCO projections. Although the phase-out from conventional ICE cars is common to the three studies, with Zero Emission Vehicles representing the vast majority of cars circulating in 2050, some differences exist in the fuel mix especially towards the year 2050. In particular, CAMECON's forecasts show larger diffusion of FCEV (about 15%, compared to 5% in REFLEX and EUCO scenarios). According to all studies, BEV and PHEV are expected to dominate in the 2050 car stock, especially in REFLEX High-RES scenarios (about 80%) while EUCO and CAMECON projections are about 65% and 60%. Such difference should however not surprise given the strong uncertainty in the technological and commercial developments to be expected in the next decades in the car passenger segment and more generally in the transport sector.

Substantial reduction in overall transport oil consumption is predicted in all policy scenarios, while the overall share of non-oil sources reaches approximately a 60% share in the 2050 final energy demand in both EUCO and the two REFLEX High-RES scenarios, there is substantial difference in the relative weight foreseen for oil-alternative fuels (see Figure 8). This concerns the relevance envisaged for biofuels, which in EUCO is estimated to get to supply about 37% of energy by 2050, more than twice than in the REFLEX High-RES scenario that in turn envisages a much greater contribution of hydrogen, whose consumption is estimated to cover up to 23% of energy demand (well above the figures projected by EUCO of 3%). In terms of electricity consumption, the projections are more aligned: the REFLEX High-RES scenarios predict a share of about 23% of demand, while in EUCO the share is about 17%. With this respect, it should be mentioned that in the REFLEX High-RES scenarios a strong support for FCEV fuels was assumed to provide flexibility potential to the electricity system.

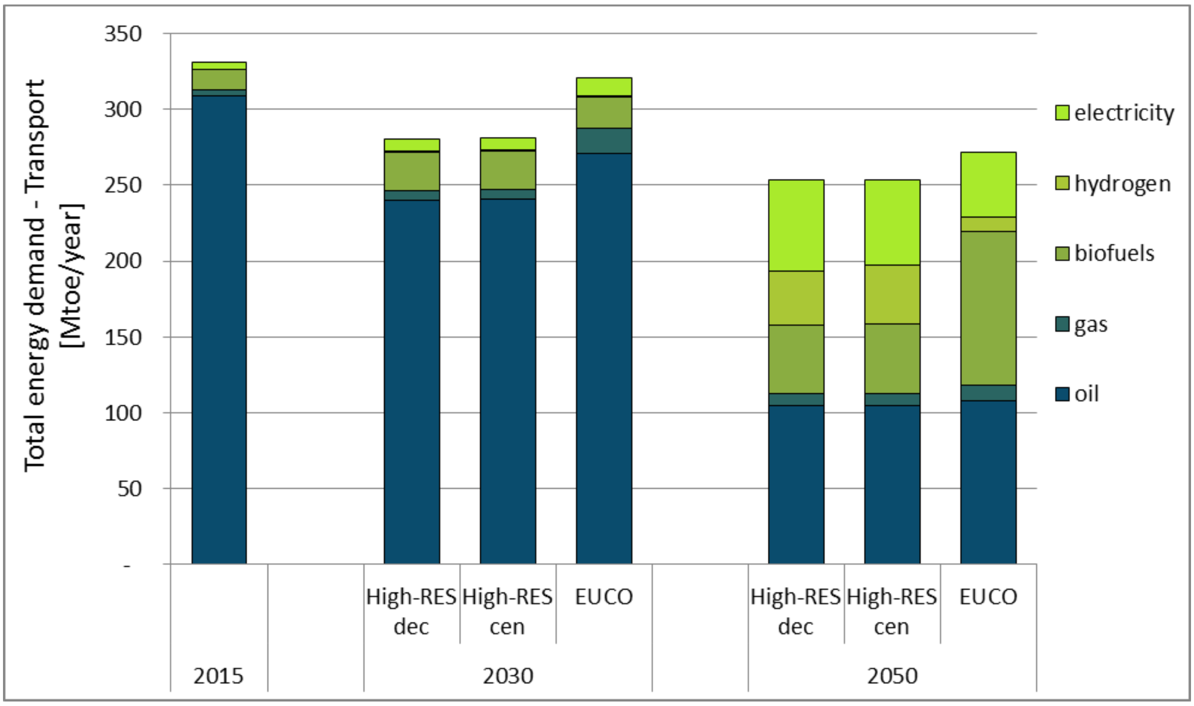


**Figure 8: Results comparison on final energy demand and fuel mix in the transport sector for EU28**

In short, while the phase-out from oil fossil fuels is common to all policy scenarios, some divergences exist between EUCO and REFLEX projections about the fuels that will lead the transition towards low-carbon transport. The most uncertain outcomes regard those sectors that are “harder to electrify”, i.e. aviation, maritime and long-distance road freight transport, for which it is more difficult to predict what fuel can better substitute conventional oil products. In this respect, REFLEX and EUCO projections are quite aligned for aviation and maritime, where advanced biofuels and gas are expected to replace current carbon intensive fuels, while for road freight transport, EUCO predicts a vast and constant diffusion of biofuels, while in REFLEX the uptake of biofuel is expected to be more limited to the transition phase (before 2040), until the take-up of electric hydrogen-powered trucks. Furthermore, it should be underlined that in REFLEX the overall energy demand of the transport sector is decreasing due to the implementation of several policies aiming at efficiency improvements (also for conventional fuels).

