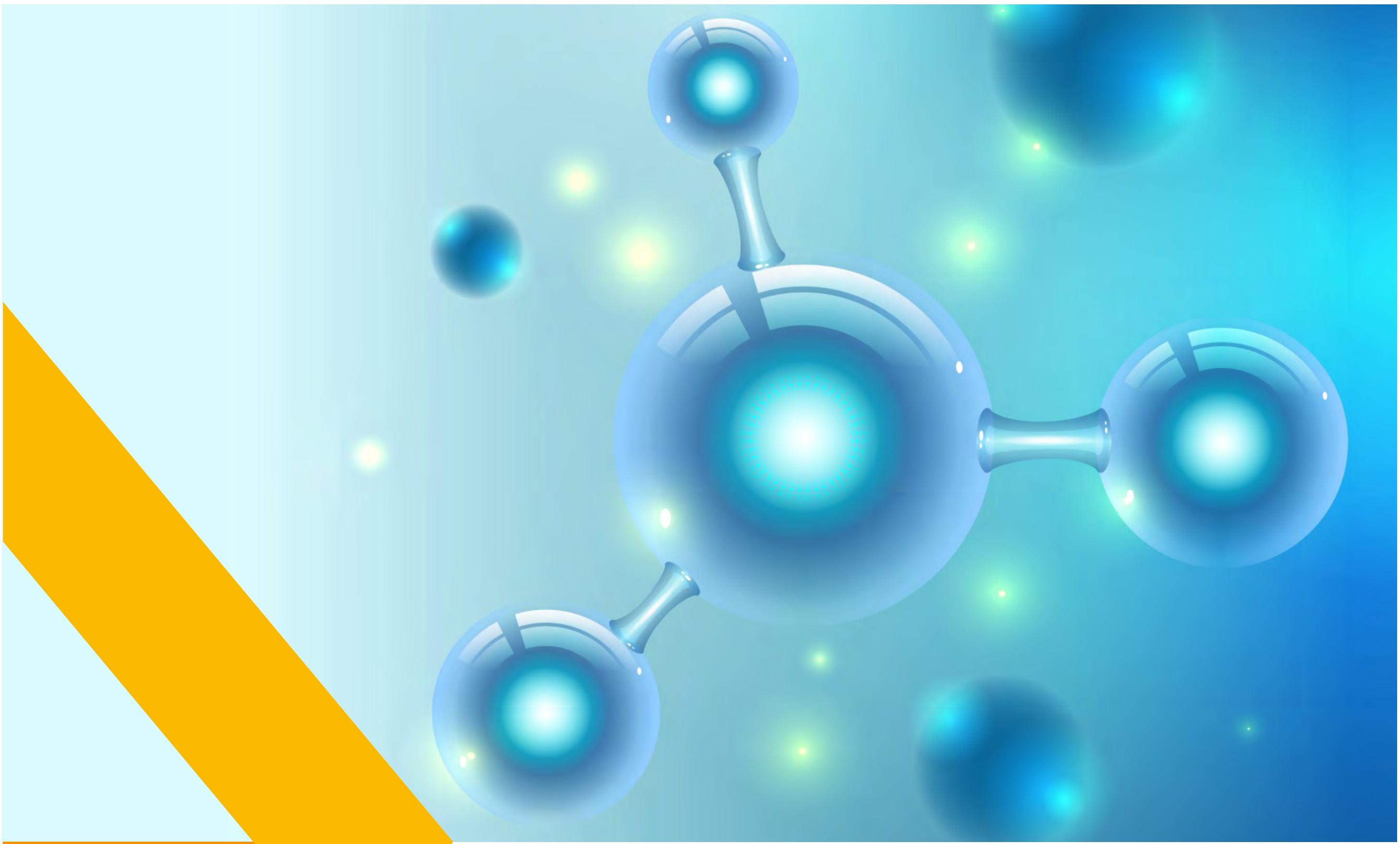

«E-FUELS» STUDY

The potential of electricity-based fuels for low-emission transport in the EU

An expertise by LBST and dena

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Contents

1 Executive summary

The study “E-Fuels – The potential of electricity-based fuels for low emission transport in the EU” analyses the future energy demand of the European transport market, along with the necessary build-up of renewable energy capacities and the related investments needed to achieve an 80-95% reduction in greenhouse gases (GHGs).

The main topics and questions of the study are:

- How can e-fuels help the transport sector meet the EU climate targets?
- To what extent do renewable energy capacities need to be increased in order to meet energy demand in the transport sector?
- What is the amount of cumulated investments needed for energy and fuel supply by 2050?

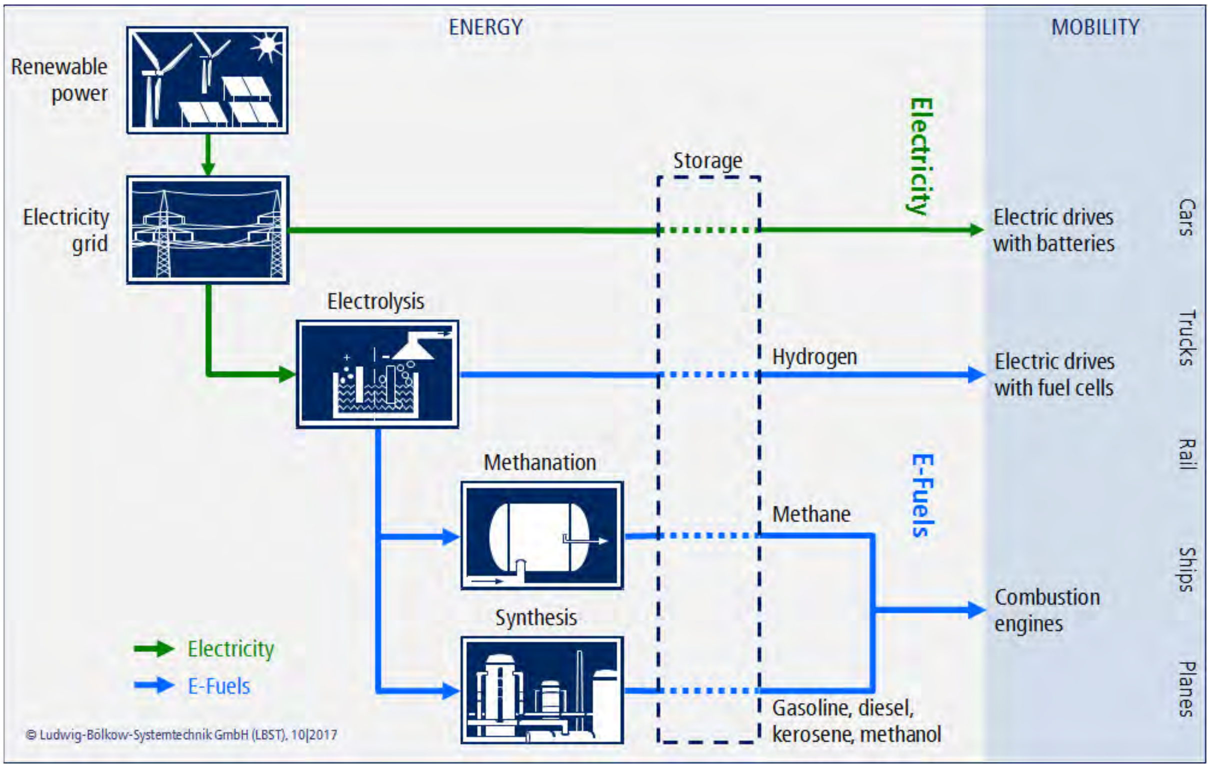
To answer these questions, this study looks at different scenarios that describe the development of the share of powertrains and fuels for all transport modes in the EU, and takes into consideration both passenger and freight transport. Based on these scenarios and assumptions pertaining to predicted values for transport development of all transport modes, the resulting energy demand of the transport sector is modelled for the period to 2050, and the necessary investment for providing the energy sources is determined. All scenarios comply with the EU climate targets laid down in the 2030 climate & energy framework and in the Energy Roadmap 2050 [COM/2011/885].

The study shows the results of the following scenarios:

- Liquid-fuel-dominated scenario with a considerable increase in transport volume and a GHG reduction of 80% compared to 1990: PtL/High/-80%$_{GHG}$
- Liquid-fuel-dominated scenario with a moderate increase in transport volume and a GHG reduction of 95% compared to 1990: PtL/Low/-95%$_{GHG}$
- Gaseous-fuel-dominated scenario with growing hydrogen use in electric power trains, a moderate increase in transport volume and a GHG reduction of 95% compared to 1990: PtG/Low/-95%$_{GHG}$
- Electric-powertrain scenario with growing use of fuel cells in freight traffic, a moderate increase in transport volume and a GHG reduction of 95% compared to 1990: eDrives/Low/-95%$_{GHG}$

Definition of E-fuels

E-fuels are gaseous and liquid fuels such as hydrogen, methane, synthetic petrol, and diesel fuels generated from renewable electricity.



E-fuel production process and overview

Key results of the study:

- E-fuels are necessary to meet the EU climate targets within the transport sector.
- Even in a battery electric drive dominated scenario, the final energy demand of all transport modes in the EU will be met with more than 70% of e-fuels in 2050. The majority of these e-fuels will be used for aviation, shipping and freight transport.
- Transportation demand is the key driver of energy use across all scenarios. In particular, truck freight, ship freight, and passenger aviation are expected to increase and drive additional fuel demand. EU transport energy demand for renewable electricity in 2050 may exceed current EU electricity production by a factor of between 1.7 (in the eDrives/Low/95% scenario) and 3 (in the PtL/High/80% scenario).
- The technological potential in Europe for renewable electricity generation is sufficient to cover the future demand of transport energy and e-fuels demand. However, a significant increase in electricity generation from renewable energies will be necessary for that. The estimated demand of renewable electricity for the entire transport sector in 2050 is ten times bigger than the current annual renewable electricity generation in the EU. Over 80% of this future demand is caused by the production of e-fuels.
- At the moment, the costs of e-fuels are high (up to 4.50 € per liter diesel equivalent). Target costs of approximately 1 € per liter diesel equivalent appear possible with imports from regions with very good solar and wind power conditions. The quoted target costs include CO2 extraction from ambient air. Nevertheless, future fuel cost are expected to also increase for all other clean transport variants based on

the high share of renewable energy required, leading to a reduction of the clean fuels cost difference when comparing combustion engines and electric powertrains.

- All scenarios require large investments into renewable power generation and in production plants for e-fuels. In the electric drive dominated scenario, the cumulated investments within the entire European transport sector between 2015 and 2050 is 15%- 30% lower than in the scenario with less electric drives (vehicle costs not considered). Assuming the full import of gaseous and liquid e-fuels (without hydrogen) from regions like North Africa with favourable e-fuels conditions, the difference in investment between the scenarios is less than 10%.
- To achieve the European climate protection target 2030 for the transport sector (-30% compared to 2005) e-fuels production capacity build-up needs to be started today. Devising a corresponding e-fuels roadmap at national, EU, and international level outlining feasible e-fuels ramp-up paths is essential to ensure that the required volumes are available in time for 2030 and on the road to 2050.

Advantages and disadvantages of e-fuels

- E-fuels have a high energy density and can therefore be transported conveniently over long distances and kept in large scale stationary storage over extended periods, allowing them to compensate even seasonal supply fluctuations and thus contribute to stabilizing the energy supply.
- The entire petrol/diesel/kerosene/gas infrastructure (pipelines, gas stations) can continue to be used.
- E-fuels can be used by the existing stock of passenger and utility vehicles (legacy) and by transport modes that are hard to electrify (aviation and shipping).
- The overall energy efficiency of electricity use in battery electric vehicles is 4-6 times, and via hydrogen in fuel cell vehicles about 2 times higher than e-fuels in combustion engines including grid integration.

Need for action

- All means of transport should be electrified or partially electrified wherever ecologically and technically feasible. E-fuels will be crucial for transport applications for which, as it stands, no electric power trains are easily available. Therefore, policy makers and the industry now have to create a framework that makes e-fuels sufficiently economically attractive.
- Policy makers and the industry will need to develop a strategic agenda for technology research, market development and regulation of e-fuels. An e-fuels platform across all sectors could begin and coordinate this process in the near future.
- E-fuels are currently in the phase of demonstration and very early market penetration. A suitable legal and economic framework is essential to encourage more investment in fuel production efficiency, to reduce cost and to accelerate market uptake. From an economic point of view, transport sector could play the key role as it is not directly facing carbon leakage challenges and customers rather inclined to environmental sustainability.

2 Introduction to the EU transport, energy and climate framework

The development and growth of the single market is closely linked to the development and increase of transport in and between the EU member states, and between the EU and other countries. The reduction of trade barriers combined with investments in infrastructure – especially road infrastructure – created a framework for fast and flexible transport which allows for decentralised production and distribution systems. Transport cost as a location factor has minor importance. In comparison to labour cost, for example. Increasing financial wealth, cost-efficient vehicle production and intelligent logistics increase the scope for individual mobility and for freight transport. On the one hand, this now means flexibility, comfort and more social participation for different social groups. On the other, the vastly increased transport volume leads to a growing energy demand and creates environmental and climate challenges. The EU and its member states try to tackle these challenges by improving vehicle efficiency, increasing the share of renewables and shifting transport towards more environmentally friendly transport modes. These efforts are embedded in a comprehensive energy and climate strategy which aims to make the EU economy more competitive and sustainable.

2.1 EU energy & climate policy

At the Paris climate conference (COP21) in December 2015, the EU member states were among the 195 countries that adopted the global climate deal. Governments agreed on a long-term goal of keeping the increase in global temperatures to below 2°C.

In the EU context, the fight against climate change is generally split into two fields: The sectors that fall under the EU Emissions Trading System (EU ETS), and those that are subject to the Effort Sharing Decision (ESD). The EU ETS is the EU's main instrument for reducing GHG emissions in the energy and industry sectors. It was created in 2005 as the largest international carbon market and is based on the principle of "cap and trade", where a cap is set on the total amount of GHG emissions admissible under the scheme. Companies are required to hold or purchase sufficient emissions allowances to cover the emissions they produce. The allowances can be traded with other companies. By creating a price on emissions, the system aims to incentivise efforts to reduce emissions.

Sectors not covered by the EU ETS are subject to the ESD. These non-ETS sectors – such as transport, buildings and agriculture – should cut emissions by 10% by 2020 compared to 2005 levels. Individual contributions for each member state were broken down according to gross domestic product (GDP) per capita. Germany, for instance, should lower emissions by 14% by 2020. Currently, a new proposal is going through the legislative process. The European Commission suggested setting a target that would reduce GHG emissions by 30% between 2021 and 2030. Furthermore, the new proposal looks to incorporate land use, land use change and forestry (LULUCF) into the EU's emissions reduction efforts. LULUCF is a term that covers emissions and sinks such as CO_2 removal from forests and soils that can be traced back to human activities (European Parliament, 2016a).

The EU has long been committed to international efforts to tackle climate change and aims to pursue robust policymaking in this area. In 2007, the European Council agreed on European climate and energy targets for the first time. The **2020 climate and energy package** contains three targets to be achieved by 2020:

- Cut EU greenhouse gas emissions to at least 20% below 1990 levels
- Increase the share of EU energy consumption coming from renewable sources to 20%
- Improve energy efficiency to reduce the amount of primary energy used by 20% compared with projected levels

In 2011, as a long term goal, the European Council confirmed the EU objective of reducing greenhouse gas emissions by 80-95% by 2050 compared to 1990 (European Commission, 2017a).

As a follow-up to the 2020 targets in October 2014, the Council agreed on the **2030 climate and energy framework**. Among other things, the agreement includes the continuation of a trio of targets in the areas of climate action, renewable energies and energy efficiency:

- 40% cut in greenhouse gas emissions compared with 1990 levels
- 27% of total energy consumption from renewable energy
- 27% increase in energy efficiency

The GHG emissions reduction target of 40% is seen as a minimum and can be increased as necessary in the context of the Paris Agreement. To achieve the target, EU ETS sectors have been asked to reduce GHG emissions by 43% compared to 2005, while non-ETS sectors should reduce them by 30% (see Figure 1). This EU-wide target is translated into an individual goal for each member state. For instance, Germany's target is 38%, while Romania has to cut its non-ETS emissions by 2%. The target of achieving a minimum 27% share of renewable energies in overall consumption is only legally binding at the EU level, and differs for each member state. The same applies for the indicative target of reducing energy consumption by at least 27% compared to the projected use of energy. It will be reviewed before 2020, with the intention of increasing it to 30%.

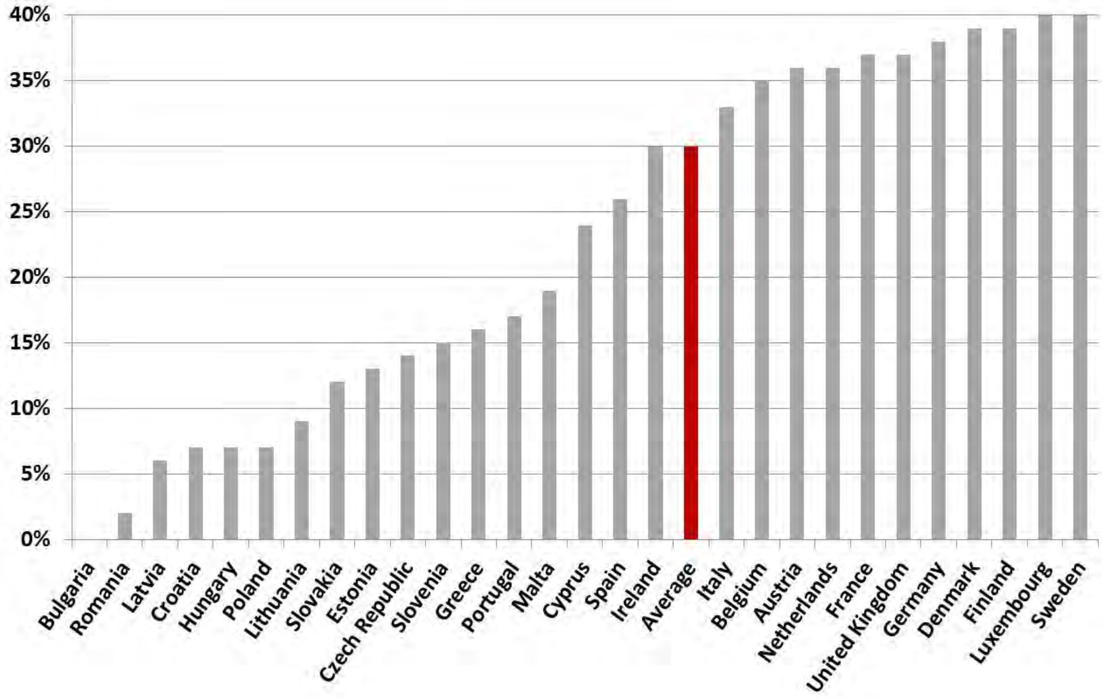


Figure 1: GHG reduction targets for non-ETS sectors by 2030 (compared to 2005). (European Commission 2016a)

From the point of view of the European Commission, the 2030 climate and energy framework is in line with the roadmap for moving to a competitive low-carbon economy in 2050, the Energy Roadmap 2050 and the EU white paper on transport.

2.2 EU transport policy

For more than 30 years, transport has been one of the EU's common policy areas. The harmonisation of national laws, regulations and administrative provisions, and of the technological, social and tax environment in which transport services are provided, has steadily risen in importance. Moreover, the completion of the European single market, the abolition of internal borders, the drop in transport prices as a result of the opening-up and liberalisation of transport markets and changes in manufacturing and stock management systems have all led to an increase in goods and passenger volumes. (European Parliament, 2016b)

The transport sector accounts for almost a quarter of all GHG emissions in the EU. In contrast to other sectors, it has not seen the same gradual decline in emissions. Road transport is the largest emitter, accounting for more than 70% of all GHG emissions from transport in 2014 (see Figure 2).

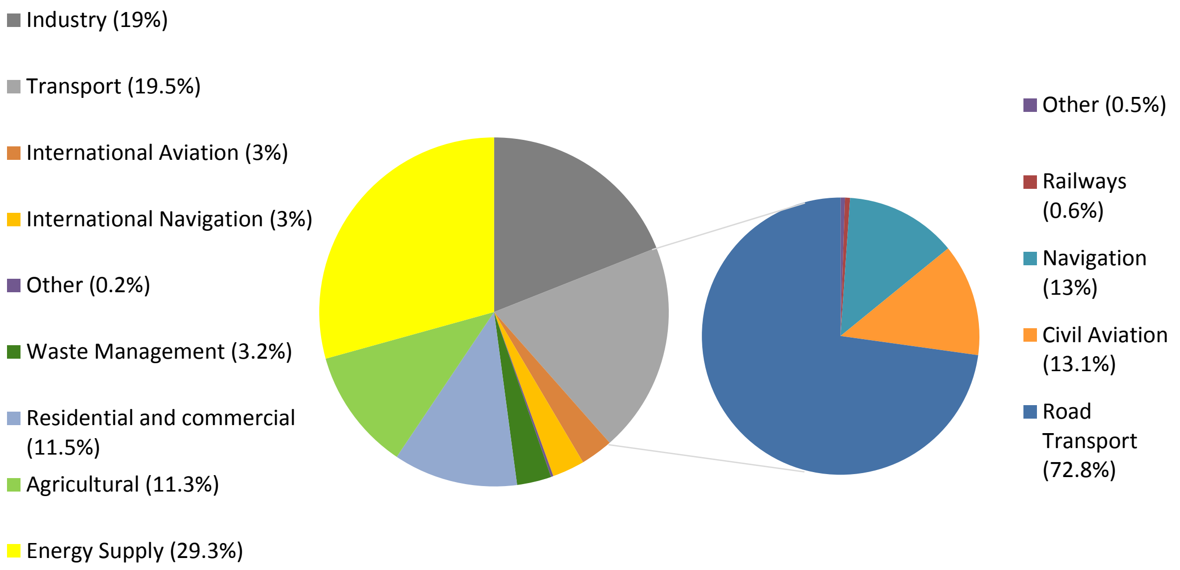


Figure 2: Sectoral GHG emissions and emissions from transport by mode (2014). (European Environment Agency 2016a; European Commission 2016b)

As explained earlier, the EU's transport sector is not covered by the EU ETS. The EU has established a range of measures aimed at tackling GHG emissions and stimulating the deployment of alternative fuels.

In July 2016, the European Commission published **A European strategy for low-emission mobility** (European Commission 2016c). It aims at framing the initiatives that the Commission is planning for the transition to a future-oriented, environmentally friendly transport and mobility sector. The main areas of action are:

- Higher efficiency of the transport system
- Low-emission alternative energies for transport
- Low- and zero-emissions vehicles

To improve transport efficiency, the European Commission aims to set up an EU-wide, distance-based road charging system, which takes account of externalities. Besides trucks, the system would include buses, passenger cars and vans. Pricing would be based on CO_2 differentiation, and communities are encouraged to set up charging systems that would run alongside motor fuel taxation.

In terms of renewable fuels, the strategy aims to strengthen advanced biofuels and synthetic renewable fuels, while food-based biofuels should be phased out. The Commission plans to evaluate the investments needed to build up capacities to compete with fossil fuels. In the Commission's view, advanced biofuels will be needed in the mid-term for aviation, trucks and coaches in particular, while methane (fossil and renewable) will be important for ships, trucks and coaches.

With regard to cars and vans, the Commission is currently working on a post-2020 carbon standard. It will also analyse how to incentivise low- and zero-emissions vehicles in a technology-neutral way. The measurement and verification of vehicle emissions is reformed and will be implemented. Independent testing, market surveillance and enforcement will be strengthened by a new type-approval framework. The post-2020 standards for cars and vans will be based on the World Harmonised Light Vehicle Test Procedure and thus deliver more realistic carbon-emission and fuel-consumption values. In its strategy, the European Commission points out that, besides the need for vehicle efficiency standards, there is a need to improve company car taxes and fuel tax in each member state, and to strengthen alternative fuels and powertrains. The strategy also envisages developing a framework for curbing carbon emissions from trucks, buses and coaches. While these vehicles have been subject to similar air pollution standards as cars and vans, neither efficiency standards nor carbon monitoring systems have been established at the European level. Consequently, the Commission will come up with a proposal on the certification of carbon dioxide emissions and fuel consumption of these vehicles, and one on the monitoring and reporting of such certified data respectively.

2.3 Regulatory framework for clean transport in the EU

The abovementioned climate, energy and transport strategies represent the targets and methods with which the EU intends to turn transport into a competitive but sustainable sector. They also show that responsibilities exist at the EU, national and local level. This section describes the regulatory instruments that the EU has developed to improve vehicle efficiency and the share of renewables in transport, and that currently have and will have an indirect influence on transport fuels and powertrains.

2.3.1 The Renewable Energy Directive (2009/28/EC)

The Renewable Energy Directive (RED) is a key policy instrument for encouraging the production and promotion of energy from renewable sources. It corresponds to the EU's 2020 goal of increasing the share of EU energy consumption coming from renewable sources to 20%. This is to be achieved through the attainment of individual national targets. More importantly for the transport sector, the RED also stipulates that 10% of final energy consumption in the transport sector must come from renewable energy sources by 2020. Fuel suppliers are also required to reduce the GHG intensity of the EU fuel mix by 6% by 2020 in comparison to 2010. Furthermore, to ensure that biofuels are produced in a sustainable and environmentally friendly manner, the RED sets out sustainability criteria for all biofuels produced or consumed in the EU. Compliance with these criteria can be monitored through national systems or voluntary schemes that are recognised by the European Commission (European Commission, 2017b).
In November 2016, the Commission published a proposal for a revised Renewable Energy Directive (so-called RED II), relating to the 2030 renewable energy target. Concerning renewable energy in the transport sector from 2021, suppliers are required to include a minimum share of renewable and low-carbon fuels, including advanced biofuels, renewable transport fuels of non-biological origin, waste-based fuels and renewable electricity. In terms of energy, the level of this obligation will progressively increase from 1.5% in 2021 to 6.8% in 2030. It will include at least 3.6% of advanced biofuels and a maximum of 1.7% of fuels set out in Part B, Annex IX of the RED proposal, such as used cooking oil (UCO) and molasses. Moreover, the potential impacts of indirect land use change will be further reduced by capping the contribution of conventional biofuels to the EU renewable energy target at 3.8% in 2030. The share of conventional biofuels should be at a maximum of 7% in 2021. The proposal's biofuels quality criteria require GHG savings of at least 50% from biofuels produced by installations that opened before 5 October 2015, at least 60% from those produced by installations that opened from 5 October 2015, and at least 70% from those produced by installations that opened after 1 January 2021. The proposal also suggests introducing national databases to ensure fuel

traceability and prevent fraud. It is currently being negotiated between the member states and the European Parliament. The final outcome is expected in 2018 (European Commission 2016d).