# 6 Conclusions and policy recommendations

In comparison to all other energy sectors, the transport sector increased its GHG emissions since 1990. These emissions need to be reduced by 2050 by at least 60% relative to 1990. Considering the continuous growth of passenger and freight transport demand, strong and timely responses are required at the policy level. Within the REFLEX project, a reference scenario (Mod-RES) and two ambitious policy scenarios (High-RES) are simulated with the ASTRA model under consideration of global learning for batteries through coupling with the TE3 model and flexibility potential provided for the electricity sector. Results indicate that a bundle of complementary measures is required to support and accelerate the transition.

## 6.1 Boosting transport system energy efficiency

- **Technological improvement and innovation**: the introduction of fuel efficiency and $CO_2$ standards for new vehicles represents a fundamental instrument to reduce overall GHG transport emissions. These standards should not only be tightened for cars and vans but also extended to heavy duty vehicles, buses and airplanes. Such standards force the automotive industry to become innovative and to change their product portfolio to vehicles with alternative zero- and low-emission powertrains. Setting intermediary as well as long-term targets beyond 2030 ensures that investments kick-start soon and are maintained based on the stability and long-term direction provided. These standards have the advantage to promote innovation while staying technology-independent which is relevant for those transport modes for which several competing technologies are under development.
- **Modal shift to more efficient modes:** it can contribute to decarbonisation. Instead of using individual cars, options for passengers include public transport, cycling and walking. High-speed train connections can replace flights. For freight, transport on railways and inland waterways are more efficient transport solutions. To achieve these shifts, investments in the rail and public transport systems are needed. Sustainable transport modes should be made more attractive and convenient, for example by urban planning measures and infrastructure provision in favour of active modes, by increasing spatial coverage, frequency and thus, reducing waiting times for public transport, and by developing and promoting an ICT-based, integrated and transparent multimodal mobility system. It is fundamental to sustain modal shift especially for short-distance passenger transport, as urban areas show the most pressing congestion challenges but also the highest potential for behavioural change and technology transition. Modal shift was mainly achieved for the decentralized High-RES scenario on the local level for passengers. For freight, a part of road transport share was shifted to rail and inland waterways, in particular due to respective investments in railway and waterway infrastructure, in multimodal freight terminals and increased taxation of fossil-fuel based road transport. However, road share increased again towards 2050 with the diffusion of low-emission fuel cell and battery electric trucks, thus showing a rebound effect.
- **Increased occupancy rates and load factors:** complementary measures aiming at increasing car occupancy rates and optimizing the city logistic chain can support the achievement of the decarbonisation target. The diffusion of shared mobility schemes in European cities, enhanced by the wide spread of information and communication devices, is becoming an alternative to individual transportation which can alleviate the

problems related to congestion, air pollution and GHG emissions by reducing the number of vehicles in circulation. Within the REFLEX scenarios, car sharing and car-pooling policies have been tested and showed interesting results for local mobility (especially in the decentralized High-RES scenario); nevertheless, shared-mobility services are currently developing in many forms and most of them are still far away from their full potential. On the freight side, the development of integrated logistics can make a more efficient use of freight vehicles, enabled also by the diffusion of digital technologies. Measures related to urban freight logistic includes a huge variety of different transport operations and logistics activities and requirements, promoting sustainable strategies for the management of the last mile of freight distribution. Measures range from road network and parking strategies, terminals and modal interchange facilities, pricing strategies, ICT-based vehicle control systems, logistics information systems etc.

## 6.2 Supporting the electrification of road transport

- **Subsidies, tax and pricing strategies:** subsidies for low-emission vehicles are required in the first years of technology market entrance, when vehicle prices are still relatively high. Battery and plug-in hybrid electric vehicles are expected to contribute to a widespread electrification of passenger transport, as they will soon become competitive with conventional oil-based cars thanks to learning effects and economies of scale in global battery production and as public charging infrastructure is deployed. Thus, subsidies for vehicles as purchase incentives or bonus-malus (or so-called feebate) systems seem only reasonable within the next few years. Furthermore, monetary advantages for homeowners with rooftop PV generating electricity for self-consumption can contribute to the diffusion of battery electric vehicles. This factor would become more relevant if the electricity system develops in a more decentralized way. Fuel cell electric vehicles could lead the technology transition for long-haul trucks; hybrid trolley trucks are a further promising technological option. Although hydrogen production is less energy-efficient compared to direct electrification, fuel cell electric trucks could become a real decarbonisation option, as hydrogen production has the potential to provide flexibility to the electricity system that has to cope with fluctuating production of renewables. Hydrogen could be produced in times of electricity oversupply and could be reconverted to electricity if needed. R&D and subsidies for fuel cell technology seem still required to achieve competitive prices. Policies that support the transition to new drive technologies by increasing their financial attractiveness compared to conventional fuel vehicles are vehicle registration taxes, road charges and fuel taxes that all depend on the respective $CO_2$ emissions.
- **Refuelling and charging infrastructure:** While prices for battery electric vehicles decline, range anxiety is currently one of the biggest barriers to the purchase of electric vehicles. Therefore, sufficient public charging infrastructure - including stations for fast charging - are key to ensure that users of battery electric vehicles can complete all their trips (see also conclusions by Funke et al. 2019). Thus, public charging stations and alternative fuel filling stations have to be deployed sufficiently and timely to reduce range anxieties as well as extra efforts for charging and refuelling actions.
- **Phase-out of pure internal combustion engine cars:** If low-emission vehicles do not diffuse fast enough regardless of the implemented measures due to soft factors of technology acceptance, phase-out decisions for pure fossil-fuel based cars (in particular gasoline, diesel and LPG) could be made by 2030 for completion in the subsequent 5 to