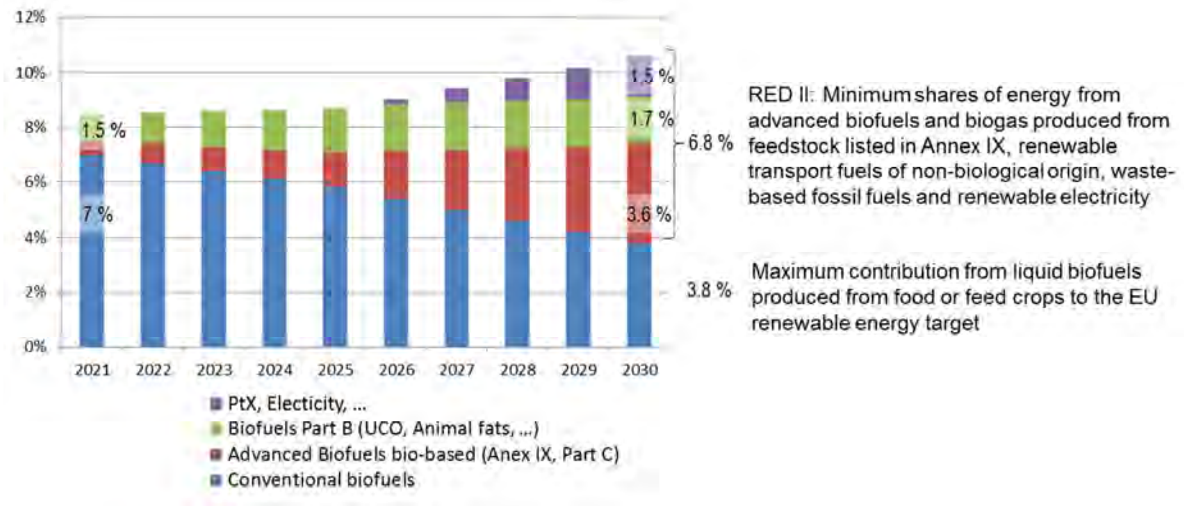


Figure 3: Threshold values for biofuels, and assumptions about the share of advanced fuels and PtX in the RED

2.3.2 Fuel Quality Directive (2009/30/EC)

The Fuel Quality Directive (FQD) was adopted in 2009 and revises Directive 98/70/EC. It sets technical standards for road transport fuels. Most importantly, it requires fuel suppliers to reduce the GHG intensity of energy supplied for road transport. By 2020, the GHG content of road fuels must be reduced by 6% compared to the average EU level of GHG per unit of energy from fossil fuels in 2010. The GHG intensity of fuels is calculated on a life-cycle basis. Reducing the GHG content of fuels is likely to be achieved through the use of biofuels, electricity, lower-carbon fossil fuels and a reduction of flaring and venting during fossil fuel extraction. The FQD sets certain sustainability criteria that biofuels must fulfil in order to count towards the 6% target. This is to minimise undesired impacts from their production. GHG emissions for biofuels must be at least 35% lower than those from the fossil fuel they replace. From 2017, this will increase to 50%. From 2018, the saving must be at least 60% for new installations. The raw materials for biofuels cannot be sourced from land with high biodiversity or high carbon stocks.

Each EU member state is responsible for successfully implementing the RED and FQD. The two directives are closely linked because renewable fuels will be the main driver for reducing the GHG intensity of all transport fuels. Nevertheless, compliance with one directive does not automatically result in compliance with the other. For instance, biodiesel currently has, on average, a high GHG reduction potential (more double counting), which means that markets with a higher share of diesel fuel can achieve the RED targets faster. However, even in diesel-dominated markets, a blending limit of 7% biodiesel has to be taken into account (except for hydrotreated vegetable oil; HVO). This means that to achieve the 2020 target, the market will need a reasonable volume of bioethanol (or biomethane), which can be above E5, but still in the range of E10 (Engineers Journal, 2017).

Even though the future RED targets for advanced renewable fuels are meant as a minimum share, they may not be ambitious enough to provide sufficient contribution to the 2030 GHG-emission reduction target. The main issues are as follows:

- If future energy demand in private transport will decrease due to improving vehicle efficiency, the indicated quota will just contribute to a small amount of renewables in transport. So there should be a discussion about a stable respectively increasing volume of advanced renewable fuels, which could speed up GHG-mitigation of road transport and being in the future available for navigation and aviation.
- Even if the share of electric vehicles will steadily increase, a high number of internal combustion engines (ICE) vehicles but also Plug-in-Hybrid Vehicles (PHEV) will still on the road in 2030. These vehicles will have to contribute to GHG-mitigation target, too, requiring an ambitious share of renewable fuels with a sustainable GHG-emission reduction.
- The indicative quota for materials in Annex IX, Part C and for those in Annex IX Part A does not seem ambitious enough if there are no other instruments to encourage the use of low-carbon fuels.

2.3.3 Regulating carbon emissions from passenger cars and light commercial vehicles in Europe (EC 443/2009)

In order to improve the fuel economy of cars and vans sold on the European market, the EU has set mandatory emissions reduction targets. Consequently, cars and vans registered in the EU must comply with carbon emissions standards.

In 2015, the target to be reached by the average car fleet was 130 g CO_2/km. This will be reduced to 95 g CO_2/km from 2021. Compared with the 2007 fleet average of 158.7 g CO_2/km, the 2015 and 2021 targets represent reductions of 18% and 40% respectively. It is important to note that only the fleet average is regulated. Emissions limits are set according to the mass of vehicle. Manufactures can still produce vehicles with emissions above the curve, as long as they are offset by vehicles below the curve. Penalties exist if a manufacturer's fleet exceeds the limit on its average carbon emissions. An "excess emissions premium" has to be paid for each car registered: €5 for the first g CO_2/km above the limit, €15 for the second, €25 for the third, and €95 for each subsequent g CO_2/km. From 2019 onwards, the cost will be €95 for every gram above the limit. In order to encourage industry to invest in vehicles with very low emissions (below 50 g CO_2/km), "super credits" have been introduced. When calculating the average specific carbon emissions, the cars with the lowest CO_2-emssions in the manufacturer's range count as more than one car (European Commission, 2017c).

A similar regulation is in place for vans. The regulation affects light commercial vehicles that carry goods weighing up to 3.5 tonnes, and weigh less than 2,610 kg when empty. From 2017, new vans registered in the EU must not emit more than an average of 175 g CO_2/km. This is 3% less than the 2012 average (180.2 g CO_2/km). In 2014, new vans on the EU market already emitted on average significantly less carbon per kilometre than the 2007 target. For 2020, the target was set at 147 g CO_2/km. Again, the emissions limits are set according to the mass of vehicle, corresponding to a limit value curve. Consequently, heavier vans are allowed higher emissions than lighter vans. As it is the manufacturer's fleet average that is regulated, manufacturers can still produce vans with emissions above the curve, as long as these are offset by vehicles with emissions below the curve. In 2014, an average of just 70% of a manufacturer's newly registered vans had to comply with the limit value curve. In 2016, it was 80%, and from 2017 onwards it will apply to all vehicles. An excess emissions premium is also payable if a manufacturer's fleet exceeds its limit value: €5 for the first g CO_2/km, €15 for the second, €25 for the third, and €95 for each subsequent g CO_2/km. From 2019 onwards, €95 will be payable for every gram above the limit (European Commission, 2017d, 2017e).

2.4 Directive on the reduction of national emissions of certain atmospheric pollutants (2016/2284/EU)

In 2013, the EU proposed and adopted the Clean Air Policy Package. The aim was to set new goals for EU air policy for 2020 and 2030. The legislative instrument to achieve these goals is the Directive on the reduction of national emissions of certain atmospheric pollutants" (2016/2284/EU), which entered into force on 31 December 2016. It replaces the National Emission Ceilings Directive (2001/81/EC) from 30 June 2018 and sets national reduction commitments for sulphur dioxide, nitrogen oxides, non-methane volatile organic compounds, ammonia and fine particulate matter (European Union, 2016a). In contrast to the Air Quality Directive (2008/50/EC), which defines peak and calendar-year limits for NO_2 PM_{10} and $PM_{2.5}$, 2016/2284/EU gives the future direction of various air pollutants. From 2030 onwards, NO_x and $PM_{2.5}$ should be 49% and 65% behind 2005 emissions respectively.

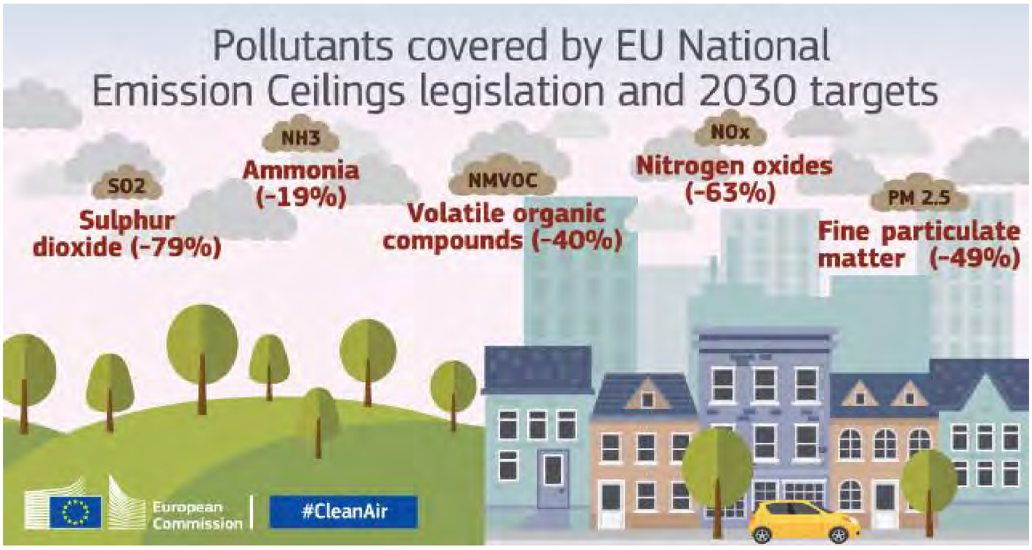


Figure 4: Pollutants covered by EU National Emission Ceilings legislation and 2030 targets (European Commission, 2017f)

3 Characteristics of the transport sectors in the EU

The following section focusses on the characteristics and evolution of the transport sectors in the EU's 28 member states. It sets out the development of transport capacities regarding the modal split, final energy consumption and GHG emissions since 1990, and the actual share of energy sources in the transport sector.

3.1 Development of transport capacities and modal split since 1990

The volume of passenger transport rose by 32% between 1990 and 2014, growing from 4,486 to 5,905 billion passenger-kilometres (pkm). As Figure 5 shows, passenger cars make up the majority of the modal split (81%), followed by buses and trains. Between 1990 and 2004, traffic rose sharply and then remained relatively stable. Volumes rose again from 2012, and further increases are expected. The EU Reference Scenario 2016 (Capros et al., 2016) assumes increases of 17% by 2030, and of 34.4% by 2050.

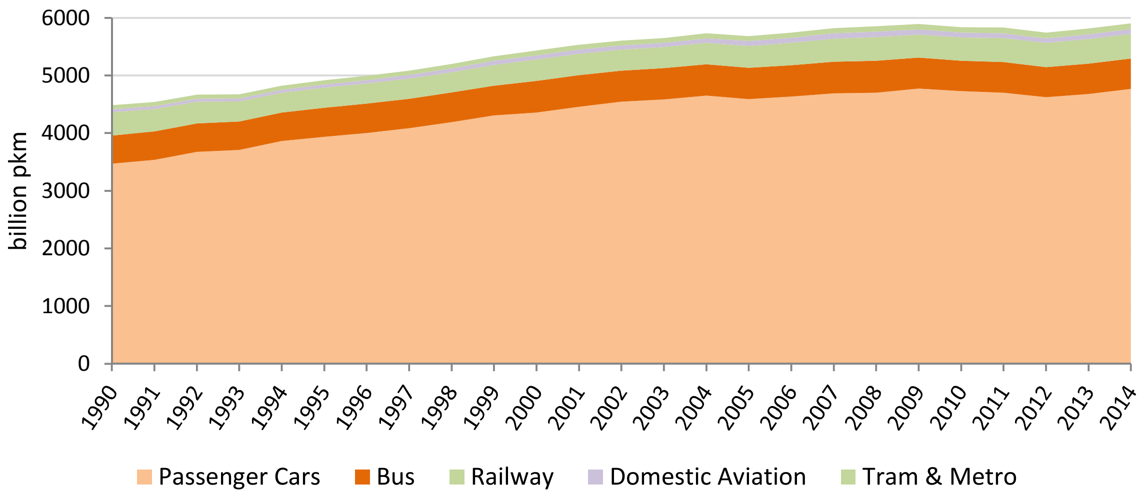


Figure 5: Passenger transport development (EU28) (Odyssee Database, 2017)

Figure 6 indicates that freight transport developed in a relatively similar way to passenger transport until 2007. However, after a large and constant increase between 1995 and 2007 (about 34.5%), a significant slump followed as a result of the global economic crisis. From 2009, freight transport rose slightly to a total volume of 3,522 billion tonne-kilometres (tkm). Today, the main forms of freight transport are road and maritime (with share of 49.0% and 31.9% of the modal split), followed by railway (11.7%), inland navigation (4.3%) and pipelines (3.2%).

Freight transport volumes are expected to grow even more than passenger transport. The EU Reference Scenario estimates an increase of 27.9% by 2030 and of 49.8% by 2050 (excluding maritime transport) (Capros et al., 2016).

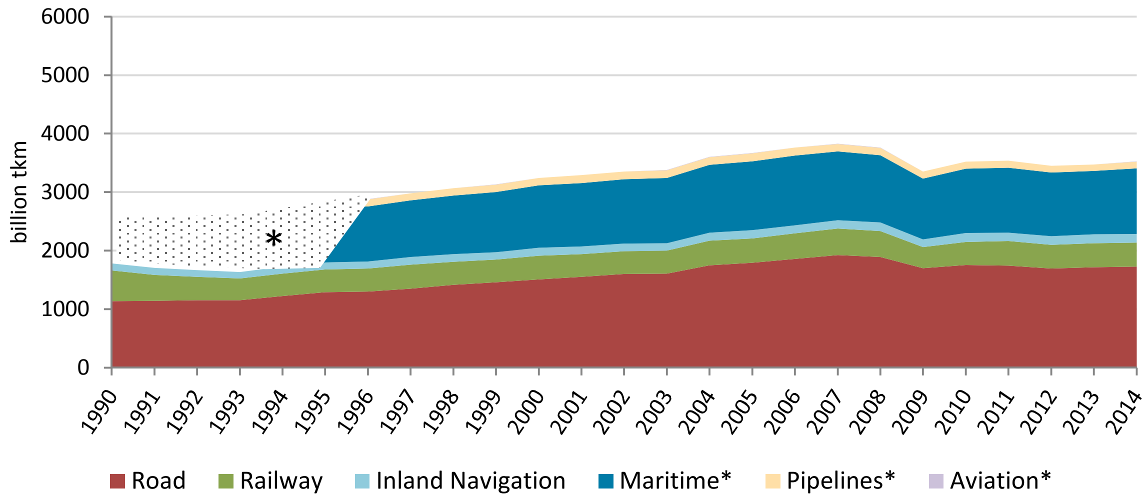


Figure 6: Freight transport development (EU28) (Capros et al., 2016; Odyssee Database, 2017)

*No data available for the period 1990 to 1994

3.2 Final energy consumption in the transport sector since 1990

Growth in transport performance caused energy consumption in the transport sector to increase significantly. In 1990, the transport sector consumed 11,893 petajoules (PJ). By 2007, the figure had risen by 35% to 16,056 PJ. This is equivalent to 21% of the overall energy consumption in the EU28. After 2007, energy consumption decreased due to a decline in traffic performance, but also due to improvements in vehicle efficiency. From 2013, however, energy consumption rose again. As shown in Figure 7, road traffic has by far the highest energy consumption, followed by international aviation. In 2015, the energy consumption of the entire transport sector was 15,016 PJ (Eurostat, 2017a).

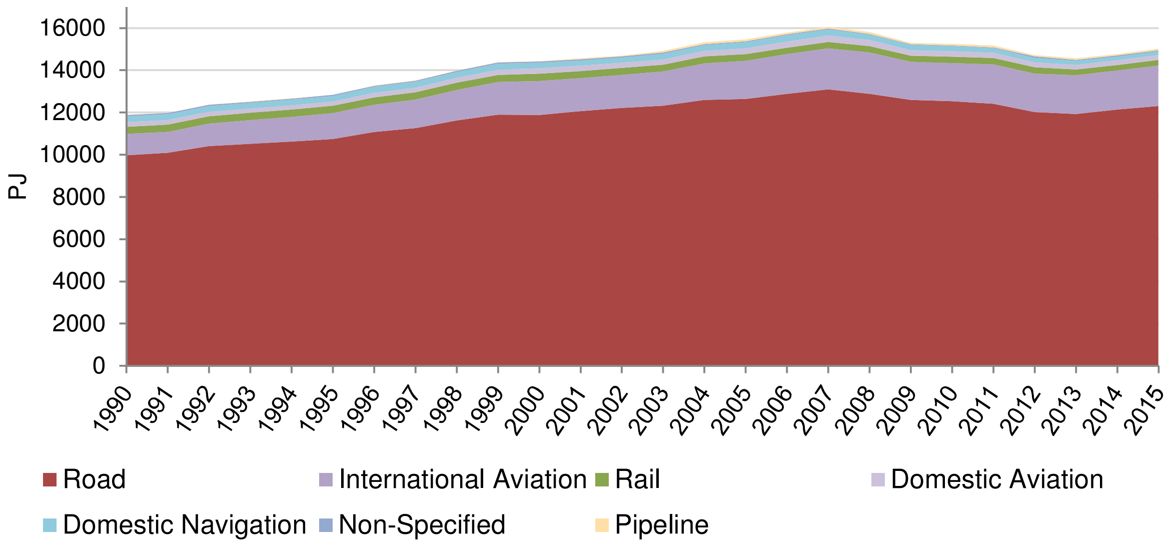


Figure 7: Final energy consumption by mode (Eurostat, 2017a)

3.3 GHG emissions in the transport sector since 1990

Figure 7 and Figure 8 show that final energy consumption and GHG emissions are practically identical in terms of their development over time. GHG emissions grew from 855 to 1,131 million tonnes between 1990 and 2007, after which they declined because of the global financial crisis. Still, the 2014 GHG emissions are much higher than those in 1990. Consequently, there is an urgent need for a consistent strategy to continuously reduce GHG emissions in transport.

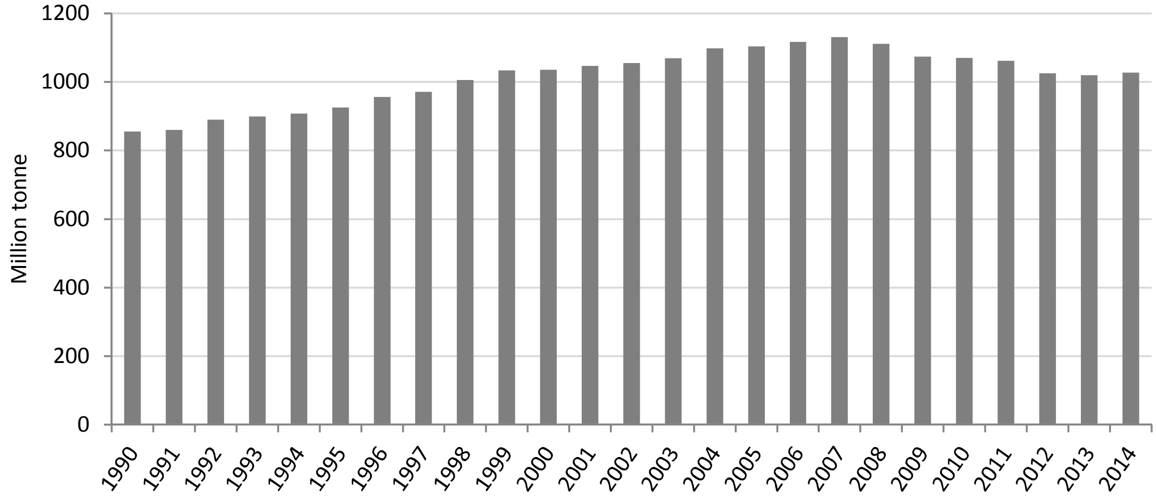


Figure 8: GHG emissions in the transport sector (EU28) (European Environment Agency, 2017a)

Figure 9 shows GHG emissions in the transport sector by country in 2014. The biggest emitter was Germany with a share of 18.1%, followed by France (14.7%), the UK (13%), Italy (11.8%) and Spain (9%). These five countries emitted two thirds of the GHG emissions from transport in the EU28.

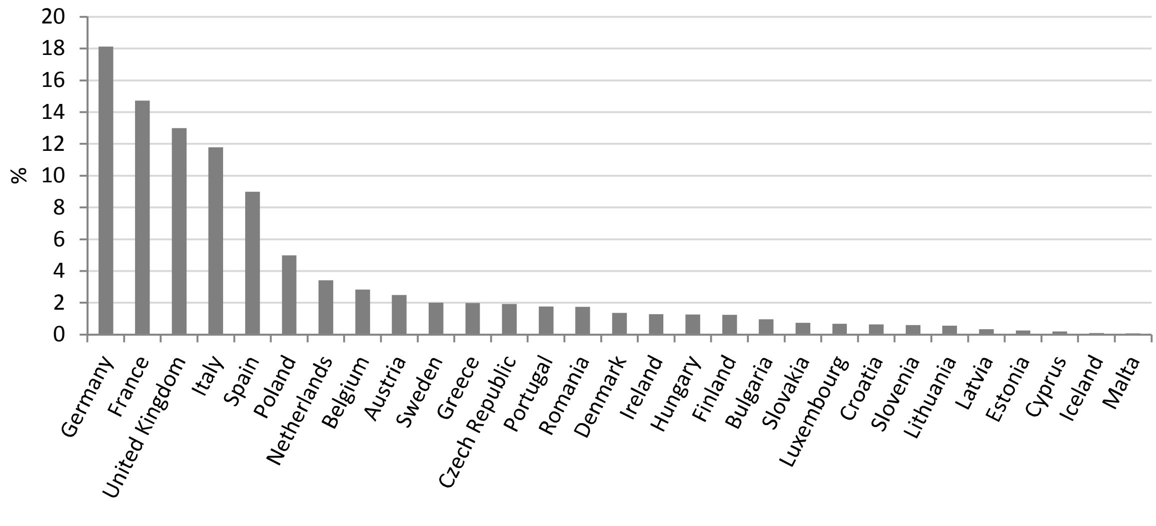


Figure 9: Share of GHG emissions in the transport sector in 2014 by country (European Environmental Agency, 2017b)

3.4 Share of energy sources in the transport sector today

As Figure 10 shows, not only did energy consumption increase between 1990 and 2015, but the share of fuels has also changed considerably. In 1990, gasoline accounted for almost 50% of energy consumption, but this figure fell to 22% in 2015. In the same period, the share of diesel increased from 37% to 56%. The share of compressed natural gas (CNG), liquefied petroleum gas (LPG) and electricity is quiet small: Only 4.04% in 2015.

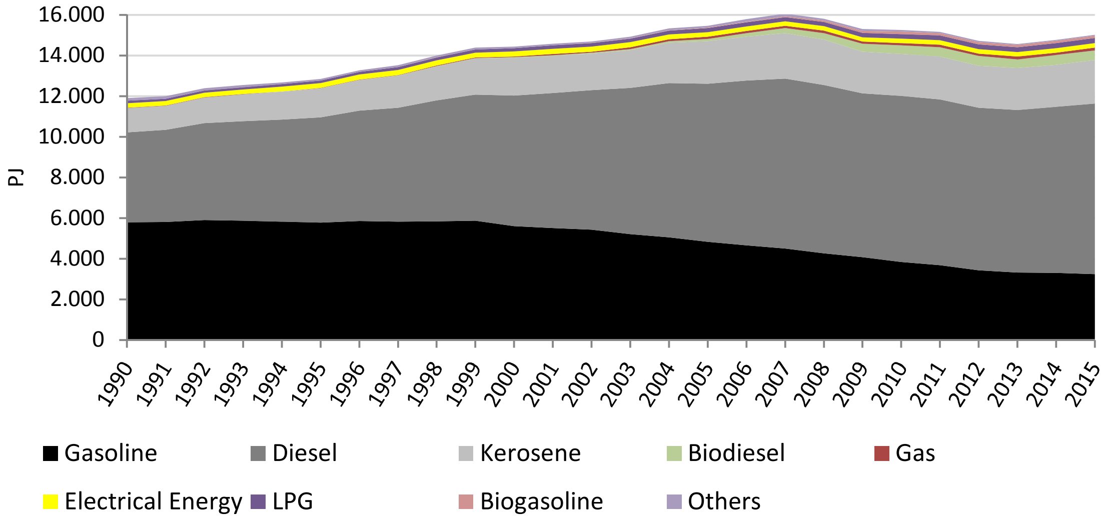


Figure 10: Final energy consumption in the transport sector by fuel in the EU28 (Eurostat, 2017a)

4 Future transport and energy demand

4.1 Two transport-demand scenarios (High and Low) | Model input

Fuel demand and the corresponding emissions are directly linked to the development of the transport sector. Transport behaviour will be characterised by developments that cannot be clearly projected for the 35 years between now and 2050. Therefore, the aim is to differentiate the scenarios using development borders.

Two scenarios for the passenger (pkm) and freight (tkm) transport demand are defined. Where possible, these scenarios were based on already existing studies and assessments.

4.1.1 Passenger and freight transportation demand, and scenario selection

Based on the goals of its white paper, "Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system" (European Commission, 2011), the European Commission commissioned various studies to investigate political and technical measures and their potential with respect to the GHG reduction targets.

The EU Reference Scenario 2013 (Capros et al., 2013) defined the reference for the development of passenger and freight transport volumes. On behalf of the Commission, a group of several institutions, led by AEA, created various scenarios (up to twelve) which differentiated individual aspects of political incentives and regulations aimed at developing scenarios and strategies that are compatible with the EU's GHG targets.

For the present purpose, the study authors classified the basic demand scenario assumptions into the following categories:

(A) Passenger transport volume (in passenger-km)

- Motorised private road transport
- Public road transport
- Short-distance rail transport
- Long-distance rail transport
- Air transport – EU aviation
- Air transport – international aviation

(B) Freight transport volume (in tonne-km)

- Van
- Medium truck
- Heavy truck
- Rail
- Inland navigation
- International navigation

The variety of these scenarios is well represented by two extreme scenarios:

- The most ambitious scenario in terms of reduced transport demand was chosen with the so called AEA Scenario C5b (Hill et al., 2012a; Hill et al., 2012b). In this scenario all technical and political options are addressed and their possible impact on transport demand reduction is calculated.

– The reference scenario is a business-as-usual (BAU) scenario. However, for the present study in 2017, the reference scenario is replaced by an updated version: the EU Reference Scenario 2016, which was published in 2016 (Capros et al., 2016). Unfortunately, the disaggregation of this new reference scenario does not match the old scenario structure in all details. Therefore, some further adaptations and interpolations were necessary. These adaptations mainly concern the handling of international, non-EU28 passenger and goods transport volumes and are discussed below.

As these two scenarios represent how the European Commission and its consultants think the EU28 will develop, they have been chosen for the present purpose.

Nevertheless, some modifications were necessary:

- Historical data (pkm and tkm) for 1995, 2010 and 2015 are taken from the EU Reference Scenario 2016 and from the “EU transport in figures – statistical pocketbook 2016” (European Commission, 2016e).
- Occupation rates and annual driving volume per vehicle have been adapted in order to closely align calculated fuel consumption, car registrations, etc. with the real data for the period 1995 to 2015. Details of the parameter setting are given in the annex.

A particular approach was required for international aviation and navigation. The EU Reference Scenario includes only inland navigation in individual member states and international bunker fuels. However, in the original AEA scenario, aviation activity and energy consumption were scaled to full flight distance from EU countries. As return flights are not accounted for, this covers the activity attributable to the country of embarkation. For the scenario calculations, the AEA demand projections were used. Due to missing data, historical data up to 2015 were based on international bunker fuels consumption. As a cross-check, this study analysed 2015 air passenger transport movements for Germany and the UK. About 5% (Germany) and 1% (UK) of pkm are due to inland movements. Approximately one third of pkm in both countries is due to intra-EU movements, and about two thirds are due to extra-EU movements. This is roughly consistent with AEA scenario assumptions.

Figure 11 shows the passenger transport volume. Historical data are taken in five-year steps from historical statistics and interpolated for the intervening periods. Therefore, the 2008 dip in activity is only reflected in these figures by 2005 and 2010 data and is therefore smoothed out. Areas represent the low scenario (AEA-C5b), while the broken lines show the high scenario assumptions (adapted EU Reference Scenario 2016).

The decline between 2015 and 2020 in the original low scenario reflects the chosen assumptions about reduced future passenger transport activity. This decline has been flattened out in the present low scenario to smoothly connect 2015 data with the 2040 and 2050 assumptions.

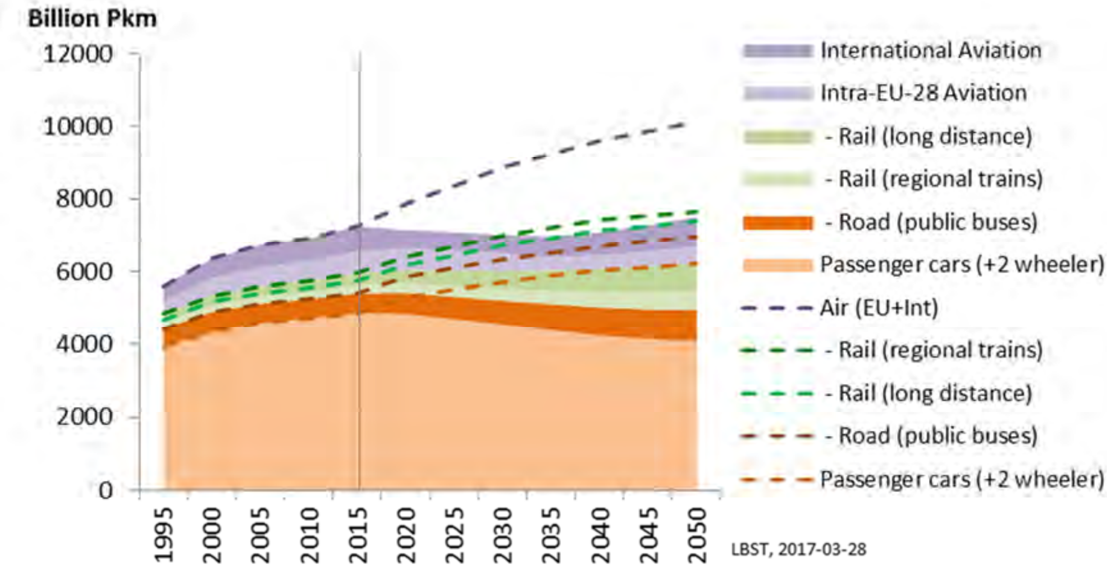


Figure 11: Overview of chosen passenger transport volumes in the EU28; the broken lines correspond to EU Reference Scenario 2016 (high), while the areas show the data for the efficiency scenario AEA-C5b (low)

Figure 12 shows the intra-EU28 goods transport demand. Road transport differentiates between vans (small, 3.5 t), medium trucks (between 3.5 t and 12 t) and heavy trucks (over 12 t). The high scenario (broken lines) and low scenario (areas) are based on the EU Reference Scenario 2016 and the AEA-C5b scenario respectively. Note that in the low scenario, the road transport volume is considerably reduced in favour of more rail transport. Regarding navigation, this chart only includes the inland form.

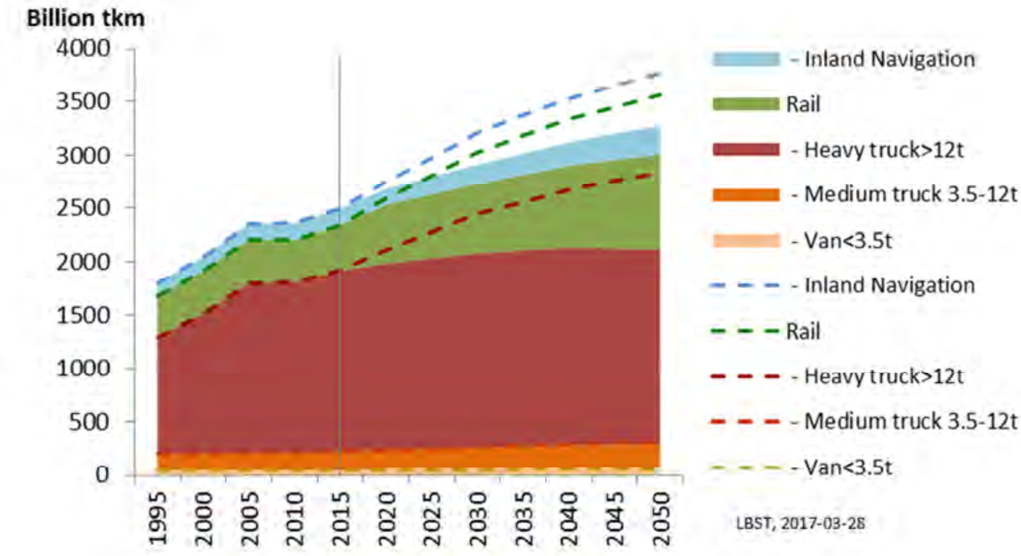


Figure 12: Overview of goods transport volumes in the EU28; the broken lines correspond to the modified EU Reference Scenario 2016 (high), while the areas show the data for the efficiency scenario AEA-C5b (low)

Figure 13 reproduces the data from Figure 12 but with the transport volumes for international navigation. The transport volume for international navigation is added from AEA. However, the data for the high scenario are adapted to the reduced demand in 2015. The scenario assumptions up to 2050 are reduced by the 2015 difference between scenario assumptions and real data.

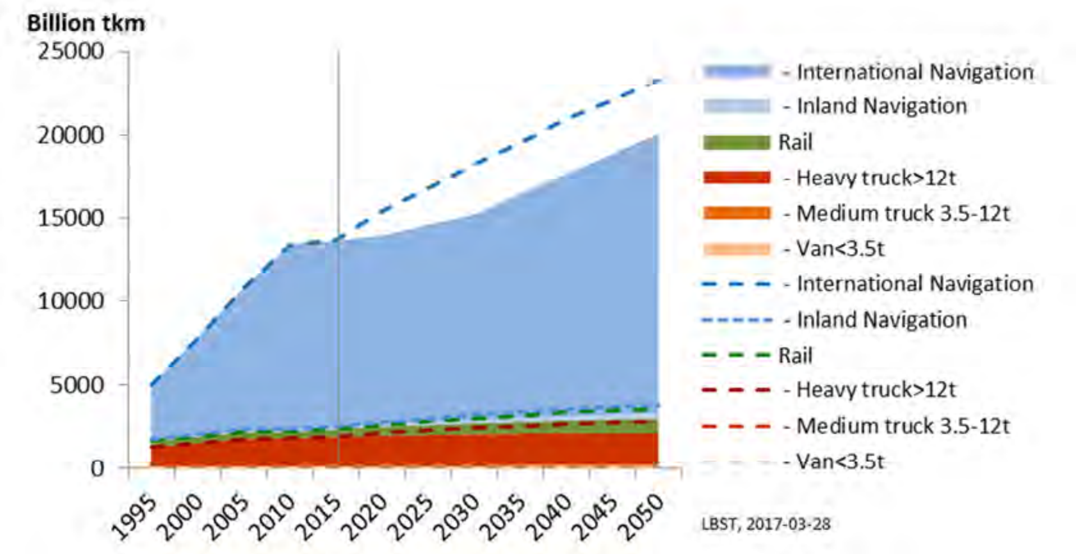


Figure 13: Overview of goods transport volumes in the EU28; the areas correspond to the modified EU Reference Scenario 2016, while the broken lines show the data for the efficiency scenario AEA-C5b; note that the intra-EU28 transport volumes are identical to Figure 12; this figure adds the data for international navigation

Further details are provided in the Annex.

4.1.2 Modelling of transportation supply

This section looks at the modelling of vehicle fleets and GHG emissions.

Using time and average annual driving distances, etc., new vehicles are adjusted to match the model results with current transportation statistics.

Figure 14 explains the basic logic behind the modelling. The target numbers to be met each year are passenger-kilometres and tonne-kilometres.

First, these numbers are translated into vehicle-kilometres and, using average driving activity, into the number of vehicles. The number of new cars is calculated according to average vehicle use. This includes the fuel mix of newly registered cars. This ensures that new cars with improved fuel performance are phased in each year, while the age distribution – and therefore the fleet mix of cars of various fuel classes – is properly accounted for in the scenario calculations.

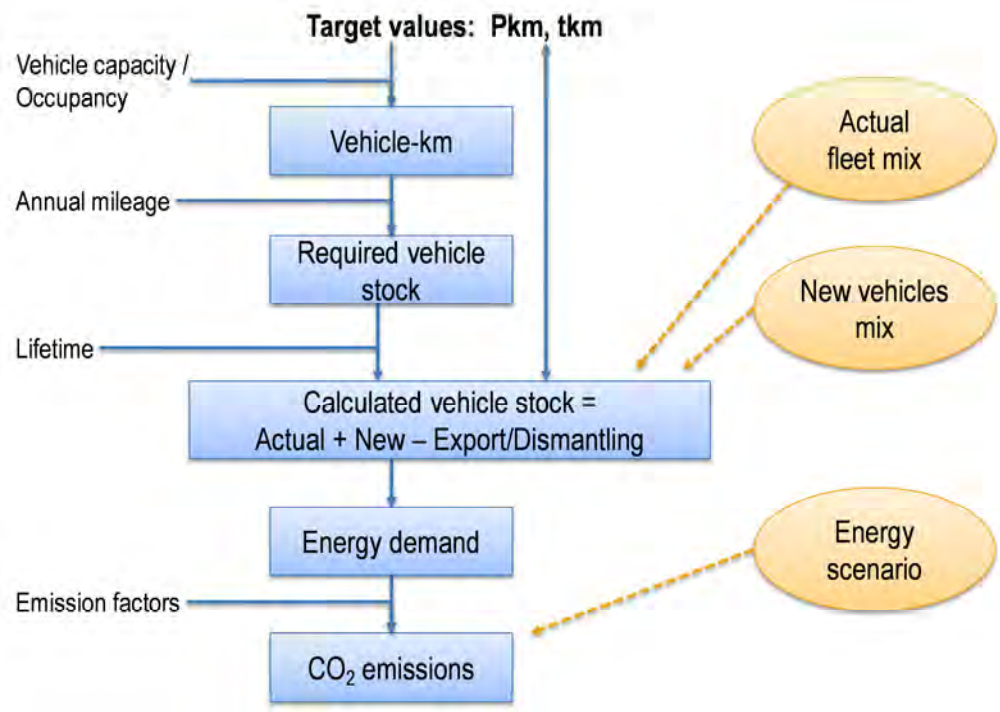


Figure 14: Key parameters and calculation approach in the fleet model

The transformation of the transport demand into fuel consumption shows that the share of the fuel consumption for shipping is much smaller than the corresponding share of the transport demand. Here, differences between the scenarios for inner-European fuel strategies and energy-saving measures dominate the total energy consumption patterns.

Table 1 summarises the parameter setting for the chosen vehicle structure for passenger transport. Table 2 summarises the same for freight transport. Details are given in the Annex.

	Capacity [seats]	**Utilisation [%] or [persons/vehicle]**	**Annual driving range [km/vehicle/year]**	**Operation time [years]**
Car		1.4 cap/car	14,000	**13.9**
Bus		22% (2010) – 23% (2020)	43,000	**14**
Short-distance train	120	33% (2010) – 41% (2050)	120,000	**30**
Long-distance train	430	45% (2010) – 48% (2050)	200,000	**25**
Aircraft	170	77% (2010) – 85%(2050)	2,500,000	**15**

Table 1: Parameter setting for passenger transport modes

	Average load [t/vehicle or train]	Empty trip km [%]	Annual driving range [km/vehicle/year]	Operation time [year]
Van	0.28	35%	10,000	**12**
Medium truck	2.0	30%	25,000	**15**
Heavy-duty truck	12.5	20%	75,000	**10**
Train	532	0%	100,000	**39**
Inland ship	1,290	20%	13,700	**60**
Maritime ship	35,000	40%	145,000	**30**

Table 2: Parameter setting for freight transport modes

The present study focuses on the potential for substitution of conventional combustion engines. As road transport has by far the largest share of transport energy consumption, the parameter setting is more detailed for road transport than for other modes. The parameter setting influences the phase-in time of new technologies, and therefore the fuel consumption and GHG emissions. However, assuming a continuous fleet development and operating times of >10 years against some 30 years left to go to the target year 2050 results in significant legacy vehicles in the fleet is only one influence for energy consumption and greenhouse gas emissions in the final scenario year 2050 among others. Further disaggregation and detailing will only marginally influence the calculation results and corresponding conclusions.

4.2 Definition of three fuel/powertrain scenarios | Model input

Three fuel/powertrain scenarios have been defined by the study based on Ricardo (2016) for passenger cars. They are explorative by nature in order to set a robust framework of distinctive input scenarios to probe the spectrum of result. However, the different evolutions could be plausible, subject to corresponding framework conditions. To reflect current discussions, a baseline number of BEVs has been assumed in both the PtL and PtG scenarios.

4.2.1 Current policy scenario (PtL-dominated)

The PtL-dominated scenario (Table 3 and Table 4) is a conservative BAU scenario based on established fuels, powertrains and infrastructures. Internal combustion engines fueled with liquid fuels produced via power-to-liquid technology dominate all transportation modes. The car mix is derived from Ricardo (2016, p. 11, low ambition). The diesel-fueled truck includes the introduction of a hybrid powertrain, which is taken into account via evolution of the specific fuel consumption.

PtL-dom car (% new reg)	ICE G/D	ICE Methane	Hybrid G/D	Hybrid Methane	PHEV/REEV G/D	PHEV/REEV Methane	BEV	FCEV
2010	100	0	0	0	0	0	0	0
2020	88	1	7	0	2	0	2	1
2030	66	0	19	1	8	0	5	2
2040	48	0	28	0	12	1	9	3
2050	35	0	30	0	16	1	14	6

Table 3: New passenger car registrations for current policy scenario (PtL-dominated)

PtL-dom truck (% new reg)	Truck <3.5 t			Truck 3.5-12 t			Truck >12 t		
	Diesel	BEV	FCEV	Diesel	Methane	BEV	Diesel	Methane	FCEV
2010	100	0	0	100	0	0	100	0	0
2020	98	1	1	98	1	1	99	1	0
2030	80	10	10	85	5	10	95	5	0
2040	70	15	15	75	10	15	90	10	0
2050	60	20	20	65	15	20	85	15	0

Table 4: New truck registrations for current policy scenario (PtL-dominated)

PtL-dom bus & train (% new reg)	Bus			Train (short distance)			Traing (long distance)[1]
	Diesel	BEV	xEV (FCEV)	Electricity (OHL)	Diesel	FCEV	Electricity (OHL)
2010	99	1	0	80	20	0	100
2020	96	3	1	80	19	1	100
2030	85	5	10	80	18	2	100
2040	80	5	15	80	16	4	100
2050	75	5	20	80	15	5	100

Table 5: New bus and train registrations for current policy scenario (PtL-dominated)

[1] Long-distance high-speed trains such as Germany's Intercity Express and France's TGV are electric trains with overhead lines in all scenarios

PtL-dom ship & aircraft (% new reg)	Maritime ships			Aircraft[2]	
	Diesel	Methane	Methanol	Kerosene	H_2-FCEV
2010	100	0	0	100	0
2020	99	1	0	100	0
2030	98	2	0	100	0
2040	96	4	0	100	0
2050	95	5	0	100	0

Table 6: New maritime ship and aircraft registrations for current policy scenario (PtL-dominated)

4.2.2 PtG-dominated scenario

The PtG-dominated scenario (Table 7 and Table 8) focuses on power-to-gas fuels being increasingly used in electrified powertrains. It comprises $PtCH_4$ for internal combustion engines and PtH_2 for fuel cells. The car mix is derived from Ricardo (2016, p. 12, high ambition).

PtG-dom car (% new reg)	ICE G/D	ICE Methane	Hybrid G/D	Hybrid Methane	PHEV/REEV G/D	PHEV/REEV Methane	BEV	FCEV
2010	100	0	0	0	0	0	0	0
2020	75	10	0	9	0	3	2	1
2030	10	10	0	40	0	22	6	12
2040	4	4	0	20	0	40	12	20
2050	0	0	0	5	0	35	25	35

Table 7: New passenger car registrations for PtG-dominated scenario

[2] Due to the long time involved in introducing new aircraft, no baseline electrification has been assumed for aircraft.

PtG-dom truck (% new reg)	Truck <3.5 t			Truck 3.5-12 t			Truck >12 t		
	Diesel	BEV	FCEV	Diesel	Methane	BEV	Diesel	Methane	FCEV
2010	100	0	0	100	0	0	100	0	0
2020	98	1	1	95	4	1	90	9	1
2030	55	30	15	60	30	10	70	25	5
2040	30	40	30	35	45	20	40	45	15
2050	10	50	40	15	55	30	10	60	30

Table 8: New truck registrations for PtG-dominated scenario

PtG-dom bus & train (% new reg)	Bus			Train (short distance)			Train (long distance)[3]
	Diesel	Methane	xEV (FCEV)	Electricity (OHL)	Diesel	FCEV	Electricity (OHL)
2010	99	1	0	80	20	0	100
2020	95	4	1	80	15	5	100
2030	60	30	10	80	10	10	100
2040	35	45	20	80	5	15	100
2050	15	55	30	80	0	20	100

Table 9: New bus and train registrations for PtG-dominated scenario

PtG-dom ship & aircraft (% new reg)	Maritime ships			Aircraft[4]	
	Diesel	Methane	Methanol	Kerosene	H_2-FCEV
2010	100	0	0	100	0
2020	95	5	0	100	0
2030	80	20	0	99	1
2040	55	45	0	96	4
2050	30	70	0	90	10

Table 10: New maritime ship and aircraft registrations for PtG-dominated scenario

[3] Long-distance high-speed trains such as Germany's Intercity Express and France's TGV are electric trains with overhead lines in all scenarios.
[4] Due to the long time involved in introducing new aircraft, no baseline electrification has been assumed for aircraft.

4.2.3 Electric-powertrain scenario (eDrives)

The eDrive-dominated scenario (**Fehler! Verweisquelle konnte nicht gefunden werden.** and **Fehler! Verweisquelle konnte nicht gefunden werden.**) has electrified powertrains in all transport modes. The passenger car registrations in 2050 mainly consist of BEVs. The truck registrations in 2050 are mainly fuel cell electric vehicles (FCEVs).

eDrive-dom car (% new reg)	ICE G/D	ICE Methane	Hybrid G/D	Hybrid Methane	PHEV/REEV G/D	PHEV/REEV Methane	BEV	FCEV
2010	100	0	0	0	0	0	0	0
2020	75	0	16	0	4	0	4	1
2030	20	0	20	0	25	0	30	5
2040	0	0	5	0	25	0	60	10
2050	0	0	0	0	10	0	70	20

Table 11: New passenger car registrations for eDrive-dominated scenario

eDrive-dom truck (% new reg)	Truck <3.5 t			Truck 3.5-12 t			Truck >12 t		
	Diesel	BEV	FCEV	Diesel	Methane	BEV	Diesel	Methane	FCEV
2010	100	0	0	100	0	0	100	0	0
2020	95	4	1	95	1	4	98	1	1
2030	50	40	10	70	5	25	80	5	15
2040	20	60	20	15	10	75	45	10	45
2050	0	70	30	0	15	85	5	15	80

Table 12: New truck registrations for eDrive-dominated scenario

eDrive-dom bus & train (% new-reg)	Bus			Train (short distance)			Train (long distance)[5]
	Diesel	Methane	xEV (FCEV)	Electricity (OHL)	Diesel	FCEV	Electricity (OHL)
2010	99	1	0	80	20	0	100
2020	97	3	1	80	15	5	100
2030	67	8	25	80	10	10	100
2040	15	10	75	80	5	15	100
2050	0	15	85	80	0	20	100

Table 13: New bus and train registrations for eDrive-dominated scenario

eDrive-dom ship & aircraft (% new reg)	Maritime ships			Aircraft[6]	
	Diesel	Methane	Methanol	Kerosene	H_2-FCEV
2010	100	0	0	100	0
2020	98	1	1	99	1
2030	78	2	20	92	8
2040	56	4	40	75	25
2050	45	5	50	65	35

Table 14: New maritime ship and aircraft registrations for eDrive-dominated scenario

4.3 Development routes

Two transport-demand scenarios, three fuel/powertrain scenarios and two GHG targets result in a large number of theoretically possible combinations. However, not all of these combinations necessarily reflect "future archetype worlds" that are coherent in themselves. For ease of analysis, communication of results, and coherence, the numerous scenario combinations were funnelled into four distinct development routes (see Figure 15). The four routes were selected to cover the full bandwidth of possible results from the set of consistent scenario combinations. In addition, power-to-methane and power-to-liquid imports have been modelled as scenario variants for the cumulated investments and renewable electricity demand.

[5] Long-distance high-speed trains such as Germany's Intercity Express and France's TGV are electric trains with overhead lines in all scenarios.
[6] Due to the long time involved in introducing new aircraft, no baseline electrification has been assumed for aircraft.

Development routes	Transportation demand scenario		Fuel/powertrain scenario			Climate mitigation ambition 2050 (base-year 1990)		Import ($PtCH_4$, PtL) variant
	HIGH	LOW	PTL	PTG	eDrives	$-80\%_{GHG}$	$-95\%_{GHG}$	
1.a BAU-moderate	■		■			■		■
1.b BAU-ambition		■	■				■	■
2. Progressed-mix		■		■			■	■
3. More-electric		■			■		■	■

Figure 15: Funnelling the scenarios into four development routes, including the import variant

Four development routes with the following characteristics have been modelled:

- BAU[7]-moderate: PtL-dominated scenario combined with high transport demand and -80% GHG emissions in 2050 compared to 1990 levels
- BAU-ambition: PtL-dominated scenario combined with low transport demand and -95% GHG emissions in 2050 compared to 1990 levels
- Progressed-mix: PtG-dominated scenario combined with low transport demand and -95% GHG emissions in 2050 compared to 1990 levels
- More-electric: eDrive-dominated scenario combined with low transport demand and -95% GHG emissions in 2050 compared to 1990 levels

Battery electric powertrains are feasible and already commercially available for distribution trucks. The potential for battery electric heavy-duty long-haul trucks is limited because of a limited range without significant payload penalty. Therefore, installing overhead catenary wires along express highways is proposed. The Ports of Los Angeles and Long Beach in the USA are planning to electrify highways for drayage operations (CE Delft & DLR, 2013; SCAQMD, 2015a). However, if electric heavy-duty vehicles for which the electricity is supplied by overhead catenary wires are to reach a significant share of overall freight transport services, a grid of overhead wires across the whole EU would be required. Only a few member states, among them Germany and Sweden, are discussing overhead catenary wires as a source of electricity for heavy-duty vehicles. However, road transport is international and overhead catenary wires have not yet been discussed in the rest of the EU. Therefore, this study does not take account of overhead catenary wires as a source of electricity for heavy-duty vehicles.

Heavy-duty trucks with fuel cell powertrains are under development in the USA (CE Delft & DLR, 2013), (SCAQMD, 2015b). Fuel cell trucks are more flexible than electric trucks that use catenary wires. Therefore,

[7] BAU is not meant as a business as usual scenario from the perspective of the OEMs, but as low efficiency powertrain scenario in contrast to eDrive scenario

this study takes heavy-duty trucks with fuel cell powertrains into account alongside diesel and methane ICE powertrains.

4.4 Vehicle fuel consumption

The fuel consumption figures for passenger vehicles are based on potential real world assumptions (LBST, 2016; ICCT/TNO/IFEU, 2015; T&E, 2017). Table 15 shows the fuel consumption of the different powertrains assumed for passenger vehicles in this study.

Powertrain	**Fuel**	**Fuel consumption (MJ/km)**				
		Today	**2020**	**2030**	**2040**	**2050**
ICE	Gasoline	2.40	2.17	1.93	1.81	1.81
	Diesel	2.00	1.94	1.65	1.51	1.51
	CNG	2.52	2.10	1.87	1.76	1.76
ICE hybrid	Gasoline/diesel	1.65	1.54	1.34	1.24	1.24
	CNG	1.89	1.58	1.40	1.32	1.32
G/D REEV	Gasoline/diesel	0.53	0.36	0.35	0.34	0.34
	Electricity	0.59	0.59	0.50	0.46	0.46
CNG REEV	CNG	0.57	0.35	0.34	0.33	0.33
	Electricity	0.59	0.59	0.50	0.46	0.46
BEV	Electricity	0.60	0.60	0.56	0.53	0.53
FCEV	Hydrogen	1.61	1.05	0.85	0.75	0.75

Table 15: Fuel consumption by passenger vehicles (including 40% addition for real-world consumption)

LBST (2016) uses the fuel consumption data indicated in LBST/IFEU/DBFZ/DLR (2015) for utility vehicles with a gross weight of up to 3.5 t. Comparison with real-world data indicated in the *lastauto omnibus katalog* (2010, 2012, 2015, 2016 and 2017) shows a significant difference (Figure 16).

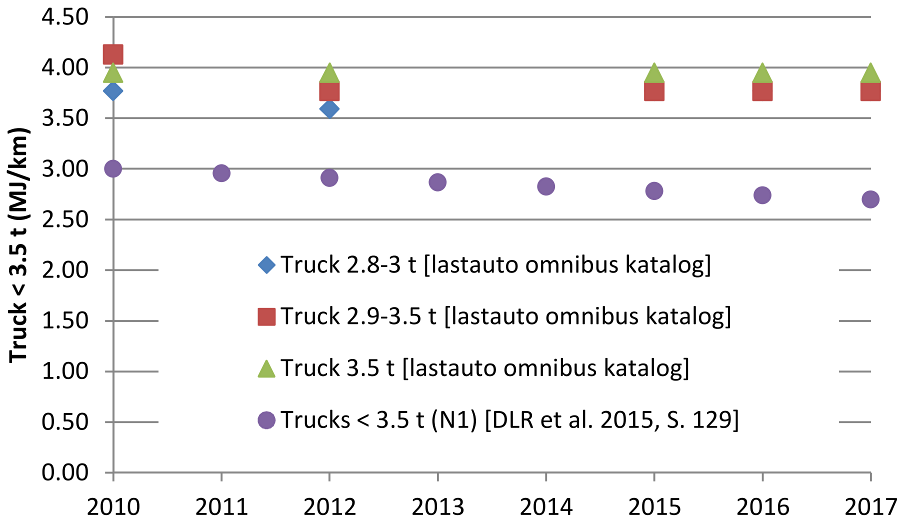


Figure 16: Fuel consumption by diesel utility vehicles with a maximum gross weight of 2.8 to 3.5 t

The fuel consumption data indicated in LBST/IFEU/DBFZ/DLR (2015) seems to be too low. Therefore, the diesel consumption by light-duty utility vehicles with a maximum gross weight of up to 3.5 t for today was derived from the *lastauto omnibus katalog* (2017). It was assumed that fuel consumption will decrease by 1.5% per year until 2030. After 2030, the assumption is that the fuel consumption remains constant.

The fuel consumption of CNG-fuelled light-duty utility vehicles with a maximum gross weight of up to 3.5 t was derived by multiplying the diesel consumption by a factor derived from NANUPOT (2011) for 2010 and 2050. The values between 2010 and 2050 were calculated by applying a factor for the reduction in electricity consumption.

For battery electric light-duty utility vehicles with a maximum gross weight of up to 3.5 t, the electricity consumption was put at 0.46 kWh/km (1.66 MJ/km) for 2010 (NANUPOT, 2011). The electricity consumption for 2016 amounts to about 0.39 kWh/km (1.40 MJ/km) and was derived from Kreisel (2016) (300 km with a battery capacity of 92 kWh) and JEC (2013) (factor 14.49/11.38 to take account of charging losses). No further reduction in electricity consumption after 2016 has been assumed.

The hydrogen consumption of the fuel cell electric light-duty utility vehicles with a maximum gross weight of up to 3.5 t was derived by multiplying the diesel consumption by a factor derived from NANUPOT (2011) for 2010 and 2050. The values between 2010 and 2050 were calculated by applying a factor for the reduction in electricity consumption.

For trucks with a maximum gross weight of 7.5 and 12 t, no reduction in diesel consumption can be observed over the last seven years (Figure 17). However, hybridisation has only been introduced now. According to Jordan (2012), hybridisation leads to fuel savings of about 12%. For the future, it is assumed that hybridisation will reduce fuel consumption by 12% for the whole fleet by 2030. No further reduction in fuel consumption has been assumed for the years after 2030.