10 years to accelerate the speed of transition towards low- and zero-emission vehicles. Announcing a phase-out in about 10 years would also be beneficial for vehicle manufacturers and suppliers as they could focus R&D in alternative fuel technologies with a secure timeline. In addition to the measures already described, banning pure fossil-fuel cars from cities could be a promising measure to prepare and support the phase-out. Within the High-RES scenarios, this approach was one of the main drivers for the diffusion of low-emission vehicles.

## 6.3 Promoting alternative fuels to cope with lack of mature low-emission technologies

Alternative fuels in form of biofuels or synthetic fuels based on electrolysis and additional treatments (Power-to-Gas (PtG) and Power-to-Liquid (PtL)) are the least efficient options, as production requires biomass as resource and renewable electricity for production with low degrees of efficiency in internal combustion engines. However, they should be used for modes for which mature low-emission drive technologies will not be developed in the near future. This is the case for aviation and for ships. Alternative fuels also play at least an intermediate role for road transport, if range anxieties result in a higher diffusion of plug-in-hybrid cars for longer distances. Moreover, new technologies for trucks might not become adequate for certain special purpose vehicles by mid-century. A clear strategy for using sustainable biofuels and synthetic fuels is needed. Adequate allocation of biomass to different demand sectors could be aligned to use resources as best as possible. The production of advanced biofuels should be supported. When sustainable production can be ensured for certain quantities, blending quotas of biofuels and PtX fuels could be established.

## 6.4 Further outlook

Achieving the 2050 target of -60% GHG emission reduction for transport compared to 1990 is challenging and requires ambitious policy measures. All three described strategies to decrease $CO_2$ emissions should be combined. Several pathways exist by adopting these strategies to different extents and with different configurations. Thus, the contribution to GHG emission reduction of the individual strategies can vary. In the investigated High-RES scenario simulations, the main drivers of $CO_2$ emission reduction are the diffusion of low-and zero emission road vehicles (achieving -26 % in 2050 relative to 1990), efficiency improvements (adding up to -44% reduction in total relative to 1990), and alternative fuels, in particular for aviation and navigation (reaching together with the above-mentioned measures -58% in total relative to 1990). Policies aiming at modal shift to active modes, public transport and sharing mobility can contribute in particular on the local level. These policies still contribute to $CO_2$ emission reduction for about -10% (2050 relative to 1990), although for the overall transport system the impact in the analysed scenarios was less compared to the other strategies.

# References

Cambridge Econometrics (2018): Low-carbon cars in Europe: A socio-economic assessment. European Climate Foundation,

European Commission (2011): A Roadmap for moving to a competitive low carbon economy in 2050. Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2011)112 final, Brussels.

European Commission (2016a): A European Strategy for Low-Emission Mobility. Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM(2016) 501 final.

European Commission (2016b): Commission Staff Working Document Accompanying the document A European Strategy for Low-Emission Mobility. SWD(2016) 244, Brussels.

European Commission (2017): EU Transport in Figures - Statistical Pocketbook 2017, https://ec.europa.eu/transport/facts-fundings/statistics/pocketbook-2017_en

European Environment Agency (2018): Greenhouse gas emissions from transport , https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-11

Fermi F., Fiorello D., Krail M., Schade W. (2014): Description of the ASTRA-EC model and of the user interface. Deliverable D4.2 of ASSIST (Assessing the social and economic impacts of past and future sustainable transport policy in Europe). Project co-funded by European Commission 7th RTD Programme. Fraunhofer-ISI, Karlsruhe, Germany.

Funke, S.Á., Plötz, P. and Wietschel, M. (2019), Invest in fast-charging infrastructure or in longer battery ranges? A cost-efficiency comparison for Germany, Applied Energy, Vol. 235, pp. 888–899.

ITF (International Transport Forum) (2012), Transport Outlook, Paris, France, https://www.oecd.org/greengrowth/greening-transport/Transport%20Outlook%202012.pdf

Schipper, L., C. Marie-Lilliu, and R. Gorham. 2000. Flexing the Link between Transport and Greenhouse Gas Emissions: A Path for the World Bank. International Energy Agency, Paris