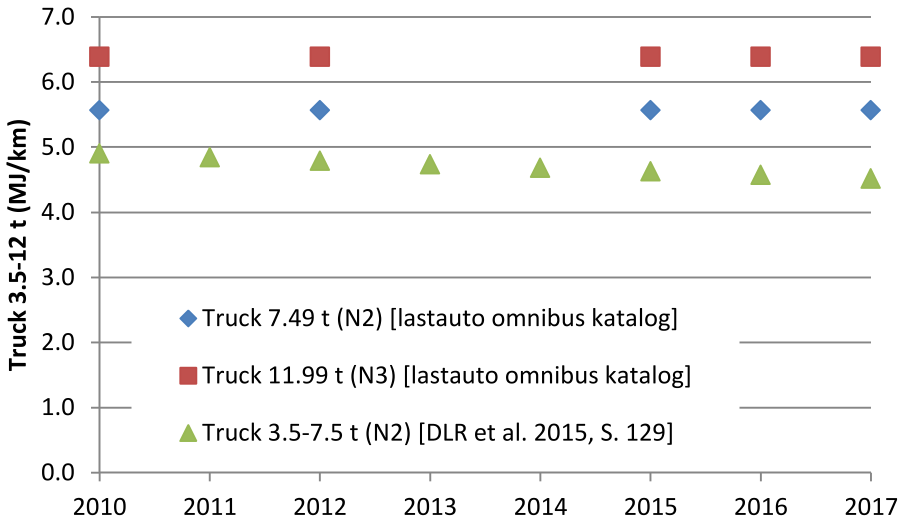


Figure 17: Fuel consumption by diesel utility vehicles with a maximum gross weight of 3.5 to 12 t

The fuel consumption of CNG-fuelled trucks with a maximum gross weight of up to 7.5 and 12 t was derived by multiplying the diesel consumption by a factor derived from NANUPOT (2011) for 2010 and 2050. The values between 2010 and 2050 were calculated by applying a factor for the reduction in electricity consumption.

The electricity consumption for battery electric trucks with a maximum gross weight of 7.5 t was assumed to be 0.72 kWh/km (2.59 MJ/km), as indicated in Orten (2016). The electricity consumption for trucks with a maximum gross weight of 12 t was assumed to be 0.82 kWh/km (2.95 MJ/km), as indicated in Emoss (2017). Hydrogen consumption was derived from the electricity consumption of the battery electric truck multiplied by the ratio of the efficiency of the BEV and the FCEV (0.73/0.50).

A weighted mix of trucks with a maximum gross weight of 7.5 and 12 t was assumed to be representative for the utility vehicles with a maximum gross weight of 3.5 to 12 t. The weighted mix is based on the annual mileage and the number of trucks.

The fuel consumption of the heavy-duty vehicles with a maximum gross weight of 40 to 44 t was derived from LBST/IFEU/DBFZ/DLR (2015).

Table 16 shows the fuel consumption by trucks used in the model.

Powertrain	Fuel	Fuel consumption (MJ/km)				
		Today	2020	2030	2040	2050
Utility vehicles – N1 (maximum gross weight < 3.5 t)						
ICE incl. hybrid	Diesel	3.8	3.6	3.1	3.1	3.1
	CNG	4.5	4.4	4.2	3.9	3.7
BEV	Electricity	1.4	1.4	1.4	1.4	1.4
FCEV	Hydrogen	2.1	2.1	2.0	2.0	1.9
Utility vehicles – weighted mix N2/N3 (maximum gross weight 3.5 to 12 t)						
ICE incl. hybrid	Diesel	5.8	5.6	5.1	5.1	5.1
	CNG	8.3	8.1	7.6	7.2	6.8
BEV	Electricity	2.7	2.7	2.7	2.7	2.7
FCEV	Hydrogen	3.9	3.9	3.9	3.9	3.9
Utility vehicles – N3 (trailer truck, maximum gross weight 40 to 44 t)						
ICE incl. hybrid	Diesel	11.1	10.0	8.8	8.4	7.9
	CNG	14.0	12.1	10.2	10.1	10.0
FCEV	Hydrogen	7.5	7.2	7.0	6.5	5.9

Table 16: Fuel consumption by trucks

4.5 Role of biofuels and fossil fuels in transport | Model input

This section defines the biofuel baseline (gaseous and liquid) and describes tolerable fossils fuels in transport to meet the GHG reduction targets of -80%$_{1990}$ and -95%$_{1990}$ by 2050.

4.5.1 GHG reduction targets

The German government and the European Council have enacted GHG reduction targets for 2030 and 2050 (Table 17) (BMUB, 2016; European Council, 2014).

Time horizon	GHG emissions target	Reference
2030	-30%$_{GHG\ 2005}$	http://ec.europa.eu/clima/policies/strategies/2030_en (non-ETS)
	-40 to -42%$_{GHG\ 1990}$	The Federal Government of Germany (transport only)
2050 (moderate)	-80%$_{GHG\ 1990}$	http://ec.europa.eu/clima/policies/strategies/2050_en The Federal Government of Germany (all sectors)
2050 (ambitious)	-95%$_{GHG\ 1990}$	

Table 17: GHG reduction targets for 2030 and 2050

This study assumes that GHG emissions decrease by 30% compared to 2005 levels by 2030. This results in GHG reductions of about 8% compared to 1990 levels, based on official EEA data. For 2050, GHG emissions decline by 80 to 95% compared to 1990 levels, depending on the scenario.

4.5.2 Greenhouse gases considered in this study

The GHGs considered in this study are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The global warming potential (GWP) of the various GHGs is expressed in carbon dioxide equivalents (CO_2e). Table 18 shows the global warming potential for a period of 100 years according to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC).

	GWP 100 (g CO_2 equiv./g)	**Reference**	**Included in our scenario calculations?**
CO_2	1	(IPCC, 2013)	Yes
CH_4	30	(IPCC, 2013)	Yes
N_2O	265	(IPCC, 2013)	Yes
Black carbon	374 – 1870	(Boucher & Reddy, 2008) (Cames & Helmers, 2013, p8)	No, see Section 4.5.5
Non-CO_2 climate impacts of aviation emissions	2	(IFEU/INFRAS/LBST, 2016)	No, see Section 4.5.6

Table 18: Global warming potential (GWP)

In the evaluation, only CO_2 emitted by the combustion of fossil fuels is considered. The combustion of biomass is carbon-neutral – i.e., the amount of CO_2 emitted during combustion is equal to the amount of CO_2 that the plants absorbed from the atmosphere while growing. Furthermore, this study does not include the climate impacts of high-altitude aviation emissions.

The study also does not consider the energy consumption and GHG emissions resulting from constructing and decommissioning manufacturing plants, infrastructure and vehicles.

4.5.3 Amount of tolerable fossil fuels in transport

To assess the amount of tolerable fossil fuels in transport, the maximum allowable GHG emissions were calculated. The maximum allowable GHG emissions were allocated to the various transportation fuels. Dividing the maximum amount of GHG emissions by the specific GHG emissions from supplying and using the fossil fuel gives the maximum tolerable amount of the fossil fuel.

The contribution of biofuels to the overall fuel supply is set at 600 PJ per year, which is about 5% of today's road fuel consumption. The 600 PJ per year is allocated to gasoline, kerosene, diesel and methane based on the share of these fuels in the overall sum of these transportation fuels. For instance, if the share of methane in the sum of gasoline, kerosene, diesel and methane demand was 10%, then 60 PJ of the annual 600 PJ of biofuels would be allocated to methane. No biofuels have been assumed for hydrogen and methanol. Since the total amount of biofuel in PJ is constant, the percentage of biofuel varies according to the total fuel demand.

Table 19 shows the specific GHG emissions savings of biofuels compared to fossil fuels assumed in this study. According to the RED (2009), the amount of GHG emissions that should be used as reference (fossil fuel comparator) is 83.8 g CO_2 equivalent per MJ of final fuel.

	Today	2030	2050	Proxy pathways for GHG emissions calculation
Liquid biofuels	-60%	-70%	-90%	short-term: rapeseed mid/long: straw BtL
Biomethane	-70%	-89%	-90%	short-term: maize mid/long: straw

Table 19: Specific GHG emissions savings compared to fossil fuel (comparator: 83.8 g/MJ)

The absolute amount of GHGs is limited to 20 or 5% of the amount emitted in 1990. In terms of the -80% GHG target, the maximum tolerable level of GHG emissions in the EU is about 230 million tonnes per year. In terms of the -95% target, the maximum tolerable level in the EU is about 60 million tonnes per year. As a result, the share of tolerable fossil transportation fuel depends on the overall fuel demand. In turn, the overall fuel demand varies according to the scenario. Table 20 shows the energy-related share (LHV) of tolerable fossil fuels in transport to comply with the -80 and -95% reduction targets.

	PtL + High (-80%$_{GHG}$)	PtL + Low (-95%$_{GHG}$)	PtG + Low (-95%$_{GHG}$)	eDrives + Low (-95%$_{GHG}$)
Gasoline, kerosene, diesel	15%	4%	5%	6%
Methane	11%	0.2%	0.9%	1.8%
Hydrogen	16%	6%	7%	8%
Methanol	-	-	-	8%

Table 20: Energy-related share of tolerable fossil fuels in transport to comply with the -80 and -95%$_{1990}$ GHG emissions reduction targets in 2050

With the moderate GHG reduction target of -80%, the share of tolerable fossil fuels ranges from 11 to 16%. With the more ambitions target of -95%, the share ranges from 0.2 to 8% for the various transportation fuels and scenarios. More efficient powertrains and lower overall fuel demand will increase the tolerable share of fossil fuels in achieving the GHG reduction target.

The assumptions above lead to the specific GHG emissions for the various energy carriers in the different scenarios shown in Figure 18.

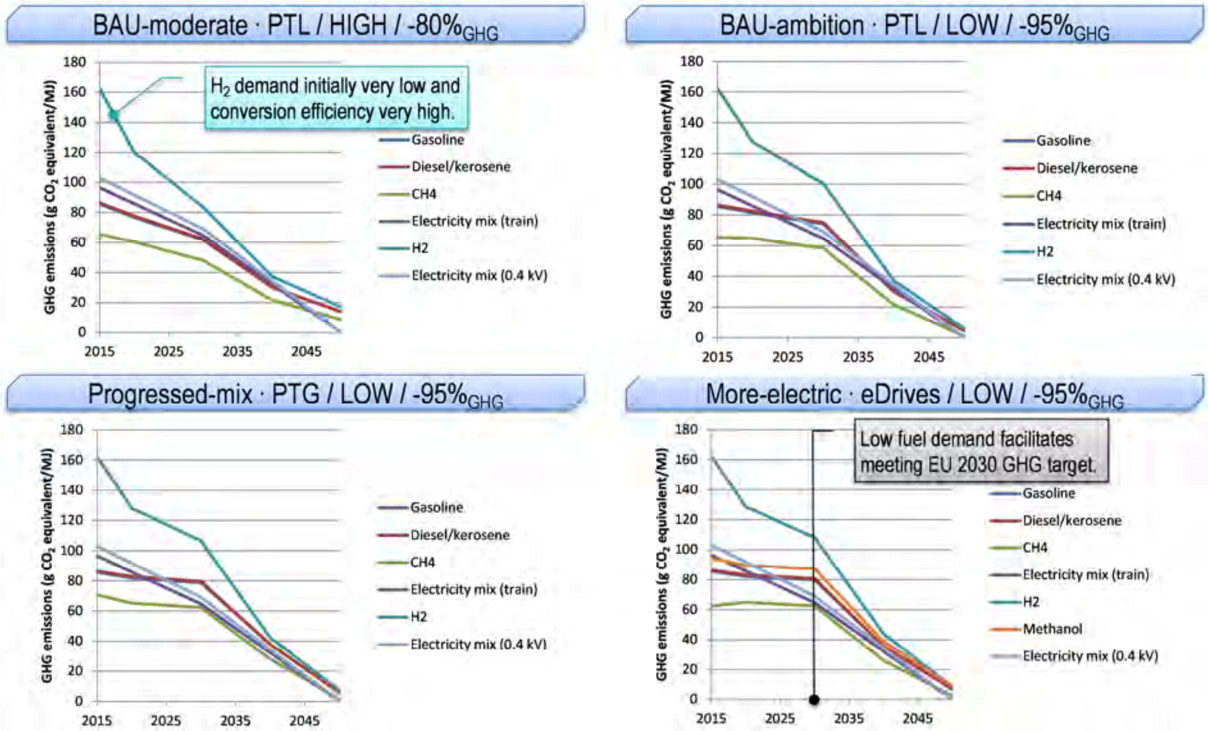


Figure 18: Development of GHG emissions from fuel between 2015 and 2050 in the different scenarios

The high GHG emissions from the supply of compressed gaseous hydrogen (CGH_2) in 2015 are caused by the high share of natural-gas-derived hydrogen and by the high electricity demand for the hydrogen refuelling stations due to high electricity consumption for pre-cooling. However, overall GHG emissions from the supply of CGH_2 decline with the increasing share of renewable hydrogen and the decreasing electricity consumption for pre-cooling. Furthermore, it should be noted that fuel cell vehicles are more efficient than ICE vehicles. This results in low well-to-wheel GHG emissions, including in the introduction phase.

In Germany, the Clean Energy Partnership (CEP) has achieved the negotiated environmental agreement to increase the share of renewable hydrogen to at least 50% (CEP, 2016).

4.5.4 Tailpipe CH_4 and N_2O emissions

If high GHG reductions of more than 95% have to be achieved, emissions of non-CO_2 greenhouse gas emissions become crucial.

Certification data from the US Environmental Protection Agency show that combined tailpipe and crankcase emissions from stoichiometric natural gas engines range from 0.6 to 1.2% of the fuel input. The crankcase emissions alone amount to about 0.6%. That means tailpipe CH_4 emissions would represent a CH_4 loss of 0.3% of the fuel input. The Euro 5 emissions limit of 0.5 g CH_4 per kWh of mechanical work for gas engines in heavy-duty trucks means a loss of 0.27% of fuel input (ICCT, 2015). The N_2O emissions from natural gas engines amount to about 0.003 g per MJ of fuel input (IPCC, 2006).

This study uses combined tailpipe emissions of 0.27% for CH_4-fuelled passenger cars and for CH_4-fuelled trucks. It assumes the crankcase emissions in the EU to be zero because of closed crankcase ventilation.

According to the ICCT (2013), the current practice with LNG-fuelled ships leads to non-CO_2 greenhouse gas emissions of 11.7 gCO_2e per MJ of fuel input based on a GWP of 25 gCO_2e per g of CH_4 (10.6 g/MJ from vessel operation and 1.1 g/MJ from bunkering). Tracing back to CH_4 leads to 0.468 gCH_4 per MJ of fuel input. Best practice leads to 2.4 gCO_2e per MJ of fuel input or 0.096 gCH_4 per MJ of fuel input (2.2 gCO_2e/MJ or 0.088 gCH_4/MJ from vessel operation, and 0.2 gCO_2e/MJ or 0.008 gCH_4/MJ from bunkering). This study assumes that best practice is fully employed in 2050. According to the IPCC (2006), N_2O emissions from ship engines amount to about 0.003 g per MJ of fuel input. It has been assumed that the N_2O emissions from the natural-gas-fuelled ship engines are the same as the emissions from ships that run on diesel or heavy fuel oil.

Table 21 shows the vehicle CH_4 and N_2O emissions.

	CH_4 slip	**CH_4 slip (g/MJ_{fuel})**	**N_2O (g/MJ_{fuel})**	**Non-CO_2 GHG (gCO_2e/MJ_{fuel})****
Passenger vehicle (gas engine)	0.27%*	0.054	0.003	2.415
Truck (gas engine)	0.27%*	0.054	0.003	2.415
Inland ship (HPDI)	2.34% (today) 0.48% (best practice)	0.468 0.096	0.002	14.57 3.41
Maritime ship (HPDI)	2.34% (today) 0.48% (best practice)	0.462	0.002	14.57 3.41

* Tailpipe emissions: 0.3%; crankcase emissions: 0.6% (ICCT, 2015), crankcase emissions are assumed to be zero in the EU because of closed crankcase ventilation

** 30 gCO_2e/gCH_4; 265 $gCO_2e/g\ N_2O$ (IPCC, 2013)

Table 21: CH_4 and N_2O emissions from methane-powered vehicles

The carbon emissions from the combustion of CH_4 would lead to 55 g per MJ. In the case of road vehicles, the CH_4 loss and the N_2O emissions results in about 2.4 gCO_2e/MJ. As a result, the non-CO_2 greenhouse gas emission would be about 4% of the CO_2 from the combustion of CH_4. In the case of ships, the GHG emissions from CH_4 losses would be 26% of the CO_2 combustion if current practices were assumed, and about 5% if best practice was assumed. Best practice has been assumed for the future. The contribution of N_2O is small.

4.5.5 Climate impacts of black carbon emissions

Particulate matter (PM) mainly consists of black carbon. Black carbon is the most light-absorbing component of PM emissions (Cai et al., 2015). The main emission sources are coal firing, open biomass burning, and diesel fuel on-road and off-road (Bond et al., 2013, p. 5504, Figure 37). According to the IPCC (2013), black carbon is recognised as a global warming agent. Scientific confidence in black carbon radiative forcing is high – it is at the same level as scientific confidence in methane radiative forcing (IPPC, 2013). The global warming potential (GWP) of black carbon cited in the literature is listed in Table 22.

(g/g)	GWP 100-year horizon	GWP 20-year horizon	Reference
Black carbon	680	2200	(Bond & Sun, 2005)*
	1870	4470	(Jacobson, 2007)*
	374	-	BC for Europe (Boucher & Reddy, 2008)
	900	3200	BC total, global (IPCC, 2013, p740, Table 8.A.6), citing Bond et al. (2013, p. 5511)
*cited in: (Cames & Helmers, 2013, p. 8)			

Table 22: Black carbon global warming potential

Black carbon aerosol is a forcing agent commonly included in climate models. Despite GWP indications from the IPCC (2013, p. 740, Table 8.A.6) and discussions that tend to favour a global GWP (IPCC, 2013, p. 718), no definitive GWP has been agreed and published by the IPCC so far. This study therefore does not include the climate impact of black carbon. However, the IPCC might include black carbon in standard GWPs in the future, which means that PM emissions from transport could become relevant to GHG reduction targets and thus require emission mitigation efforts to be increased beyond the levels discussed in this study. Reducing PM emissions thus results in the combined benefits of improving local air quality, reducing global warming and increasing the robustness of the transformation process.

4.5.6 High-altitude climate impacts from aviation

Today, subsonic aircraft fly in the upper troposphere and lower stratosphere (at altitudes of about 9 to 13 km) (IPCC, 1999). Emissions from fuel combustion at high altitude result in more global warming than would be expected from the emitted greenhouse gases (CO_2, CH_4 and N_2O) alone. Aircraft engines emit CO_2, NO_x, SO_x, and soot. At high altitude, even emissions of water vapour cause significant global warming because it takes a long time for them to be washed out by the rain.

The radiative forcing index (RFI) is the ratio of total radiative forcing to that from carbon emissions alone. It is a measure of the importance of aircraft-induced climate change relative to that from an equivalent sector with the same fossil fuel use but without any effect other than CO_2. According to the IPCC (1999), the best estimate for the RFI of aircraft emissions at altitudes above 9 km amounts to 2.7 (range: 1.9 to 4.7). According to Lee et al. (2009), the best estimate for the RFI amounts to 3.1 (the contribution of aviation to total anthropogenic radiative forcing amounts to 4.9% including effects of emissions at high altitudes, and 1.6% for CO_2 alone) with a range of 2.5 to 6.1.

So far, the IPCC has not agreed or published any GWP figures. Hence, this study does not take account of high-altitude climate impacts from aviation. However, high-altitude climate impacts could make it hard to achieve GHG reductions of more than 95% in transport.

Influence of high-altitude climate impacts from aviation on German GHG reduction

In IFEU/INFRAS/LBST (2016), international aviation transport demand is assumed to grow by a factor of 2.3 between 2005 and 2050. If radiative forcing from high-altitude emissions were included using a GWP of 2 g/g for CO_2 emitted from aircraft turbines, this would result in 35 million tonnes of carbon dioxide equivalents in 2050. Even if all other transportation modes were carbon-neutral by 2050, GHG emissions from transport in 2050 would only decline by 81%$_{1990}$ (IFEU/INFRAS/LBST, 2016).

4.6 Fuel and electricity demand from transport | Model output

4.6.1 Final energy demand in transport

Figure 19 shows the final energy consumption in transport (direct electricity and PtX fuels) by transport mode in the four different scenarios modelled in this study.

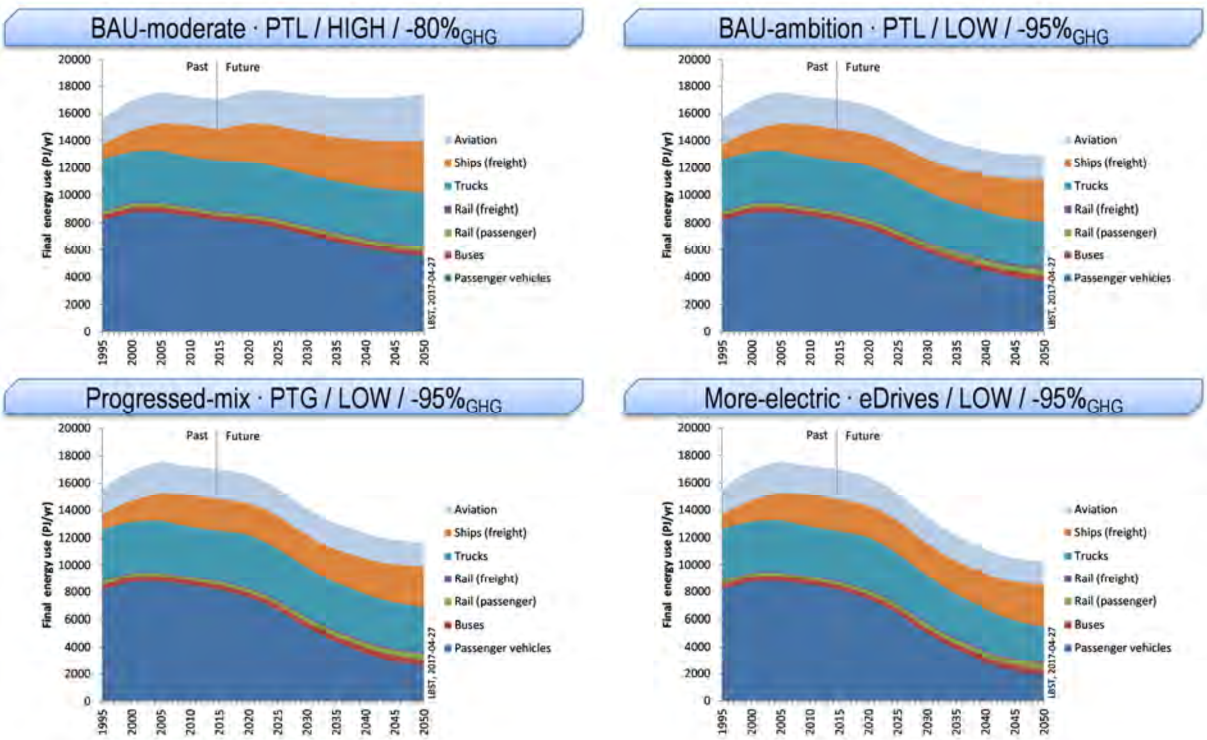


Figure 19: Final energy demand in EU transport from 1995 to 2050 by transport mode

The contribution of ships to the overall final energy demand is rather high and exceeds the final energy demand of passenger vehicles in the Progressed-mix PtG scenario and in the More-electric eDrives scenario. The fuel consumption in ships mainly comes from international navigation.

Figure 20 shows the final fuel consumption in transport by fuel in the four scenarios modelled in this study.

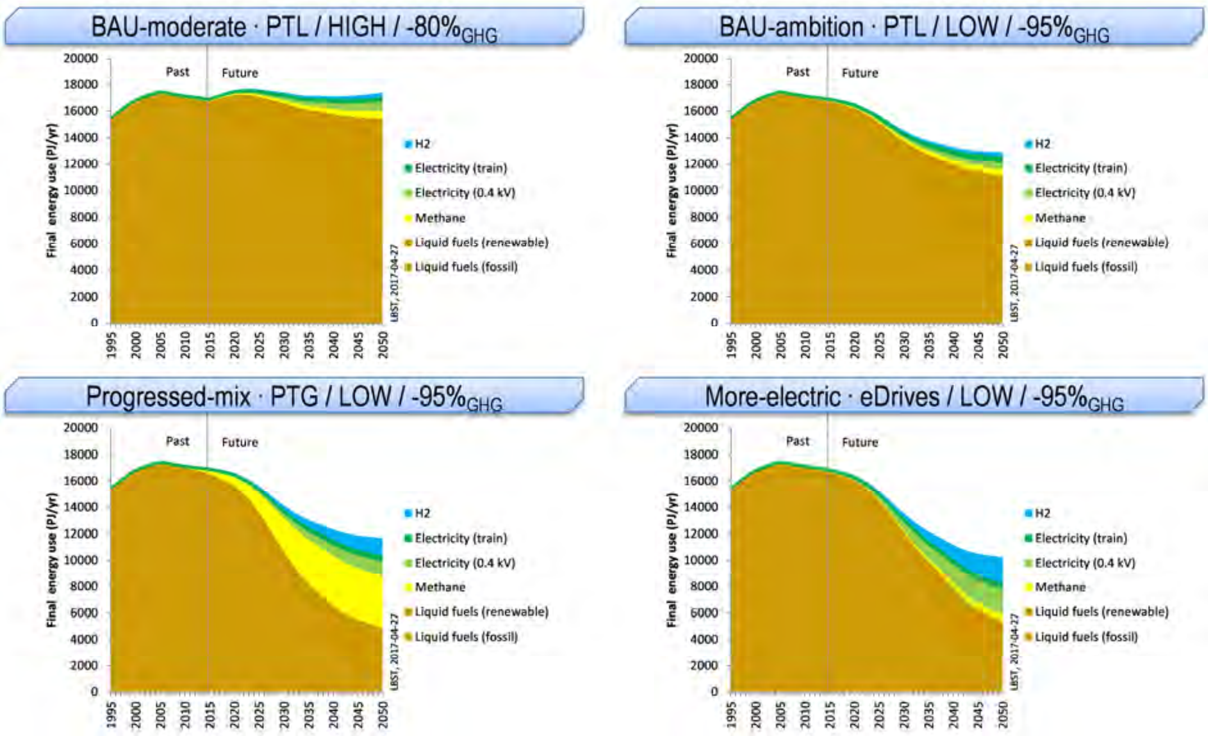


Figure 20: Final energy demand in EU transport from 1995 to 2050 by fuel

The final fuel consumption strongly depends on the transport demand. Although the energy efficiency of the ICE vehicles increases in both business-as-usual scenario due to internal combustion engines that are embedded in successively more electrified (hybrid) powertrains (by 2050 predominantly in range extender configurations), the overall final fuel demand remains approximately at today's level in the scenario BAU-moderate. In the BAU-moderate scenario route, the increasing transportation demand compensates the improvements in powertrain efficiencies. In contrast to that, the BAU-ambition scenario route leads to a decrease of final fuel demand despite the dominant use of vehicles using internal combustion engines (ICE) because of LOW growth in BAU-ambition versus HIGH growth in BAU-moderate.

The final energy demand for the direct use of electricity (e.g. for BEVs and range extender electric vehicles (REEVs) operated in the electricity mode) is low because the electric powertrain is so efficient. However, even in the eDrives scenario, the demand for liquid fuels is still high in 2050. The reason is the high fuel demand from international navigation (both in the high and low transport fuel demand case). Furthermore, even by 2050, a significant number of legacy ICE vehicles are still operating throughout all scenarios.

Whatever the energy demand from transport will be in future, the key to achieving an 80 to 95% reduction in GHG emissions is helping the primary energy base to transition to renewable sources. Based on the assumptions for biofuels and fossil fuel use in Section 4.5, the share of renewable energy in transport fuels develops as depicted in Figure 21.

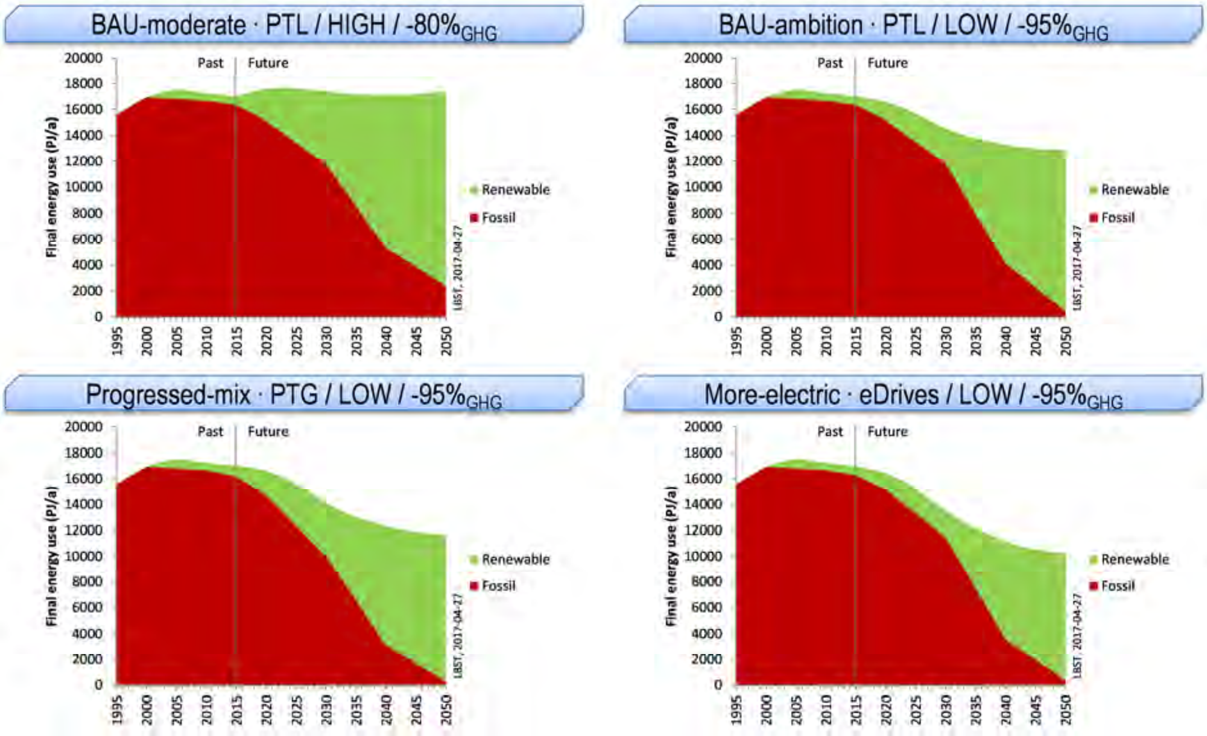


Figure 21: Renewable energy share in EU transport fuels from 1995 to 2050

4.6.2 Transport electricity demand (direct and for PtX fuel)

Figure 22 shows the renewable electricity required to generate liquid and gaseous fuels and to supply electricity for the direct consumption of electricity in transport. The information is divided by transport mode.

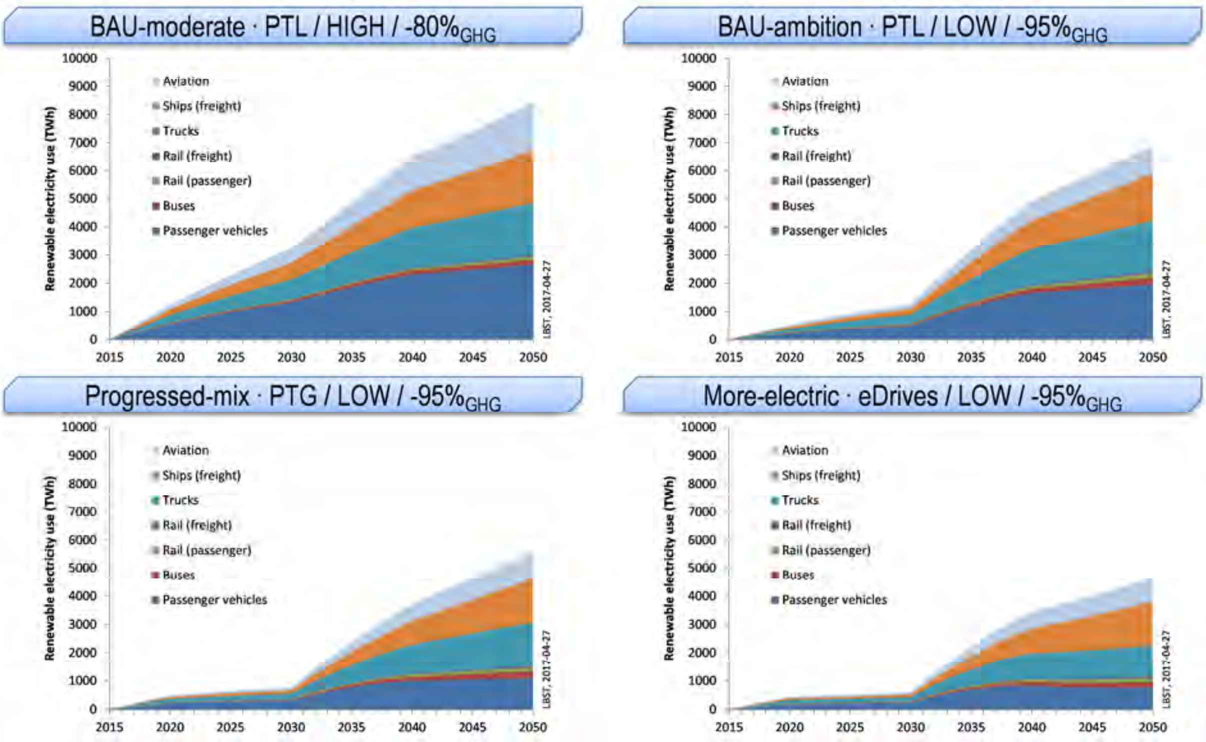


Figure 22: Renewable electricity required for PtX plants and for direct electricity use in transport by mode

Figure 23 shows the renewable electricity required to generate liquid and gaseous fuels and to supply electricity for direct electricity use. The information is divided according to the type of fuel used in transport.

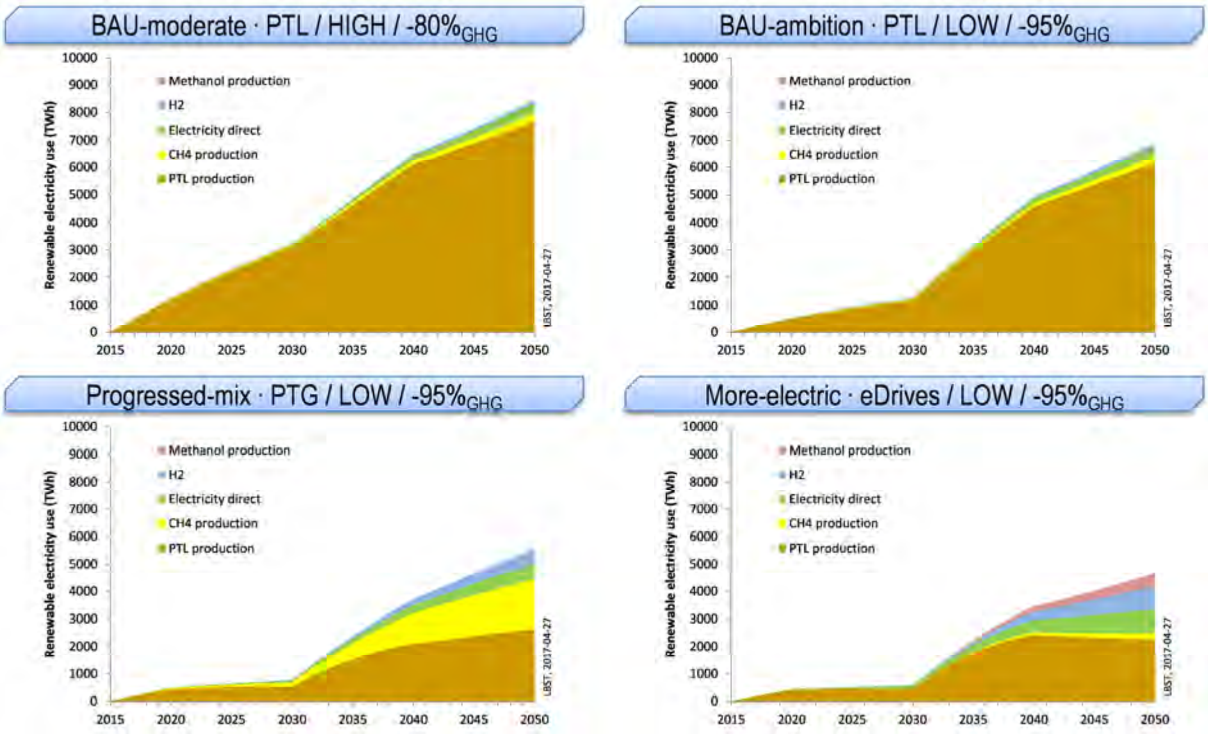


Figure 23: Renewable electricity required for PtX plants and for direct electricity use in transport by fuel

The renewable electricity needed for direct use (e.g. in BEVs and REEVs operated in electricity mode) is also relatively low in the eDrives scenario due to the high efficiency of electric powertrains and the electricity supply. The renewable electricity needed for hydrogen production is also relatively low, even in scenarios with a high penetration of FCEVs. This is due to the high efficiency of fuel cell powertrains.

4.6.3 Renewable electricity demand vs. production potentials

In 2015, the net electricity demand in the EU was 2,744 TWh (Figure 24).

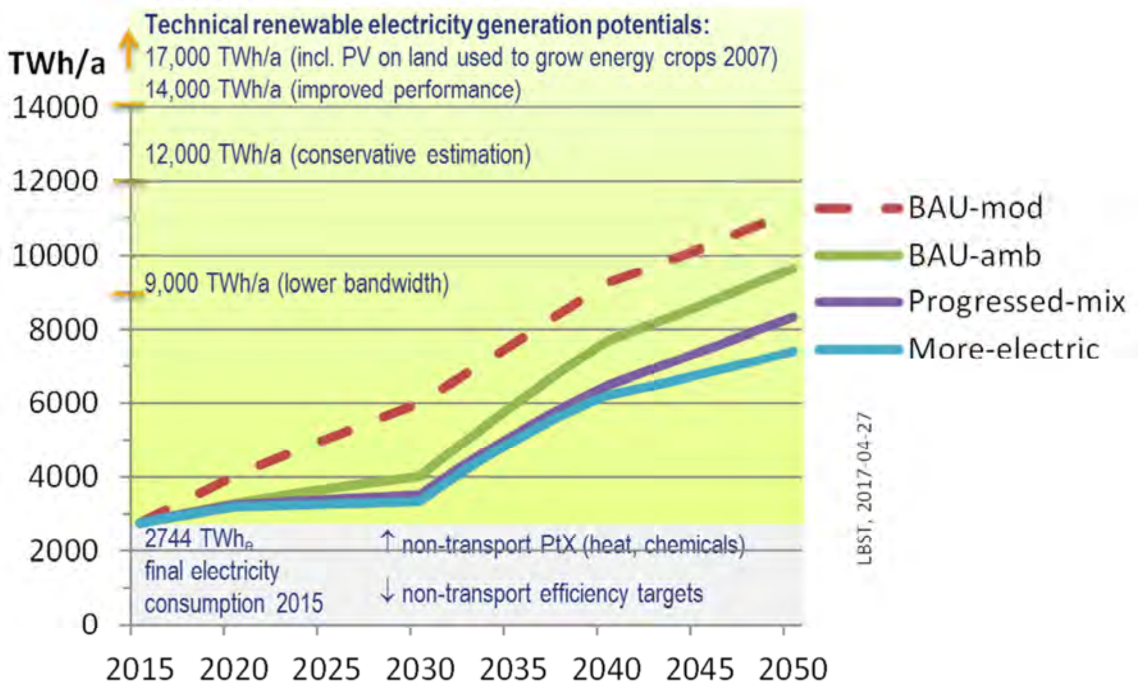


Figure 24: Electricity demand for transport in the different scenarios compared with the electricity demand in the EU in 2015 and the potentials for renewable electricity in the EU

Transportation demand is the key driver of energy use across all scenarios. In particular, truck freight, ship freight, and passenger aviation increase fuel demand. The total electricity demand from transport in 2050 increases by a factor of 1.7 to 3.0 of today's final electricity demand. All scenarios could be feasible with domestic renewable electricity production (see Section 5). However, PtL and $PtCH_4$ imports are likely because of existing infrastructure (export and import terminals for liqud hydrocarbons, ships, tanker trucks, liquid hydrocarbon product pipelines, natural gas pipelines) and costs.

Table 23 shows the final energy demand for transport including direct electricity use, total electricity demand for transport including electricity for PtX plants, and the share of BEVs in electricity demand.

	Final energy demand* (PJ/yr)	**Electricity demand** (TWh/yr)**	**Share of electricity demand for BEV, train**
BAU-moderate PtL/High/-80%$_{GHG1990}$	17,400 (4,830 TWh/yr)	8,460	4%
BAU-ambition PtL/Low/-95%$_{GHG1990}$	12,900 (3,580 TWh/yr)	6,900	5%
Progressed-mix PtG/Low/-95%$_{GHG1990}$	11,680 (3,250 TWh/yr)	5,580	10%
More-electric eDrives/Low/-95%$_{GHG1990}$	10,270 (2850 TWh/yr)	4,670	18%
For comparison: Transportation fuel demand in 2015	~17,000 (~4700 TWh/yr)	~20	100%

* Including direct use of electricity in transport
** All electricity used in transport, including electricity for PtX plants

Table 23: Energy consumption in transport in 2050

The BAU-moderate scenario leads to roughly the same final energy demand for transportation (including international navigation) in 2050 as in 2015. In 2015, electricity use in transport mainly consists of electricity for trains. Therefore, the share of direct electricity use in the overall electricity demand in transport was close to 100%.

In all scenarios, the share of electricity for BEVs and REEVs operated in electricity mode is relatively low. Even in the eDrives scenario, it will be just one fifth. This is because of the high efficiency of electric powertrains, the high efficiency of the electricity supply, and the high fuel demand for international navigation, aviation and road freight transport.

5 E-fuel supply scenarios

5.1 Technical renewable power generation potential in the EU28

To assess technical renewable electricity production potential in the EU28, the study authors updated a meta-study of the literature and added their own calculations where assumptions were lacking. The basic approach for assessing renewable power resources in the EU28 is described in MKS (2015) and LBST (2016). The following renewable electricity sources were assessed and are characterised in the subsections offshore wind, onshore wind, photovoltaics (PV), hydropower and geothermal power.

Wind power

By the end of 2016, the EU had 153.7 GW of installed wind energy capacity (141.7 GW in 2015). In an average wind year, this would produce some 300 TWh of electricity, or 10.4% of the EU's electricity consumption (WindEurope, 2017).

Offshore wind

Around 12.6 GW of offshore wind turbines are currently installed throughout Europe (11.03 GW in 2015). The average size of an offshore wind turbine installed in 2016 was 4.8 MW, compared to 4.2 MW in 2015. The average water depth of wind farms was 29 m (27.1 m in 2015) and the average distance to shore was 44 km (43.3 km in 2015) (WindEurope/Offshore, 2017). Like the size of installed turbines, the average water depths and distances to shore will increase over time because easily accessible areas with high production potentials are typically exploited first, and technology also progresses.

According to the European Wind Energy Association (WindEurope), up to 66 GW of offshore turbines might be installed in 2030 (EWEA, 2015). According to Matthies et al. (1995), the technical potential of offshore wind power in Europe is 3,028 TWh per year. A maximum water depth of 40 m and a maximum distance to shore of 30 km was assumed. Meanwhile, locations that are significantly further from the coast are considered as realistic for the installation of offshore wind farms, especially in the relatively shallow waters of the North Sea off the German coast. In fact, only a few of the approved offshore wind farms in Germany are closer than 12 nautical miles (22 km) to the coastline. Offshore wind farms in the UK are generally located closer to the coast than those in Germany.

IWES (2012) analysed the technical potential of offshore renewable energy resources in selected European countries. It concluded that some 70% of the offshore wind power potential (8,100 TWh/yr of 11,197 TWh/yr) can be found in water depths > 50 m, especially along west-facing Atlantic coastlines (i.e. those in the UK, Ireland, Spain and Portugal), as well as the northern parts of the North Sea (Norway, UK). However, for water depths of > 50 m, floating structures are required which are still in the early stages of development. This study uses a conservative estimate of the technical potential of offshore wind power production by only considering water depths ≤ 50 m.

For the lower limit, the study uses the values indicated by IWES (2012) for water depths ≤ 50 m (with the exception of Belgium, Germany and Greece). For Belgium and Greece it uses the value indicated in Matthies et al. (1995) and for Germany it uses the value indicated in Viertel et al. (2005). The upper values are derived from IWES (2012), except for Belgium, Denmark, France, Greece, Ireland, Portugal, Spain and the UK, for which the values indicated in Matthies et al. (1995) are used. In total, between 2,132 and 3,735 TWh of electricity per year might be available as technical offshore wind power potential in EU member states at water depths of up to 50 m. Technical offshore wind power potential in Europe alone thus exceeds current EU electricity demands.

Onshore wind

Around 141.1 GW of onshore wind turbines are currently installed throughout Europe (130.2 GW in 2015). The average size and type of wind turbines installed in 2016 varied between member states: They averaged less than 2 MW per turbine in the UK and Spain, and more than 3.1 MW per turbine in Sweden. Regional differences are due to limits on turbine height, the duration of projects, and different wind regimes (WindEurope, 2017).

Estimates for onshore wind power generation potential are based on the following assumptions:

- Installed nominal power of wind turbines for low wind speeds (inland): 4.2 MW; rotor diameter: 141 m
- Installed nominal power of wind turbines for medium wind speeds (coast): 4 MW; rotor diameter: 127 m
- Distance between wind turbines: 4 rotor diameters (BWE, 2013)
- Equivalent full-load period: 2,000 to 3,700 hours per year, depending on the EU member state.

The study also applies the following assumptions for onshore wind power in member states other than Germany:

- The upper boundary is similar to the actual wind turbine density in the German state of Schleswig-Holstein today, i.e. 2.5% of the area (including spacing of 4 rotor diameters between turbines). By the end of 2016, 6,449 MW of rated wind power capacity had been installed in Schleswig-Holstein. The surface area of Schleswig-Holstein is 15,731 km^2, which translates into an average of 0.41 MW per km^2.
- The lower boundary is similar to the actual wind turbine density in the German state of Saxony-Anhalt, i.e. 1.8% of the area (including spacing of 4 rotor diameters between the turbines). By the end of 2016, 4,914 MW of rated wind power capacity had been installed in Saxony-Anhalt. The surface area of Saxony-Anhalt is 20,446 km^2, which translates into an average of 0.24 MW per km^2.

In the case of Germany, the potential indicated by the German Wind Energy Association (BWE, 2013) has been used where wind turbines occupy 2% of the surface area excluding an outside protection perimeter of 1,000 m to, e.g. nearby buildings (including the protection perimeter would be equivalent to a land use density of some 4% of the land area). According to BWE (2013), about 198,000 MW could be installed in Germany. The surface area of Germany is 356,968 km^2, which equates to about 0.55 MW per km^2.

The assumptions described above lead to the technical potential for electricity from onshore wind power in the EU shown in Table 24.

Member state	**Rated capacity**		**Equivalent full-load period**	**Electricity generation potential**	
	Min. (MW)	**Max. (MW)**	**(h/yr)**	**Min. (TWh/yr)**	**Max. (TWh/yr)**
Austria	19,885	33,919	2,150	42.8	72.9
Belgium	7,265	12,393	2,309	16.8	28.6

Member state	Rated capacity		Equivalent full-load period	Electricity generation potential	
	Min. (MW)	Max. (MW)	(h/yr)	Min. (TWh/yr)	Max. (TWh/yr)
Bulgaria	26,656	45,468	3,077	82.0	139.9
Croatia	13,559	23,127	2,703	36.6	62.5
Cyprus	2,221	3,788	2,731	6.1	10.3
Czech Republic	18,573	31,680	2,022	37.5	64.0
Denmark	10,189	17,380	2,260	23.0	39.3
Estonia	10,385	17,715	1,977	20.5	35.0
Finland	73,417	125,229	3,696	271.3	462.8
France	131,137	223,684	2,435	319.3	544.6
Germany	101,321	194,458	2,038	206.5	394.3
Greece	31,437	53,622	1,957	61.5	104.9
Hungary	22,193	37,855	2,200	48.8	83.3
Ireland	16,557	28,242	2,667	44.2	75.3
Italy	70,665	120,535	2,172	153.5	261.8
Latvia	15,523	26,479	2,460	38.2	55.7
Lithuania	15,670	26,729	3,504	54.9	93.7
Luxemburg	622	1,060	1,991	1.2	2.1
Malta	76	130	2,533	0.2	0.3
Netherlands	8,145	13,893	3,100	25.2	48.3
Poland	73,175	124,817	1,978	144.7	449.3
Portugal	22,100	37,696	2,544	56.2	95.9
Romania	57.081	97,364	2,932	167.4	285.5
Slovakia	11,729	20,006	2,000	23.5	40.0
Slovenia	4,868	8,303	2,000	9.7	16.6
Spain	120,060	204,790	2,238	268.7	458.4
Sweden	98,764	168,464	2,826	279.1	476.1
UK	58,064	99,041	2,506	145.5	248.2
Total EU28	**1,041,335**	**1,797,864**	**-**	**2,585**	**4,650**

Table 24: Technical potential for electricity generation from onshore wind power in the EU28

Overall, the technical potential for onshore wind in Europe is between 2,585 and 4,650 TWh_e per year.

Solar power

Photovoltaics

For photovoltaics (PV), the potential depends heavily on a number of parameters.

The methodological approach described by Quaschning (2000) is used to calculate the technical PV production potentials in the EU.

The roof area of residential buildings has been derived from the dwelling area per capita. The dwelling area in Germany was derived from DESTATIS (2012). The average dwelling area in the other member states was estimated using an approach described in BIOCLIMECO (2002, p. 19). According to BIOCLIMECO (2002), there is a relationship between the dwelling area per capita and the gross domestic product (GDP) per capita. In the case of developed countries, the relationship is:

$$A = 0.981 \times x^{0.3581}$$

where

A = dwelling area per capita in [m²]

x = GDP per capita in [US$/cap] (purchasing power parity)

The dwelling area per capita is multiplied by the population in the different countries. For the conversion of the dwelling area to the roof area, a factor of 0.8 was used as indicated in Quaschning (2000), i.e. the roof area is 80% of the dwelling area.

The calculation for estimating the roof area of non-residential buildings is based on the specific roof area of non-residential buildings per capita in Germany as indicated in Quaschning (2000). It is assumed that the area of non-residential buildings is proportional to GDP (a higher GDP leads to more office and industrial buildings and thus to a larger roof area).

Because of shading and other constraints, it is assumed that 40% of the roof area is not suitable for PV systems. It is also assumed that the PV modules cover only 50% of the total area suitable for PV. As a consequence, the potential PV area amounts to about 30% of the total roof area. For the technical potential of renewable electricity production from PV, this study primarily considers rooftop PV. Two thirds of suitable rooftop areas are allocated for PV use; the remaining third is reserved for potential use by solar thermal installations.

To calculate the electricity potential, the irradiation values in the different countries are used. In addition, the deviation of the inclination from the optimum inclination is accounted for by applying factors as described in Quaschning (2000). An additional factor is applied to consider shading and fouling. Table 25 shows the reduction factors for calculating the potential for electricity from roof-mounted PV systems.

Class	Share	Azimuth angle	Inclination	Losses from		Total losses (average)
				Inclination (average)	Shading and fouling	
I	25% of sloped roof*	up to +/-45°	up to 60°	10%	5%	15%
	50% of flat roof*	0°	30°	0%	10%	10%
II	75% of sloped roof*	+/-90°	up to 60°	15%	5%	20%
	50% of flat roof*	0°	30°	0%	10%	10%
*adequate for solar energy (30% of total roof area)						

Table 25: Reduction factors for calculating PV energy potential

In the case of sloped roofs suitable for PV systems, 25% (7.5% of all sloped roofs) meet the requirements for Class I, while 75% (22.5% of all sloped roofs) meet the requirements for Class II.

Of the flat roofs suitable for PV systems, 50% (15% of all flat roofs) are Class I roofs and 50% (15% of all flat roofs) are Class II roofs. The study assumes that the share of sloped roofs is 69%, and that the share of flat roofs is 31%.

The efficiency of PV panels that use silicon cells ranges from 14 to 20%. In addition, losses from DC/AC converters and cables (balance of plant) must be taken into account. The figures here are assumed to be between 5 and 11%, which gives an efficiency of between 89 and 95%. Table 26 show the efficiency ranges of the PV systems assumed in this study.

Efficiency	Min.	Max.
PV panel	14%	20%
DC/AC converter, cables	89%	95%
Total	**12.5%**	**19%**

Table 26: PV system efficiencies

The assumptions described above lead to the technical potential for electricity from roof-mounted PV systems shown in Table 27.

Member state	Irradiation	Roof area*	PV potential	
	(kWh/(m²*yr))	(km²)	Min. (TWh/yr)	Max. (TWh/yr)
Austria	1,200	154	13	19
Belgium	1,000	189	13	20

Member state	Irradiation	Roof area*	PV potential	
	(kWh/(m²*yr))	(km²)	Min. (TWh/yr)	Max. (TWh/yr)
Bulgaria	1,400	70	7	10
Croatia	1,400	50	5	7
Cyprus	1,800	12	2	2
Czech Republic	1,000	145	10	15
Denmark	1,000	97	7	10
Estonia	1,000	16	1	2
Finland	900	90	6	9
France	1,300	1,069	96	146
Germany	1,200	1,422	118	180
Greece	1,500	169	18	27
Hungary	1,200	118	10	15
Ireland	1,000	81	6	9
Italy	1,400	924	89	136
Latvia	1,000	23	2	2
Lithuania	1,000	36	3	4
Luxemburg	1,000	15	1	2
Malta	1,800	6	1	1
Netherlands	1,000	312	22	33
Poland	1,200	450	37	57
Portugal	1,800	141	18	27
Romania	1,500	196	20	31
Slovakia	1,200	70	6	9
Slovenia	1,300	30	3	4
Spain	1,600	709	78	120
Sweden	1,000	167	12	18
UK	1,000	1,061	73	112
Total EU28	**-**	**7,823**	**673**	**1,026**
*Technical potential for electricity from roof-mounted PV systems				

Table 27: Technical potential for electricity from roof-mounted PV systems

Utility-scale PV is only considered to a small extent, which is in line with some regulatory frameworks, such as Germany's earlier Renewable Energy Sources Act (EEG). Here, PV systems on building facades and along motorways and railway tracks are included. The length of railway tracks and motorways was derived from Eurostat (2015), with the exception of the length of railway tracks in Austria, Denmark and the Netherlands, which were derived from Lexas (2015).

According to IWES PV (2012), 110 metres on both sides of railway tracks and motorways could theoretically be used for PV installations. Of that, 20% is technically useable, and it has been assumed that 33% of this 20% is occupied by PV systems. Table 28 shows the corresponding technical potential for utility-scale PV power generation.

Member state	**Railway**	**Motorway**	**PV panel area**	**PV potential**	
	(km)	**(km)**	**(km²)**	**Min. (TWh/yr)**	**Max. (TWh/yr)**
Austria	6,399	1,719	27	4	6
Belgium	6,436	1,763	10	1	2
Bulgaria	5,658	541	28	4	7
Croatia	4,090	1,295	12	2	3
Cyprus	0	257	0	0	0
Czech Republic	15,636	751	51	6	9
Denmark	2,667	1,128	7	1	1
Estonia	2,146	140	4	0	1
Finland	8,523	810	116	12	18
France	51,217	11,465	1,391	203	309
Germany	41,328	12,917	1,458*	196	299
Greece	3,062		16	3	4
Hungary	13,378	1,515.1	56	8	11
Ireland	2,421	897	9	1	2
Italy	24,277	6,726	371	58	89
Latvia	2,161		6	1	1
Lithuania	2,184	309	7	1	1
Luxemburg	275	152	0	0	0
Malta	0		0	0	0
Netherlands	2,896	2,631	8	1	1

Member state	Railway	Motorway	PV panel area	PV potential	
	(km)	(km)	(km²)	Min. (TWh/yr)	Max. (TWh/yr)
Poland	36,939	1,482	476	64	98
Portugal	2,541	2,988	21	4	6
Romania	20,284	644	202	34	52
Slovakia	3,631	419.2	8	1	2
Slovenia	2,178	770	2	0	1
Spain	19,285	14,701	690	124	189
Sweden	15,601	1,891	292	33	50
UK	31,324	3,685.7	344	39	59
Total EU28	**326,538**	**71,597**	**5,611**	**799**	**1,219**
* Includes 670 km² of PV panel area on impervious surface areas (IWES PV, 2012)					

Table 28: Area data for calculating technical potential for electricity from PV systems alongside railway tracks and motorways

Following this, the technical PV potential in the EU28 is between 1,472 and 2,245 TWh_e per year if only PV systems on rooftops, building facades, and along railway tracks and motorways are taken into account.

Including the technical production potential of PV systems on rooftops and building facades, and along railway tracks and motorways results in a technical PV electricity production potential of 5,230 TWh_e/yr in the EU. This potential is about twice the current net electricity consumption in the EU28.

By 2015, cumulative solar PV installations had reached some 97.1 GW in the EU28, and were generating about 102 TWh_e per year (Statista, 2017; Eurostat, 2017b). The vast potential of PV is thus still available for exploitation.

Sensitivity analysis: PV generation potential from EU energy crop land

The most recent developments in regulatory frameworks, such as in Germany's Renewable Energy Sources Act (EEG), successively allow for utility-scale PV on certain types of land (GVBL, 2017; UMBWL, 2017).

If land areas currently used for growing energy crops – i.e. some 4.6 million hectares in 2007, or 2.5% of agricultural land in use in the EU (Eurostat, 2013, planned update: 12/2018) for, e.g. biofuels – were equipped with PV modules covering the equivalent of one third of the total area, this would create some 2,985 TWh_e/yr of solar power production potential. This is roughly equivalent to the current electricity consumption in the EU28. If the 4.6 million hectares were planted with energy crops for biogas generation and downstream electricity generation, about 70 TWh of electricity would be generated on the same area per year*. If upgraded bio-methane were generated instead of electricity, about 190 TWh of pure methane could be generated per year**, e.g. for CNG vehicles. There is a factor of 42 (2985/70) between the annual energy yields, which shows the significantly higher solar conversion efficiency of photovoltaics compared to solar-to-biomass-to-X.

Solar panels in utility-scale PV installations are always mounted on elevated supporting frameworks. This could allow for a range of additional land uses, such as ecosystem services from wild grass, grass for cattle or biogas feed, or grazing sheep and goats underneath and between the panels. Newer research and demonstration projects explore the practicability of combining utility-scale PV with greenhouses (Schettler-Gruppe, 2017) and cultivating vegetables underneath higher utility-scale PV systems (ISE, 2013; ISE, 2015a). In semi-arid and arid regions, partial shading from utility-scale solar can improve agriculture (Uni Hohenheim, 2016). The panels reduce solar radiation pressure on the land, thus minimizing evaporation pressure and facilitating plant cultivation and livestock breeding. Nevertheless practical implementation could be challenging because of typical utilization rates of at least 20 years for PV systems.

*Assumptions: yield 17.5 t of dry substance per ha and year; silage losses 12%; biogas yield 300 Nm^3/t of dry substance; net electricity generation efficiency 32%
**Assumption: energy requirement for biogas and upgrading plant is 10% of the gross biogas yield

Solar thermal power

Klaiß et al. (1992) and Trieb et al. (2005) assessed the technical potential for solar thermal power generation in the Mediterranean and the Middle East. The calculations are still robust, as there have been no fundamental changes in technical performance figures for solar thermal power since their work. According to the studies, the technical potential for solar thermal power is between 1,404 and 2,239 TWh_e per year.

Solar thermal power requires high levels of direct solar irradiation. The potential can also be increased with PV technology (but not necessarily vice versa).

Hydropower

Rivers (runoff)

Assumptions for the overall technical potential of inland hydropower vary largely between the different potential studies analysed. In EU member states that already have significant hydropower installations, such as Switzerland and Norway, new hydropower plants typically fail to receive the required public acceptance for ecological and social reasons. The technical potential for renewable electricity from hydropower in the EU28 is assumed to be between 576 and 631 TWh_e per year.

With some 360 TWh_e, inland hydropower plants provided by far the largest share of electricity from all renewable electricity sources in the EU28 in 2015 (Eurostat, 2017b).

Tidal, wave and ocean energy

Besides established hydropower generation from rivers (runoff), development and demonstration efforts for tidal and wave energy are underway in France and the UK (Eurostat, 2017b). Ocean energy supplied some 0.05% of all electricity generated from renewable sources in the EU28 in 2015. Figures from SI OCEAN (2014) show that Europe could have up to 100 GW of wave and tidal energy capacity installed by 2050 (260 TWh per year). According to Salter (2000), the technical electricity generation potential from wave energy in Europe is 600 TWh_e per year. IWES (2012) says that the potential of ocean energy in certain European countries is 900 TWh per year. A range of 600 to 900 TWh_e per year is thus assumed as the technical potential from tidal and wave energy in the EU.

Geothermal power

According to Kaltschmitt et al. (1997), TAB (2003), Stefansson (2005) and MNH (2005), the technical potential for geothermal power (excluding fracking) is between 44 and 83 TWh_e per year in the EU28.

The capacity of the 51 geothermal power plants currently in operation is about 0.95 GW_e. Sweden, Germany and Italy are the countries with most installed geothermal capacity in the EU28. Geothermal energy provided about 0.2% of the total final electricity demand in the EU in 2015 (Eurostat, 2017b).

Results

Figure 25 shows the technical production potential from renewable electricity sources in Europe by energy source.

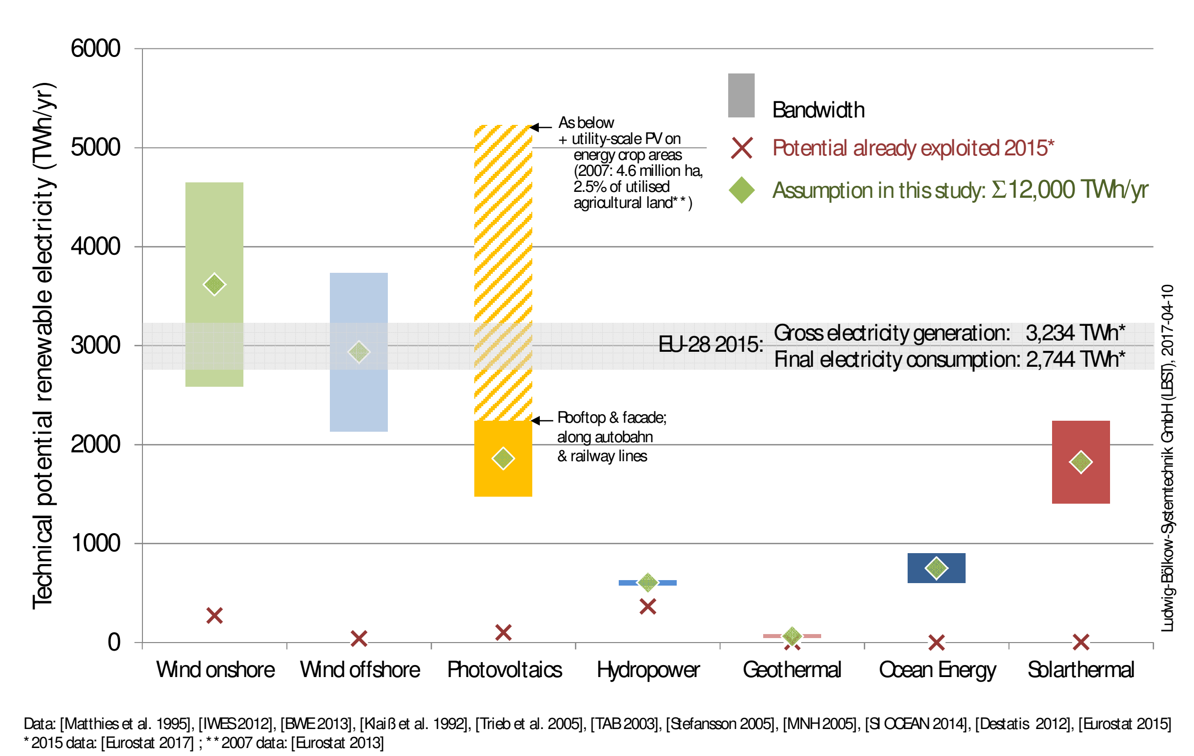


Figure 25: Renewable electricity potential in the EU28 by source

Technology	Renewable electricity potential in the EU28 [TWh/yr]			Potential already exploited (2015) [TWh/yr]
	Lower level	Upper level	This study	
Onshore wind	2,585	4,650	3,617	274
Offshore wind	2,132	3,735	2,934	40
PV*	1,472	5,230*	1,858	102
Solar thermal	1,404	2,240	1,822	6
Geothermal	44	83	63	6
Hydropower	576	631	604	364
Ocean energy	600	900	750	0.5
Total EU (rounded)	9,000	14,000	12,000	792

* excludes PV generation on land currently used for the production of energy crops

Table 29: Renewable electricity potential in the EU28

The EU has significant technical renewable electricity supply potential, mainly from onshore wind, offshore wind and PV. Conservative assumptions (lower level) result in an overall renewable electricity potential of 9,000 TWh_e per year. An assumption of more progressive installation density and yield parameters results in renewable electricity supply potentials of 14,000 TWh_e per year. Furthermore, including PV generation on land currently used for producing energy crops results in an upper level of 17,000 TWh_e per year. For comparison, in 2015 the final electricity consumption in the EU28 was 2,744 TWh_e and gross electricity generation[8] was 3,234 TWh_e (Eurostat, 2017b). The renewable electricity potential thus exceeds today's electricity consumption by a factor of 3 to 6.

This study assumes a conservative technical renewable electricity potential of 12,000 TWh_e per year for the EU28. The EU28 has so far only exploited some 6% of this potential.

[8] The electricity measured at the outlet of the main transformers, i.e. incl. the amount of electricity used in the plant auxiliaries and in the transformers.

Technical renewable power generation potential in Germany

In the bandwidth of technical renewable electricity generation potentials are depicted. The bandwidth have been taken from literature, including own calculations as detailed in (LBST, 2016). In an exploratory case the PV power generation potentials are included here if today's energy crop areas (i.e. 14% of utilised agricultural land in 2016) were also used for utility-scale solar power production. This PV potential alone would be the equivalent of about 1,500 TWh/yr, or roughly three times the German electricity demand today.

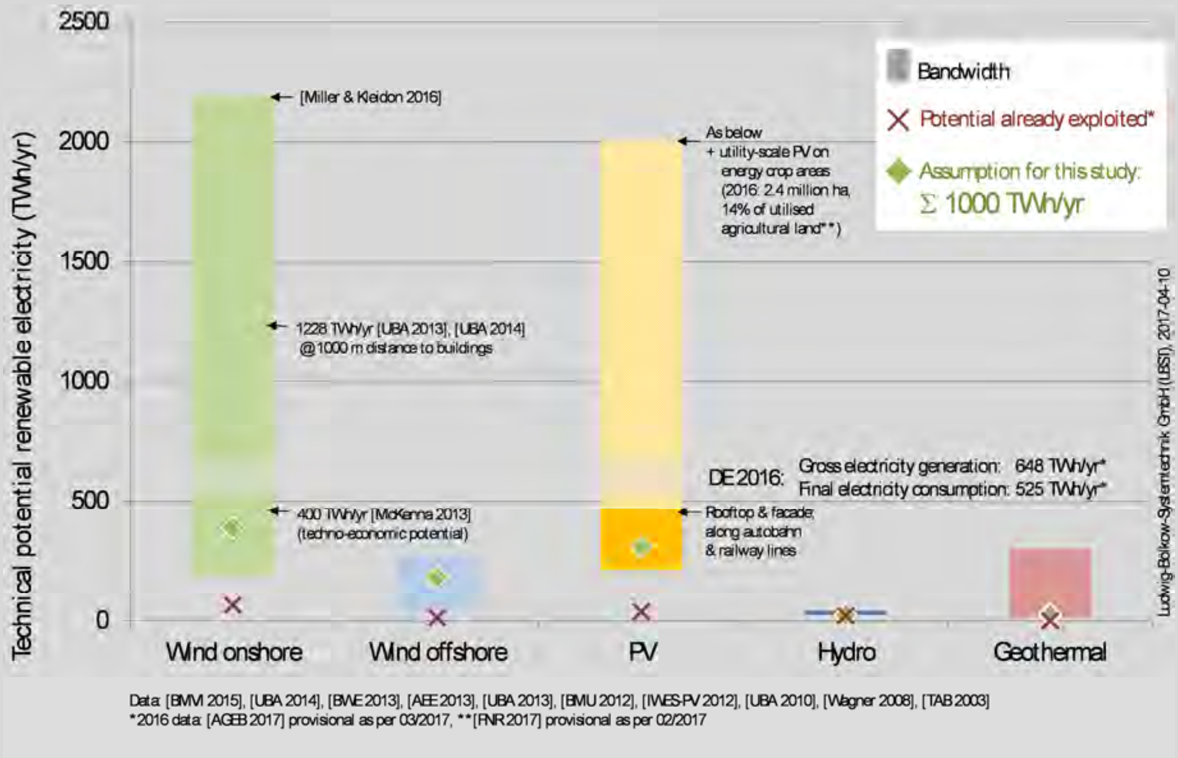


Figure 26: Renewable electricity generation potential for Germany, depicted by source

Takeaway: Germany has significant technical renewable power production potential, which is conservatively estimated at approximately 1000 TWh/yr. This is more than 1.6 times the current electricity demand of some 595 TWh/yr.

5.2 CO_2 feedstocks for PtX

Carbon dioxide is need for the methanation and synthesis of liquid hydrocarbons. It can either be sourced from concentrated sources or extracted from the air.

5.2.1 CO_2 from the air

Various technologies for extracting CO_2 from the air exist.

One option involves using a scrubbing agent such as sodium hydroxide (NaOH) or potassium hydroxide (KOH), which is converted to sodium carbonate (Na_2CO_3) or potassium carbonate (K_2CO_3). The decomposition is done via electrodialysis.

The ZSW process described in Specht et al. (1996) is based on absorption with sodium hydroxide (NaOH), stripping the CO_2 with sulphuric acid (H_2SO_4), and regenerating the Na_2SO_4 via electrodialysis. The following reactions occur:

CO_2 absorption:	$CO_2 + 2\ NaOH$	$\rightarrow Na_2CO_3 + H_2O$
Stripping:	$Na_2CO_3 + H_2SO_4 \rightarrow Na_2SO_4 + CO_2 + H_2O$	
Electrodialysis:	$Na_2SO_4 + H_2O$	$\rightarrow 2\ NaOH + H_2SO_4$

The specific electricity consumption depends on the current density of the elecrodialysis system. The higher the current density, the higher the specific electricity consumption. At a current density of 100 mA per cm^2 of electrodialysis cell area, the electricity consumption for the whole process, including fan blower, amounts to 430 kJ per mole of CO_2, or about 9.8 MJ per kg of CO_2 (Specht et al., 1998). Specht (1999) indicates an electricity consumption of about 12.3 MJ per kg of CO_2 due to a higher current density. Sterner (2009) indicates an energy consumption of about 8.2 MJ per kg of CO_2 for extracting CO_2 from air via the ZSW process (of that, 6.4 MJ/kg is for the electrodialysis needed to regenerate the scrubbing agent).

A process developed by the Palo Alto Research Center (PARC) uses KOH as a scrubbing agent. Eisaman et al. (2010) describe a process where KOH is used as the scrubbing agent. The following reactions occur:

CO_2 absorption:	$2\ KOH + CO_2$	$\rightarrow K_2CO_3 + H_2O$
	$CO_2 + KOH$	$\rightarrow KHCO_3$
Electrodialysis:	$K_2CO_3 + H_2O$	$\rightarrow CO_2 + 2\ KOH$
	$KHCO_3$	$\rightarrow CO_2 + KOH$

The electricity consumption is indicated with 300 kJ per mole of CO_2 (of that, 100 kJ is for the electrodialysis of the $KHCO_3$ solution from CO_2 absorption with KOH), which results in about 6.8 MJ per kg of CO_2.

The process developed by the Canadian company Carbon Engineering (CE) consists of CO_2 absorption with KOH, formation of $CaCO_3$ from K2CO$_3$ and regeneration of the $CaCO_3$ via calcination and subsequent conversion to $Ca(OH)_2$. The following reactions occur:

CO_2 absorption:	$2\ KOH + CO_2$	$\rightarrow K_2CO_3 + H_2O$
Regeneration of KOH:	$K_2CO_3 + Ca(OH)_2$	$\rightarrow 2\ KOH + CaCO_3$

Calcination: $CaCO_3 \rightarrow CaO + CO_2$

Regeneration of $Ca(OH)_2$: $CaO + H_2O \rightarrow Ca(OH)_2$

The calcination process requires very high temperatures of more than 800°C to convert the $CaCO_3$ back to CaO to recover the CO_2. Carbon Engineering assumes that natural gas is used as fuel for the calcination process and for the supply of electricity for the whole process. It indicates a natural gas consumption of about 10 MJ per kg of CO_2 (CE, 2015). The theoretical minimum heat requirement for the calcination reaction is about 4.1 MJ per kg of CO_2.

Another option is the technology developed by the Swiss company Climeworks. Climeworks (an ETH Zurich spinoff) uses an adsorption/desorption cycle to extract CO_2 from the air. The CO_2 is chemically bound on a sorbent (in contrast to most adsorption processes, this uses chemisorption instead of physisorption). The regeneration of the sorbent is carried out at low temperatures (95°C) (Climeworks, 2015a). The process can also be referred to as a temperature swing adsorption (TSA) process (Climeworks, 2015b). TSA has been applied at Sunfire's power-to-liquid plant in Dresden, which uses high-temperature electrolysis with downstream Fischer-Tropsch synthesis.

Table 30 shows the various technologies for extracting CO_2 from air.

	Unit	ZSW	PARC	CE	Climeworks	This study
Technology	-	Absorption/ electrodialysis	Absorption/ electrodialysis	Absorption/ calcination	Adsorption/ desorption	Absorption/ desorption
Natural gas*	MJ/kg_{CO2}	-	-	10*	-	-
Heat	MJ/kg_{CO2}	-	-	-	5.4-7.2	5.4-7.2
Electricity	MJ/kg_{CO2}	8.2-12.3	6.8	-	0.72-1.08	0.72-1.08
T (heat)	°C	n.d.a.	n.d.a.	>850°C	95%	95%
CO_2 purity	-	>99%	>99%	-	>99.5%	>99.5%

*Natural gas is used for heat and electricity; n.d.a. = no data available

Table 30: Technologies for extracting CO_2 from air

For the scenarios, this study assumes CO_2 from air, and uses the extraction technology from Climeworks. Table 31 shows the economic data for extracting CO_2 from air via TSA for different plant capacities. The economic data supplied by Climeworks for 2015 were in Swiss francs (CHF), which have been converted to € using an exchange rate of 0.95€/CHF.

Unit	0.125 t CO_2/h	2 t CO_2/h	20 t CO_2/h
€	1,662,500	15,200,000	91,200,000
€/(kg/h)	13,300	7,600	4,560

Table 31: Costs of extracting CO_2 from the air using TSA

The data in Table 31 can be used to produce a curve for the specific investment depending on the capacity of the plant (Figure 27).

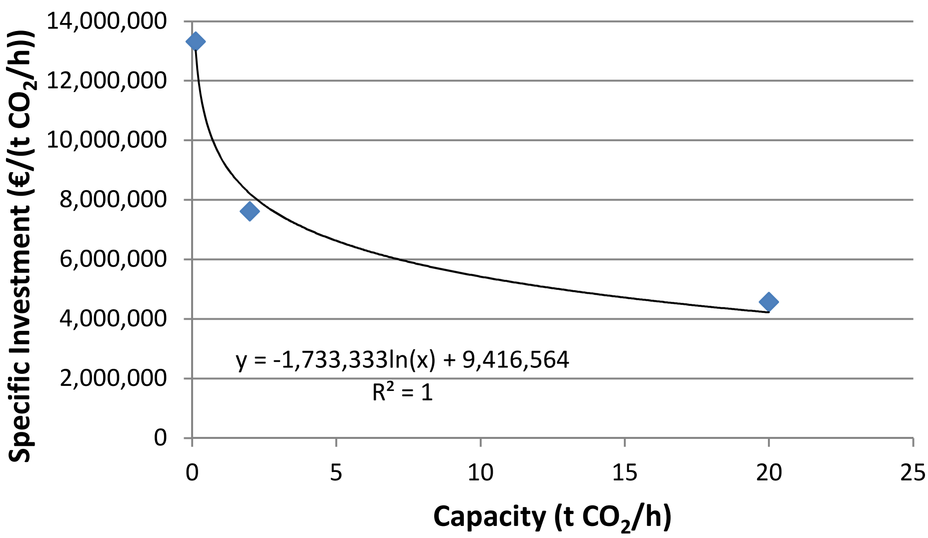


Figure 27: Specific investment for extracting CO_2 from air via TSA

From this curve, the investment for extracting CO_2 from air via TSA has been calculated. The maintenance costs are assumed to be 2% of the investment per year.

5.2.2 CO_2 from concentrated sources, and extraction processes for CO_2 supply

Biogenic CO_2 sources are biogas-upgrading plants, CO_2 from ethanol plants, and CO_2 from the combustion of biogas and solid biomass.

The CO_2 content of biogas ranges from 25 to 55% (Eder & Schulz, 2006). The CO_2 can be separated from the biogas stream via scrubbing with amines or via pressure swing adsorption (PSA). Both technologies provide sufficient CO_2 purity (99%). Alternatively, if methane is the desired product, the biogas stream including the CO_2 is fed directly into a methanation reactor (direct methanation) (Rieke, 2013). The CO_2 fraction is converted to methane. The methane gas is swept through the methanation reactor like an inert gas. In this case, no CO_2-separation step is required.

The CO_2 content of other concentrated sources such as flue gas, blast furnace gas and coke-oven gas ranges from 2 to 18% (Table 32).

	Flue gas from solid biomass ST	Blast furnace gas	Coke-oven gas	Crude biogas
CO_2 content (vol.)	12.5%	18.0%	2.0%	25-55%
Reference	(GEMIS, 2016)	(GEMIS, 2016)	(GEMIS, 2016)	(Eder & Schulz, 2006)

Table 32: CO_2 content of various concentrated sources

The state-of-the-art approach is to extract CO_2 from flue gas via scrubbing with amines such as monoethanolamine (MEA). The scrubbing agent washes the CO_2 from the gas stream, and is regenerated through heating.

Another process is described in Taniguchi et al. (2014). At first, the CO_2 is washed out from the gas stream via scrubbing with K_2CO_3 solution. The CO_2 concentration in the scrubbing agent is then elevated via electrodialysis and stripped out by a vacuum pump.

A process described in Allam et al. (2006) uses a combination of PSA and TSA.

Table 33 shows the energy demand for various methods of extracting CO_2 from flue gases. The CO_2 concentration of the flue gas ranges from 10 to 13%.

	Unit	MEA	Next-generation solvent	Absorption/ electrodialysis	PSA/TSA
CO_2 content	-	12.8%	11%	10%	10-13%
Heat	MJ/kg_{CO2}	3.84-4.30	n.d.a.	-	n.d.a.
Electricity	MJ/kg_{CO2}	0.033	n.d.a.	0.756	n.d.a.
Total	MJ/kg_{CO2}	3.873-4.333	2.5	0.756	2.016
T (heat)	°C	97	120	-	n.d.a.
Reference	-	(APS, 2011), (ZSW, 1995)	(Bergins et al., 2010)	(Taniguchi et al., 2014)	(Allam et al., 2006)

n.d.a. = no data available

Table 33: Processes for extracting CO_2 from flue gases from, e.g. biomass combustion or industrial processes

5.2.3 CO_2 purification and storage

Pure CO_2 with a very low oxygen content is needed to avoid damaging the catalysts used for methanation and synthesis. The CO_2 is purified via liquefaction.

The calculation is based on an existing CO_2 liquefaction plant with onsite carbon storage at an ethanol plant in Lüdinghausen in North Rhine-Westphalia in Germany, which has been in operation since 2013. The temperature of liquefied CO_2 is about -25°C at an elevated pressure, and the purity amounts to 99.999% (vol.) (WIR, 2014). The oxygen content after liquefaction is less than 5 ppm (Buchhauser et al., 2005), which is sufficient for the catalysts used in methanation and synthesis. Table 34 shows the technical and economic data for the CO_2 liquefaction plant in Lüdinghausen.

Parameter	Value
Capacity	2,300 kg CO_2/h
Production	17,000 t CO_2/yr
Electricity consumption	3.5 GWh/yr
Storage capacity	300 t (3 tanks, each 100 t)
Investment	€3.5 million

Table 34: CO_2 liquefaction plant, including storage, in Lüdinghausen, Germany

The investment required for a CO_2 liquefaction plant for the $PtCH_4$ and PtL plants is derived from the data in Table 34 by scaling to the required capacity using a scaling exponent of 0.7.

5.2.4 Sustainability of concentrated CO_2 sources

Carbon dioxide from concentrated sources is in principle an attractive feedstock for the synthesis of e-fuels, especially in the early phase of e-fuel deployment. This is because the energy needed for fuel production is lower and investments in CO_2 extraction from the air can be avoided. However, CO_2 from concentrated sources is limited if environmental/sustainability aspects for the various sources are taken into account:

- Fossil fuel phase-out because of the Paris Climate Agreement
- Renewable CO_2 from biomass because of limited biomass potential regarding energy consumption
- Industrial CO_2 phase-out, e.g. because of direct reduction with renewable PtH_2 in steel works

Not all CO_2 sources can be considered equally sustainable. Table 35 gives an overview of the sustainability of various concentrated sources. The different "shades of greenness" are depicted in traffic light colours.

CO_2 sources	Environmental sustainability	Alternative CO_2 uses	Towards carbon-neutrality
Extraction from air	Subject to electricity source		
Biogas upgrading	Subject to feedstock & process	Synthesis with PtH_2	Other biomass uses
Solid biomass fired heat (and power) plants	Subject to feedstock & process	Bio-CCS	Other biomass uses
Fermentation to alcohols	Subject to feedstock & process	Mineral water, tap beverages	Other biomass uses
Geothermal sources	Subject to geophys. CO_2 cycle	CO_2 re-injection (closed-loop)	Hot dry rock a potential no-go
Cement production	What level is "unavoidable'"?	Power-to-chemicals	Shift to alternative materials
Steel production	Short-term exemptions?	Top-gas for heating & reduction	Shift to direct reduction with hydrogen
Fossil fuel firing	Short-term exemptions?	Carbon capture & storage (CCS)	Phase-out, technology lock-in

Table 35: Sustainability, competing uses and long-term strategic aspects of different concentrated CO_2 sources

Sustainability safeguards are necessary to avoid unintended collateral damage, such as the lock-in of fossil technologies. "Technology lock-in" means that infrastructures due to be phased out for, e.g. environmental reasons remain in operation because of improved economics and a (perceived) lack of alternatives.

A robust sustainability framework is also important to give stakeholders the confidence to build value chains, e.g. regarding CO_2 burden sharing (no leakage into unregulated sectors).

Excursus: On the carbon-neutrality of CO_2 from geothermal sources

Carbon dioxide from geothermal sources can be carbon-neutral, but not necessarily. The applicable sustainability criteria is whether the CO_2 dissolved in geothermal water is part of an ongoing geophysical CO_2 cycle or mobilised from a carbon sink where the CO_2 was trapped a long time ago. In the first case, the CO_2 would be released into the atmosphere anyway (and bound again within a reasonable timeframe). In the latter, the CO_2 is considered “fossil”.

In Germany, geothermal water for power production is typically used in closed loops, i.e. the heat from the geothermal freshwater is extracted via a heat exchanger and then re-injected underground a few miles away from the extraction site. In other parts of the world, geothermal water is regularly used in open systems to save on the additional equipment and investments needed for closing the loop.

If hydraulic fracturing (fracking) is used for activating geothermal reservoirs, this is a strong indication that fossil CO_2 is being mobilised. In a closed water system, geothermal energy may still be considered carbon-neutral*. In an open system or upon extraction of the CO_2 and eventual emission into the atmosphere, the CO_2 emissions would have to be considered fossil.

The following list of GHG emissions indicates the CO_2 content of geothermal sources using Iceland as an example [ESMAP, 2016]:

- Reykjanes: ~30-40 g_{CO2}/kWh
- Svartsengi: ~90-460 g_{CO2}/kWh
- Hellisheidi: ~30-60 g_{CO2}/kWh
- Nesjavellir: ~20-40 g_{CO2}/kWh
- Bjarnarflag: ~50-560 g_{CO2}/kWh
- Krafla: ~70-300 g_{CO2}/kWh
- TOTAL: ~60-370 g_{CO2}/kWh

The CO_2 from the Svartsengi geothermal plant is used in applications such as power-to-methanol synthesis.

* but not necessarily “sustainable” because it may also mobilise naturally occuring radioactive materials and heavy metals, for instance (PIRSA, 2009)

5.2.5 Potential future availability of concentrated CO_2 sources

This section provides a ballpark estimate of the availability of concentrated CO_2 from biogenic and industrial sources in the EU28. It also provides a more in-depth analysis comprising strategic implications from GHG reduction targets in Germany.

Biogenic CO_2 sources for use in e-fuel production need to be stationary and of reasonable size to minimise the aggregation efforts from various small sources. Thus, only larger plants can be considered as relevant sources of CO_2 for e-fuel production. Data on relevant CO_2 sources in Europe is very limited. Eurostat (2016) publishes the annual gross inland consumption of solid biofuels, biogas and municipal waste for the EU28. Using this dataset, the total stationary biogenic CO_2 emissions can be estimated for each country. Figure 28 clearly shows that Germany currently has the highest biogenic CO_2 emissions. For all EU28 countries, the total amounts to almost 500 million tonnes per year.

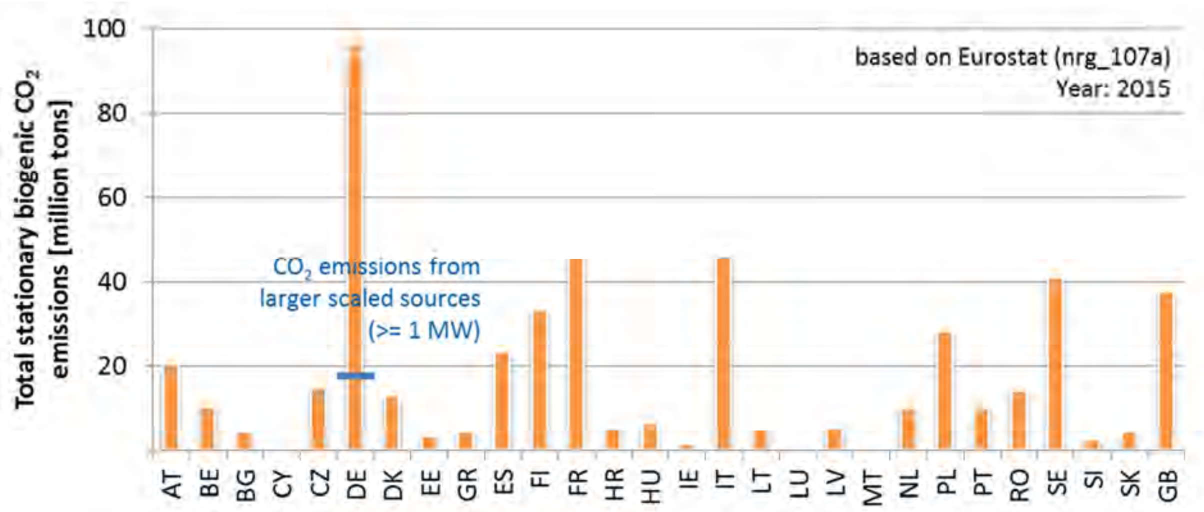


Figure 28: Total stationary biogenic CO_2 emissions per country in 2015, based on Eurostat (2016)

The figure above includes biogenic CO_2 emissions from all types and sizes of plants: Central and distributed, heating, CHP, and power plants. In Germany, the biogenic CO_2 potential from biogas-upgrading and solid biomass CHP plants larger than 1 MW_e is about 17 million tonnes (Table 36). This is about 18% of the total biogenic CO_2 emissions estimated from Eurostat data. Applying this percentage to the EU28 total results in an annual useable CO_2 potential of about 85 million tonnes in Europe. This CO_2 potential would be enough to produce about 1,600 PJ of methane or 1,100 PJ of liquid transportation fuels, and thus for meeting about 8 to 11% of today's transportation fuel demand (including international aviation, excluding international navigation).

CO_2 from industrial sources includes cement production, lime kilns, iron and steel production using blast furnaces, and the oxidation of carbon anodes used in primary aluminium production. In the long term, industrial CO_2 emissions can be reduced to zero by using renewable energy and/or new production processes.

Process heat can be generated by renewable sources to avoid CO_2 emissions. If the blast furnace process is replaced by the direct reduced iron (DRI) process and the required hydrogen for DRI is derived from renewable energy sources, no CO_2 emissions from iron and steel production will occur. If carbon anodes are replaced by metal anodes, no process-related CO_2 emissions will occur in aluminium production.

However, CO_2 emissions from certain chemical reactions cannot be avoided. Cement production is the most relevant example. Industrial CO_2 emissions would only result from cement production and the production of lime in kilns via the reaction:

$$CaCO_3 \rightarrow CaO + CO_2$$

The total unavoidable CO_2 emissions from cement production can be roughly estimated using the emissions presented in Table 36 and annual cement production rates in European countries. The annual unavoidable CO_2 emissions from this source amount to just below 80 million tonnes (based on 2012 cement production rates). Germany and Italy each account for almost 20% of the emissions, while France and Poland each account for about 10%.

Germany [million t/yr]	**As of 2008: Industrial processes**	**Step 1: … of which from chemical reactions**	**Step 2: Top gas recycling blast furnace**	**Step 3: Optimisation of iron, steel and aluminium***	**References**
Industrial processes	**81.6**	**72.8**	**54.4**	**19.7**	(Herrman et al., 2012)
Cement	21	13.7	13.7	13.7	
Lime (CaO)	7.5	6	6	6.0	
Iron and steel	52.3	52.3	34.0	0.0	
Aluminium	0.8	0.8	0.8	0.0	
Biogenic sources	**17**	**17**	**17**	**17**	(MKS, 2014)
Biogas	1.9	1.9	1.9	1.9	
Biomass CHP	15.1	15.1	15.1	15.1	
TOTAL	**98.6**	**89.8**	**71.4**	**36.7**	

Towards an increasingly sustainable world

* Direct reduction of iron and steel with hydrogen; inert anodes for primary aluminium production

Table 36: Availability of concentrated CO_2 sources in Germany for a carbon-neutral future

Table 37 shows the availability of CO_2 and the associated potential for the production of transportation fuel in the EU28.

EU28		Biogenic sources	Industrial processes	TOTAL
CO_2 potential	million t/yr	85.9	78.9	**164.8**
	billion Nm^3/yr	43.7	40.2	**83.9**
PtL potential	TWh/yr	311	286	597
	PJ/yr	1,121	1,029	2,150
$PtCH_4$ potential	TWh/yr	434	399	832
	PJ/yr	1,562	1,435	2,997

Table 37: Concentrated CO_2 potential from biogenic and industrial sources in the EU28, and resulting PtL/$PtCH_4$ production potentials

About 3,000 PJ of methane could be produced each year using CO_2 from concentrated sources. According to Eurostat (2017c), the consumption of transportation fuel in the EU in 2015 amounted to about 15,000 PJ (including international aviation, excluding international navigation). As a result, about 20% of today's transportation fuel demand in the EU could be met by methane from concentrated CO_2 sources. Alternatively, about 2,150 PJ of liquid hydrocarbons (gasoline, jet fuel, diesel fuel) could be produced from CO_2 from concentrated sources – which is about 14% of today's transportation fuel demand.

However, stabilizing the electricity supply in the stationary electricity sector with synthetic fuels from concentrated CO_2 sources may be the preferred allocation of these (limited) sources by society. According to [LBST/IFEU/IWES 2016] for a scenario with high penetration of BEV about 48 GW of dispatchable electricity sources are required in Germany generating about 59 TWh of electricity per year. Furthermore, about 20 TWh of electricity are imported. If both the 59 TWh from the dispatchable electricity sources and the imported 20 TWh per year were supplied by a methane fired combined cycle gas turbine (CCGT) power plant with an efficiency of 60 % about 132 TWh of renewable methane would be required. Then about 70 % of the German CO_2 potential from concentrated sources would be required. As a result only 7 % (instead of 26 % in the German case) of the German transportation fuel demand from 2015 could be met by methane from CO_2 from concentrated sources.

It can be expected that the situation in the EU is similar. Therefore, this study assumes that CO_2 from air will be used to produce methane and liquid hydrocarbons for transportation fuel.

5.2.6 Conclusions

- Concentrated biogenic CO_2 sources are limited in terms of the fuel consumption levels discussed in this study, and as a result of feedstock competition for various uses, such as energy, beverages and chemicals.
- As we move towards a carbon-neutral future, concentrated industrial/fossil CO_2 sources will decline in importance over the next decade(s) so that we can achieve the GHG reduction targets.

- CO_2 extracted from air will thus have to become the main carbon source for fuel synthesis in the long run.
- The relative importance of concentrated CO_2 as a feedstock for e-fuels will increase with decreasing transportation demands.

5.3 Deployment of renewable power and PtX production plants in 2030/2050 according to the scenarios

Regarding to the scenario assumptions set out in Section 3, an ambitious deployment of renewable energies and e-fuel plants is needed to reduce GHG emissions in transport.

Figure 29 and Figure 30 show the renewable electricity plant build-up required for the two PtL-dominated scenarios: BAU-moderate (PtL/High/-80%$_{GHG}$) and BAU-ambition (PtL/Low/-95%$_{GHG}$).

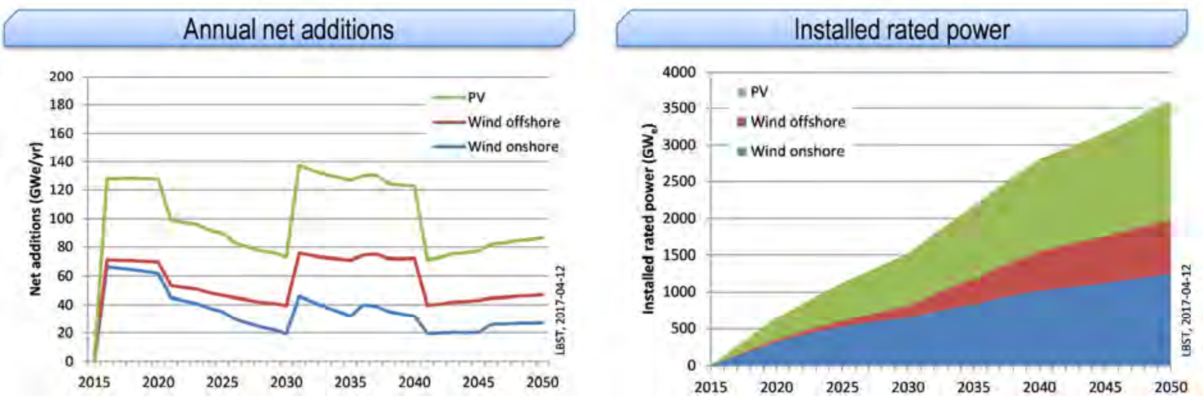


Figure 29: Electricity plant build-up required for the BAU-moderate scenario (PtL/High/-80%$_{GHG}$)

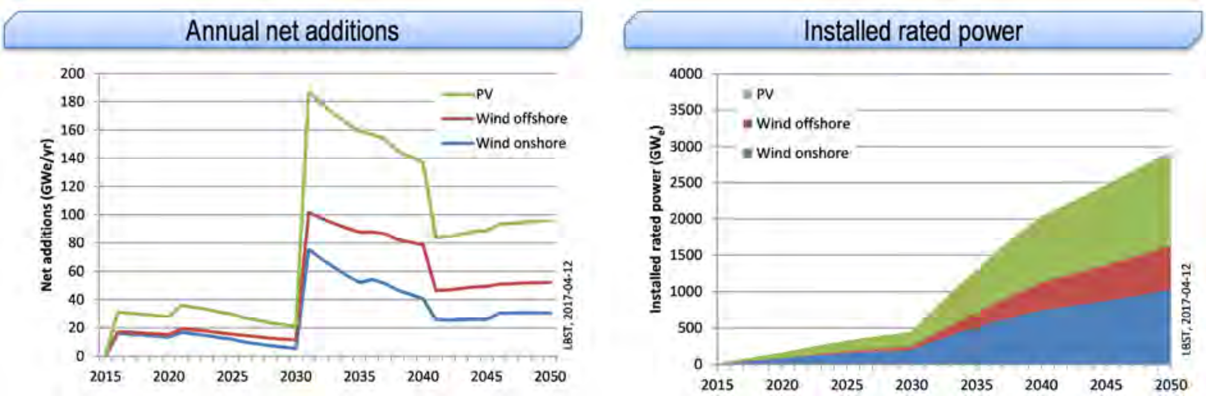


Figure 30: Electricity plant build-up required for the BAU-ambition scenario (PtL/Low/-95%$_{GHG}$)

Despite its more ambitious GHG reduction (-95% in 2050 compared to 1990 levels), the PtL/Low/-95%$_{GHG}$ scenario requires significantly fewer renewable power plants than the PtL/High/-80%$_{GHG}$ scenario. This is because of the low transport demand. In particular, to achieve the EU's 2030 non-ETS GHG reduction target, a scenario with high transport demand would require much more renewable energy than one with very low transport growth.

Figure 31 and Figure 32 show the renewable electricity plant build-up required for the PtG-dominated Progressed-mix scenario (PtG/Low/-95%$_{GHG}$) and the More-electric scenario (eDrives/Low/-95%$_{GHG}$).

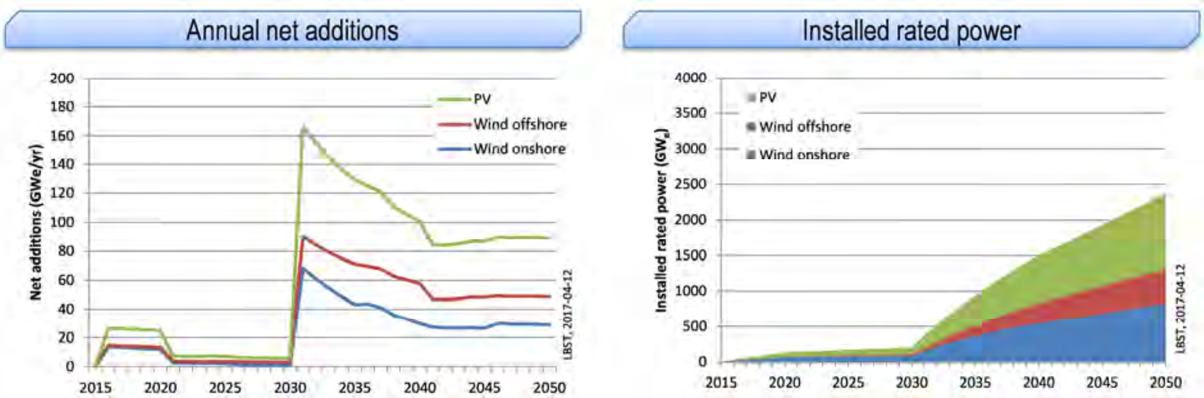


Figure 31: Electricity plant build-up required for the Progressed-mix scenario (PtG/Low/-95%$_{GHG}$)

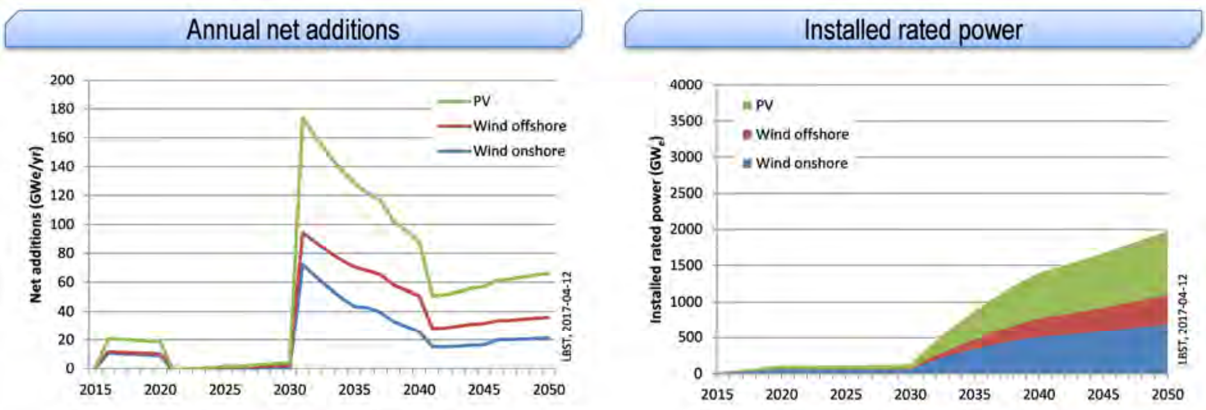


Figure 32: Electricity plant build-up required for the More-electric scenario (eDrives/Low/-95%$_{GHG}$)

In the development routes with low transport demand (BAU-ambition, Progressed-mix, More-electric), the addition of installed renewable electricity generation capacity up to 2030 is relatively low, although the GHG emissions decrease by about 95% instead of by about 80% (BAU-moderate). This is because the same GHG target for 2030 (-30% GHG compared to 2005) has been applied in all development routes.

Table 38 shows the average additions of renewable electricity generation capacity between 2030 and 2050, and the installed capacity at the end of 2050.

Development route	Average annual new installations, 2030-2050 (GW/yr)			Installations at the end of 2050 (GW)		
	Onshore wind	Offshore wind	PV	Onshore wind	Offshore wind	PV
PtL/High/-80%	30	28	46	1,266	739	1,625
PtL/Low/-95%	39	27	53	1,032	603	1,325
PtG/Low/-95%	34	22	45	835	488	1,072
eDrives/Low/-95%	29	19	38	698	408	896

Table 38: Renewable electricity plant build-up, and installed capacity at the end of 2050 for energy in transport

By the end of 2016, some 400 GW of renewable power were installed in the EU28. Of this, 150 GW came from hydropower, 142 GW from onshore wind, 12 GW from offshore wind, and 101 GW from PV. In 2050, some 2,000 to 3,600 GW of installed renewable power generation capacities are needed for an energy transition in EU transport following the More-electric (eDrives/Low/-95%) and BAU-moderate (PtL/High/-80%) scenarios.

In 2015, new renewable power plant additions in the EU28 were 9.8 GW of onshore wind, 3.0 GW of offshore wind, and 8.5 GW of PV. To achieve the energy transition in transport, annual deployment rates must increase by at least 3 to 4 times in the case of onshore wind, 6 to 10 times in the case of offshore wind, and 4 to 6 times in the case of PV.

The current pace of renewable power plant deployment in the EU does not yet reflect an ambition to comply with the international agreement achieved in Paris in December 2015, let alone to achieve an energy transition in transport.

Besides pursuing an ambitious renewable development path, the EU also needs to increase its e-fuels capacity in order to defossilise all transport modes. The more full-load hours an e-fuel plant has, the more cost-efficient it will be. Wind and PV electricity are complementary to a large extent. Periods of high wind speeds occur during times of low solar irradiation, and vice versa. According to Fasihi et al. (2016b), many regions of the EU and other parts of the world can expect an equivalent full-load period of more than 4,000 hours per year for e-fuel plants. Certain locations outside the EU can even expect an equivalent full-load period of about 7,000 hours per year for e-fuel plants connected to wind turbines and PV systems.

This study assumes an equivalent full-load period of 4,000 hours per year for e-fuel plants installed in the EU. This results in the required e-fuel plant build-up shown in Figure 33.

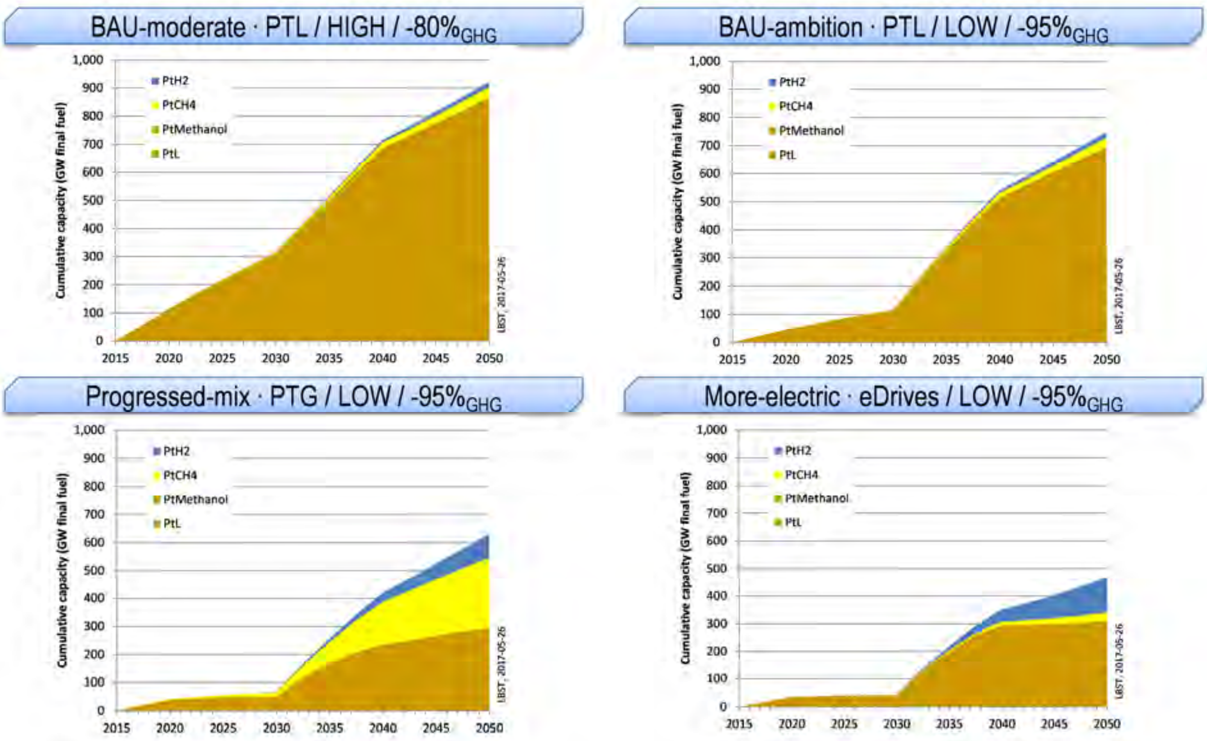


Figure 33: E-fuels plant build-up required for the different scenarios

The required e-fuel capacity in scenarios with less efficient powertrains is significantly higher. In particular, high plant capacity is required for the scenario with high transport demand (BAU-moderate), even though the GHG reduction is 80% instead of 95%.

Conclusions

Current deployment rates for renewable power and e-fuel plant capacities are yet not in line with the Paris Agreement and with the objective of keeping global temperature rise to below 2°C. In the coming years, a constant and ambitious build-up of renewable power and e-fuel plants is necessary to significantly defossilise all transport modes. The bigger the growth in passenger and freight transport, the harder it will be to achieve the renewable build-up goal. The reflections above focus on electricity demand from transport, i.e. power-to-fuels. Established and possible new electricity demands, such as those from the stationary sector, power-to-heat and power-to-chemicals, would come on top of that.

Renewable power generation technologies such as wind and PV have different characteristics to the dispatchable power generation capacities of the past. Electricity demands from the transport sector are likely to outstrip today's electricity demands (and probably also those for power-to-heat and power-to-chemicals). The transport sector will thus become a major player in the electricity system. For reflections on linking different energy sectors (sector coupling) and on integrating (fluctuating) renewable electricity, see Section 5.8.

5.4 Investment needed for an energy transition in EU transport

In order to understand the macro-economic dimension of an energy transition in transport at the EU level, the study authors calculated the cumulated investment needed to deploy renewable power generation capacities, e-fuel production plants and fuel infrastructure.

The cumulated investments were calculated using the following assumptions:

- An e-fuel plant has a lifetime of 25 years.
- The investments for end-of-life replacements are included in the cost model.
- Renewable power generation and e-fuel production plant assets are installed in Europe. As a sensitivity analysis, the authors assessed the import of power-to-methane ($PtCH_4$) and power-to-liquids (PtL) from outside the EU.
- Technology-specific earning curves were taken into account for key components, i.e. the first e-fuel production plant is more expensive than the n^{th} plant.
- BEV infrastructures for grid integration and energy balancing of slow and fast charging are taken into account in the cumulated investments. This includes stationary short and long-term electricity storage. Not included are additional investments into grid enforcements. These costs are included in the transport fuel costs through voltage level specific grid fees (see 5.5.3).

Vehicle costs were not included. In the case of passenger cars, trucks and buses, it was assumed that the vehicle costs of ICEs and electric vehicles converge with tighter emission rules for conventional powertrains on the one hand, and mass deployment of more-electric and all-electric powertrains on the other.

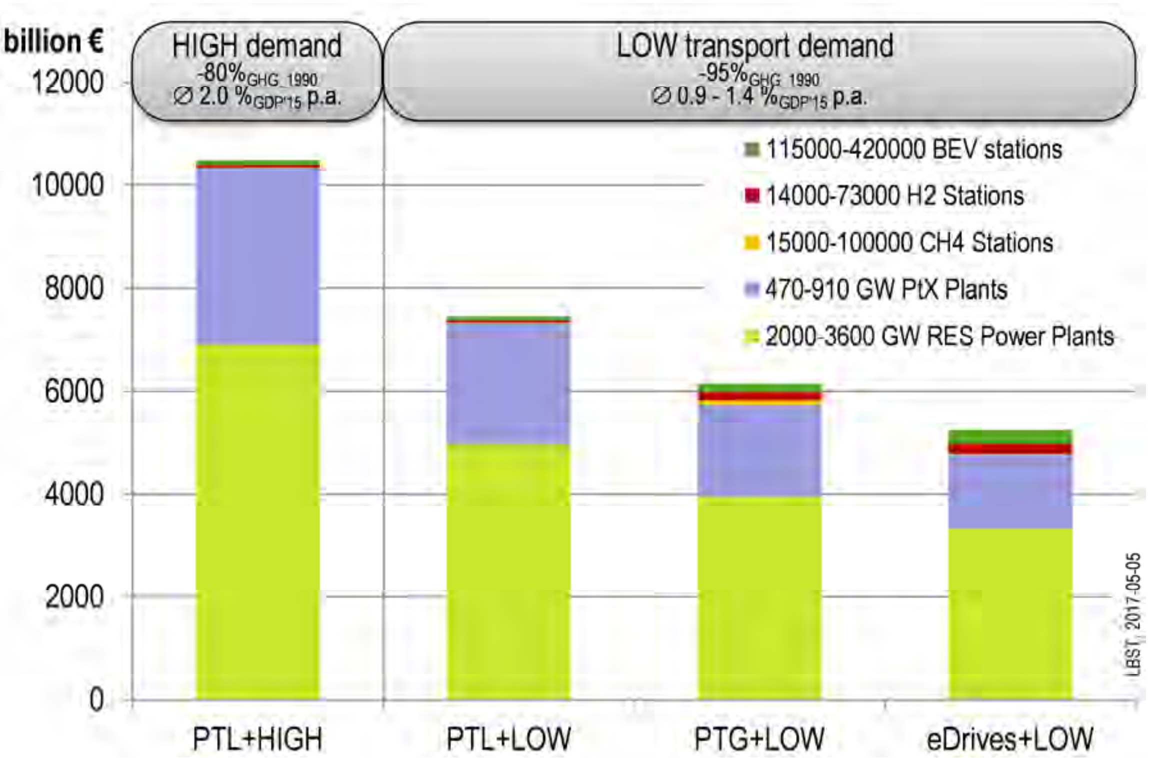


Figure 34: Cumulated investments for the energy transition in EU transport up to 2050

Asset	Deployed quantities	PtL/High/-80% (€ billion)	PtL/Low/-95% (€ billion)	PtG/Low/-95% (€ billion)	eDrives/Low/-95% (€ billion)
RES power plants	2,000–3,600 GW	6,899	4,969	3,952	3,322
PtX plants	470–910 GW	3,448	2,358	1,784	1,444
CH_4 stations	15,000–100,000	12	10	93	9
H_2 stations	14,000–73,000	45	45	163	199
BEV stations	115,000–420,000	95	74	154	273
Total cumulated investments		**10,498**	**7,456**	**6,146**	**5,246**

Table 39: Cumulated investments and assets required for the energy transition in EU transport up to 2050

The resulting cumulated investments range from roughly €10,500 billion (PtL/High/-80%$_{GHG}$) to €5,250 billion (eDrives/Low/-95%$_{GHG}$). The cumulated investments are dominated by investments needed for renewable power generation assets, followed by those for e-fuel plants. Investment needed for distribution infrastructures are as low as 1% (PtL/High/-80%$_{GHG}$) and 9% (eDrives/Low/-95%$_{GHG}$) of the cumulated investments until 2050. This is due to the applied assumptions which take into account that, for instance, peak loads for BEVs are avoided by local battery storage and long-term hydrogen storage. The cost of the storage is included in the investment cost (see Section 5.5.3). Therefore, from a macro-economic point of view, investments in distribution infrastructure are almost negligible in this study compared to the investment needs for renewable power generation and e-fuel production assets. From this, it can be concluded that investments needed for distribution infrastructure alone is not a sufficient basis for discussions about technology preferences for future fuel/powertrain strategies.

For a liquidity analysis, the development routes in Figure 35 show the corresponding annual investments over time.

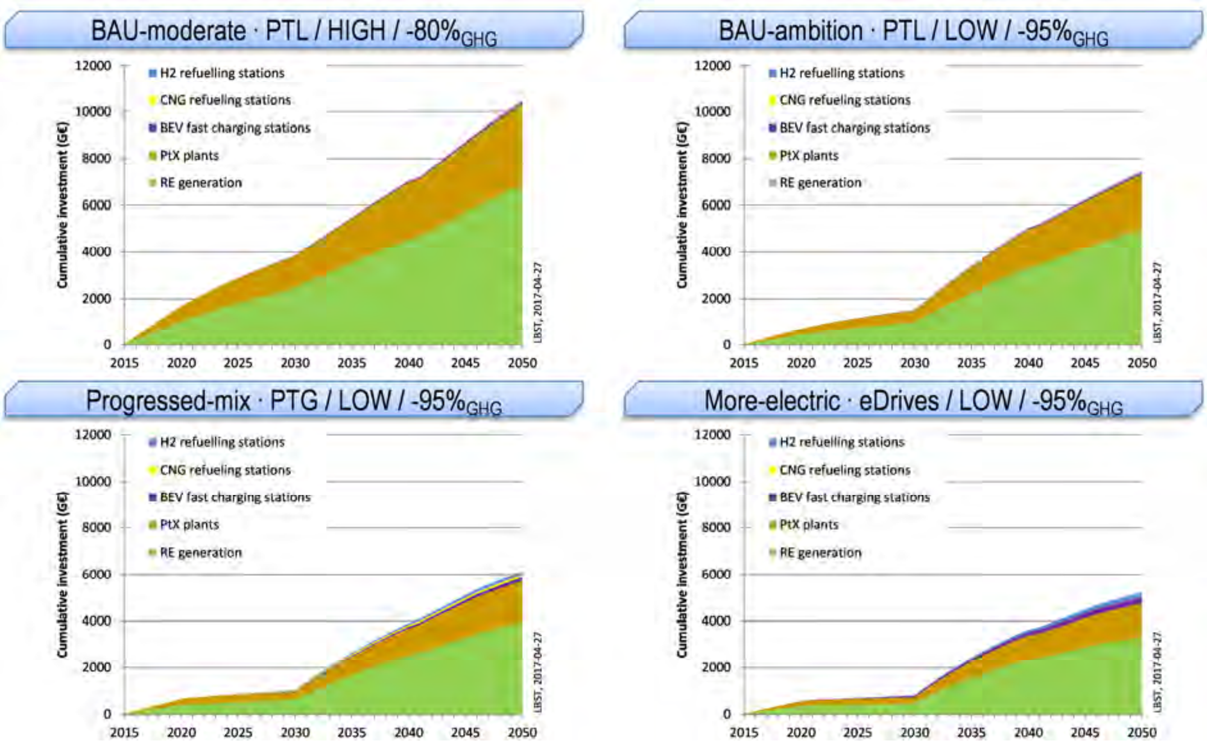


Figure 35: Annual investments for the energy transition in EU transport by scenario and asset

Annual investments in the BAU-moderate scenario are rather evenly distributed up to 2050. In the three scenarios with low transport demand (BAU-ambition, Progressed-mix, More-electric), the 30% GHG reduction target in 2030 versus the reference year 2005, and the assumption of significant progress in powertrain efficiencies result in moderate investment needs up to 2030. After 2030, however, the investment needs sharply increase in order to achieve the -95% GHG target by 2050 (versus the reference year 1990).

For comparison

The capacity and investment figures laid out above are large numbers considering the all-encompassing transition of the primary energy and fuel base in transport. The numbers thus have to be put into context.

In 2016, annual GDP in the EU28 was €14,820 billion according to Eurostat figures from 9 August 2017. Assuming a linear distribution of investments over 33 years results in average annual investments of €160 to €320 billion, which is roughly 1 to 2.1% of GDP each year until 2050. Investments in the energy transition will, however, also replace (to some extent) investments that would also be required in a business-as-usual situation. Furthermore, investing in domestic renewable power and e-fuel plants in the EU will strengthen the EU economy and increasingly reduce annual spending on fossil fuel imports beyond 2050. In 2013, annual oil spending in the EU amounted to about €290 billion. Currently, the EU spends some €187 billion on crude oil imports per year (European Commission, 2017g). This is thanks to fairly low prices for fossil fuels and CO_2 emission certificates.

Sensitivity analysis

In many parts of the world, the power generation costs of hybrid PV/wind systems can be significantly lower than those in Europe because of the average European meteorological situation (see Section 0). Such regions can achieve more full-load hours per year, which leads to lower renewable power plant capacities, and thus lower investment needs. In order to determine the lower boundary of cumulated investments, this study assumes that all $PtCH_4$ and PtL fuels are imported from outside the EU. The resulting cumulated investments are shown in Figure 36 (white arrows) as reduction potentials.

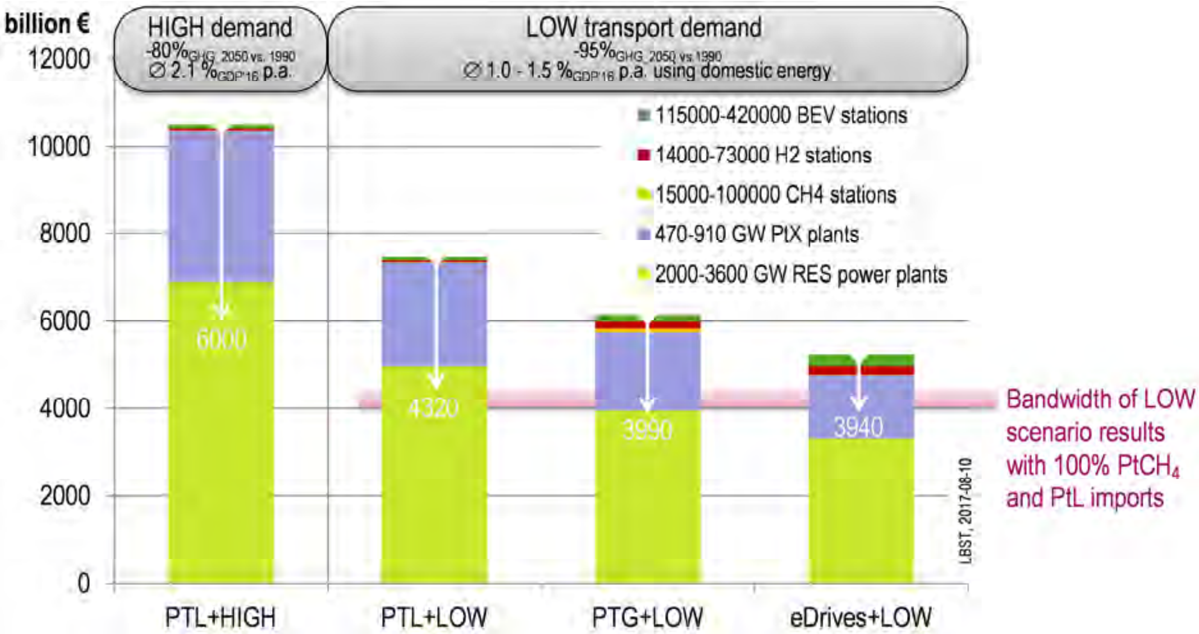


Figure 36: Cumulated investment sensitivity assuming 100% $PtCH_4$ and PtL imports (white arrows)

Asset	Deployed quantities	PtL/High/-80 % (€ billion)	PtL/Low/-95% (€ billion)	PtG/Low/-95% (€ billion)	eDrives/Low/-95% (€ billion)
RES power plants	1,660–2550 GW	3,790	2,775	2,426	2,401
PtX plants	350–550 GW	2,059	1,421	1,152	1,061
CH_4 stations	14,000–100,000 GW	12	10	93	9
H_2 stations	14,500–73,000 GW	45	45	163	199
BEV stations	115,000–420,000 GW	95	74	154	273
Total cumulated investments		**6,001**	**4,324**	**3,988**	**3,942**

Table 40: Cumulated investments and assets required, including $PtCH_4$ and PtL imports

Figure 36 shows that assuming imports of $PtCH_4$ and PtL causes the resulting cumulated investments to converge in the low scenarios. High renewable electricity yields in regions with both excellent wind and solar availability plus the higher utilisation of e-fuels production plants reduce investments most pronouncedly in scenarios with high consumption of PtCH4 and PtL in absolut terms (see the figures on scenario-specific fuel demands in Section 4.6.1).

5.5 Costs of PtL, $PtCH_4$, PtH_2 and BEV-charging compared to fossil fuels

5.5.1 Costs of electricity generation

The costs of renewable electricity generation depend on the specific investment, the equivalent full-load period, and the costs for administration, insurance, maintenance and repair.

The investment and equivalent full-load period for onshore wind were derived from existing plants and by extrapolation up to 2050. The specific investment and equivalent full-load period for offshore wind were derived from Fichtner & Prognos (2013, mix of locations A, B and C in Scenario 1). The specific investment indicated in Fichtner & Prognos (2013) for 2023 was extrapolated using the cost-reduction up to 2050 indicated in DLR et al. (2012). The specific investment and equivalent full-load period for PV systems were derived from ISE (2015b).

Table 41 shows the specific investment, equivalent full-load periods, and share of the different renewable electricity plants in the EU assumed in this study.

	2015	2020	2030	2040	2050
Specific investment (€/kW)					
Onshore wind	2,000	1,900	1,700	1,500	1,400
Offshore wind	4,107	3,618	3,224	2,865	2,686
PV	1,055	892	753	674	606
Equivalent full-load period (h/yr)					
Onshore wind	2,500	2,520	2,560	2,600	2,640
Offshore wind	4,012	4,077	4,239	4,239	4,239
PV	1,000	1,066	1,181	1,221	1,220
Share of renewable electricity					
Onshore wind	69%	65%	52%	41%	40%
Offshore wind	7%	10%	23%	35%	37%
PV	23%	25%	26%	24%	23%

Table 41: Electricity power-plant mix in the EU

To calculate the electricity generation costs, the specific investment for some technologies was altered for some locations – for instance, due to shallower water, the specific investment for offshore wind in the UK is lower than it is for Germany, which results in lower electricity generation costs in the UK. Table 42 and Figure 37 show the evolution of the costs of renewable electricity generation in the EU.

(ct/kWh)	2015	2020	2030	2040	2050
Onshore wind	8.5	8.1	7.5	6.8	6.4
Offshore wind	12.9	10.8	9.0	8.2	7.3
PV	8.6	7.9	6.5	5.8	5.1
Weighted mix	8.8	8.3	7.6	6.9	6.3

Table 42: Electricity generation costs for all plants in the EU

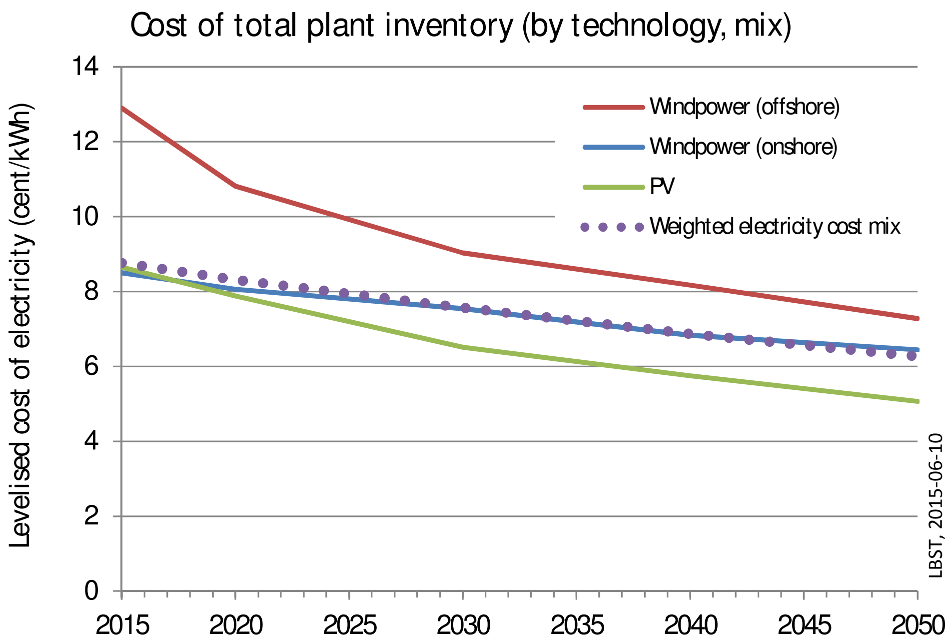


Figure 37: Electricity generation costs for all plants in the EU

The electricity generations costs shown in Figure 37 must not be confused with the bidding prices published recently for electricity from offshore wind. DONG Energy was awarded three German offshore wind projects with bids of between zero and 6 eurocents per kWh of electricity. DONG Energy only will build the offshore wind farms if the realization window is extended to 2024 and several nuclear and coal power stations are shut down in Germany (leading to higher electricity prices on the exchange), if larger wind turbines with a capacity of 13 to 15 MW per unit are available in 2024, and if the operating lifetime is extended to 30 years. Grid connection is not included in the bidding price. The final investment decision will be made 2021 (DONG, 2017).

The electricity is transported and distributed to the e-fuel plants via the electricity grid. The cost of electricity transport and distribution depends on the voltage level and the equivalent full-load period.

The electricity costs presented above do not include losses from electricity transport and distribution, or the costs of the electricity grid. Table 43 shows the losses from electricity transport and distribution in the ENTSO-E grid.

Grid level	Efficiency per electricity transmission/distribution step	Cumulative efficiency of electricity transmission and distribution
UHV (380 kV, 220 kV)	100.0%	100.0%
HV (110 kV)	96.4%	96.4%
MV (10-20 kV)	98.3%	94.8%
LV (0.4 kV)	93.7%	88.7%

Table 43: Efficiency of electricity transport and distribution in ENTSO-E (Itten et al., 2014)

No data are available for the average cost of electricity transport and distribution in the EU. As a rough estimate, this study assumes that the cost of electricity in a grid in North Rhine-Westphalia in Germany is representative. Table 44 shows electricity transport and distribution costs indicated by grid operator Westnetz (Westnetz, 2017).

	Unit	<2500 h/yr	>2500 h/yr
Energy rate			
UHV (380 kV, 220 kV)	€/kWh	0.01588	0.00386
UHV, HV (110 kV)	€/kWh	0.0243	0.0013
UHV, HV, MV (10-20 kV)	€/kWh	0.0358	0.0065
UHV, HV, MV, LV (0.4 kV)	€/kWh	0.0412	0.0257
Demand rate			
UHV (380 kV, 220 kV)	€/(kW*yr)	7.09	37.14
UHV, HV (110 kV)	€/(kW*yr)	7.67	65.17
UHV, HV, MV (10-20 kV)	€/(kW*yr)	10.52	83.77
UHV, HV, MV, LV (0.4 kV)	€/(kW*yr)	11.12	49.87
Other			
Concession levy	€/kWh	0.0011	0.0011

Table 44: Electricity transport and distribution costs (cumulative)

The voltage level depends on the maximum power demand from electricity consumers (Table 45).

	Maximum power demand (MW)	Reference
HV (110 kV)	500	Estimate
MV (10-20 kV)	15	(Westnetz, 2017)
LV (0.4 kV)	0.20	(Westnetz, 2017)

Table 45: Maximum power demand for the different voltage levels

For instance, if an electricity consumer has a maximum power demand of 10 MW and an equivalent full-load period of 4,000 hours per year, the cost of electricity transport and distribution would be about 2.9 eurocents per kWh of electricity[9].

[9] (83.77 €/(kW*yr) * 10 MW / (10 MW * 4000 h/yr) + 0.0065 €/kWh + 0.0011 €/kWh).

5.5.2 E-fuel plants

Electricity costs are the main drivers of costs in e-fuel plants. This study assumes that the PtL and $PtCH_4$ plants are connected to the high-voltage (110 kV) grid. In the case of PtL and $PtCH_4$, the electricity costs, including transport and distribution, amount to about 11 eurocents per kWh of electricity in 2015, and about 8.4 eurocents per kWh of electricity in 2050.

Table 46 shows the cost assumptions for the PtL plants.

		2015				**2050**			
		LT electrolysis		**HT electrolysis**		**LT electrolysis**		**HT electrolysis**	
		Via CH_3OH	**Via FT**	**Via CH_3OH**	**Via FT**	**Via CH_3OH**	**Via FT**	**Via CH_3OH**	**Via FT**
Key technical data									
Electricity input	MW_e	25	24	29	28	128	127	148	141
Capacity	MW_{PtL}	9	9	14	13	55	53	70	68
Efficiency (PtL plant)		37%	36%	46%	47%	43%	42%	47%	48%
Investment									
Electrolysis	€/kW_{PtL}	2,707	2,791	4,592	4,734	366	378	467	481
H_2 storage	€/kW_{PtL}	56	622	-	-	56	622	-	-
CO_2 supply	€/kW_{PtL}	2,422	2,493	2,214	2,280	1,637	1,685	1,555	1,601
Synthesis	€/kW_{PtL}	916	885	809	782	531	513	495	478
Total	€/kW_{PtL}	6,101	6,792	7,615	7,795	2,590	3,198	2,517	2,561
Overall costs									
Fuel costs WTT	€/GJ_{PtL}	123	128	139	139	72	76	68	67
	€/MWh_{PtL}	441	462	499	501	258	274	245	242
of which CO_2 costs	€/MWh_{PtL}	101	102	111	112	73	73	82	83
	€/t_{CO2}	366	358	403	394	263	258	297	291

Table 46: PtL cost assumptions

Table 47 shows the cost assumptions for the $PtCH_4$ plants.

		2015				2050			
		LT electrolysis		HT electrolysis		LT electrolysis		HT electrolysis	
		As CNG	As LNG	As CNG	As LNG	As CNG	As LNG	As CNG	As LNG
Key technical data									
Electricity input	MW_e	23	23	25	25	116	116	128	128
Capacity	MW_{CH4}	10	10	15	15	59	59	75	75
Efficiency (PtL plant)	-	43%	43%	57%	57%	51%	51%	58%	58%
Investment									
Electrolysis	€/kW_{CH4}	2,521	2,522	4,277	4,277	341	341	435	435
H_2 storage	€/kW_{CH4}	44	44	-	-	44	44	-	-
CO_2 supply	€/kW_{CH4}	1,839	1,839	1,681	1,681	1,242	1,242	1,180	1,180
Synthesis	€/kW_{CH4}	574	574	501	501	322	322	299	299
Total	€/kW_{CH4}	4,978	4,978	6,459	6,459	1,948	1,948	1,914	1,914
Overall costs									
Fuel costs WTT	€/GJ_{CH4}	109.3	111.2	121.3	123.2	63.6	65.5	57.8	59.7
	€/MWh_{CH4}	393	400	437	444	229	236	208	215
of which CO_2 costs	€/MWh_{CH4}	64	64	75	75	45	45	55	55
	€/t_{CO2}	323	323	380	380	229	229	279	279

Table 47: $PtCH_4$ cost assumptions

In the case of LNG, the CH_4 liquefaction is carried out onsite at the LNG refuelling station. LNG is used for trucks. CNG can be used for both passenger vehicles and trucks. The technical and economic data for the LNG truck refuelling station were derived from Hendrickx (2015) and LBST (2016b). The economic data for the CNG passenger car refuelling station were derived from Smith & Gonzales (2014). The electricity consumption for CH_4 compression at the CNG refuelling station was derived from JEC (2014). The electricity consumption for onsite CH_4 liquefaction was derived from Galileo (2013).

Table 48 shows the technical and economic data for the CNG and LNG refuelling stations.

		CNG passenger car refuelling station	**LNG truck refuelling station**
Key technical data			
Electricity consumption	$kWh/kWh_{CH4, LHV}$	0.022 (CH_4 compression)	0.060 (CH_4 liquefaction)
Number of dispensers	-	1	2
Number of fillings	-	50-80 fillings/day	36 fillings/day
Average fuel output	GWh/yr	8.0	22.4
Investment			
Dispenser(s)	€	44,400*	189,000
Card reader/ fuel management system	€	7,400*	
LNG storage	€	-	145,000
Cryopump incl. valves and controller	€	-	129,000
CMG storage	€	51,800*	20,000 (for boil-off)
Compressor	€	148,000*	25,000 (for boil-off)
Gas drier	€	7,400*	-
Odorization boil-off	€	-	26,000
Equipment for data transfer	€	-	10,000
Installation	€	168,350**	-
Civil work (roof, payment system)	€	included in installation	400,000
Project management, documentation	€	included in installation	80,000
Approval	€	2,000	10,000
Subtotal refuelling station	**€**	**429,350**	**1,034,000**
CH_4 liquefaction plant	€	-	1,739,000
Total investment	**€**	**429,350**	**2.773,000**

* Converted from US$ to €, exchange rate in 2014 (date of reference): 0.74 €/US$1; ** installation factor 0.65 of the sum of equipment cost

Table 48: Technical and economic data for CNG and LNG refuelling stations

In the case of hydrogen, the study assumes that the hydrogen is generated onsite at the refuelling station. The CGH_2 refuelling station with onsite electrolysis is connected to the medium-voltage grid. The electricity costs, including transport and distribution, amount to about 12.1 eurocents per kWh of electricity in 2015, and to about 9.5 eurocents per kWh of electricity in 2050.

Table 49 shows PtH_2 cost assumptions.

		2015	2050
Key technical data			
Electricity input	MW_e	3.11	2.34
Capacity	MW_{CH4}	1.52	1.52
Efficiency		49%	65%
Fuel output	GWh/yr	6.08	6.08
Average fuel output	kg_{H2}/d	500	500
Net storage capacity	kg H_2	1030	1023
Investment			
Electrolysis	€ million	4.14	0.95
Refuelling station	€ million	3.30	1.98
Total	€ million	7.44	2.93
Overall costs			
Fuel costs well-to-tank	€/GJ_{H2}	100	54
	€/MWh_{H2}	359	193

Table 49: PtH_2 cost assumptions

5.5.3 BEV charging

The study assessed two variants: One with slow charging at home (0.4 kV) and one with fast charging using 120 kW at a public charging station.

Slow charging

The study assumed that the electricity for stationary applications and for slow charging is fully met by renewable energy sources in 2050. Therefore, stationary electricity storage is required. The stationary electricity storage uses stationary battery systems and combined cycle gas turbine plants (CCGT) fuelled by CH_4 from $PtCH_4$. The share of electricity supplied via electricity storage was derived from a scenario for Germany described in LBST/IFEU/IWES (2016). Table 50 shows the calculation of the costs of electricity for slow charging, excluding electricity transport and distribution.

		2050	Comment/reference
General			
Costs of wind/PV electricity	€/kWh	0.063	
Electricity demand	TWh/yr	765	(LBST/IFEU/IWES, 2016)
CH_4 fuelled CCGT			
Capacity	GW	63	
Efficiency		60%	(SWU, 2012)
Equivalent full-load period	h/yr	937	
Investment	€/kW_e	750	(SWU, 2012)
	billion €	47.25	
Lifetime CCGT	Yr	35	(DLR, 1999)
Interest rate		4%	
CH_4 via $PtCH_4$	€/kWh_{CH4}	0.182	
	€ billion/yr	17.9	
Capital costs	€ billion/yr	2.5	
O&M	€ billion/yr	0.9	1.7% of investment/yr + labour
Total	€ billion/yr	21,4	
Electricity generation from CCGT	TWh/yr	59	(LBST/IFEU/IWES, 2016)
Share of electricity from CCGT		7.7%	
Battery systems			
Capacity	MW/unit	5	(SW&W, 2014)
	GW	43	(LBST/IFEU/IWES, 2016)
	MWh/unit	5	(SW&W, 2014)
Efficiency	-	86%	
Number of full-cycle equivalent	-	200	(Younicos, 2013)
Investment	€ million/unit	0.8	
	€ billion	6.98	
Lifetime battery system	Yr	20	(SW&W, 2014)
Battery system costs	billion €/yr	1.1	

Share of electricity from battery	-	1.1%	
Composition of electricity cost			
Electricity via CCGT	€/kWhe	0.028	
Electricity via battery system	€/kWhe	0.0015	
Electricity direct	€/kWh	0.057	
Electricity costs including storage	**€/kWh$_e$**	**0.087**	

Table 50: Costs of electricity for slow charging, excluding transport and distribution

Of the electricity for slow-charging BEVs, 91.2% comes directly from renewable power stations, 7.7% is supplied by CCGT plants fuelled with CH_4 from $PtCH_4$, and 1.1% is supplied by electricity stored in stationary battery systems.

The electricity is distributed via the electricity grid. According to Westnetz (2017), the energy rate for households and small businesses amounts to 5 ct/kWh, the demand rate amounts to €51.1/yr, and the metering costs amount to about €11.77/yr. The concession levy amounts to about 2 ct/kWh. The electricity consumption, including the electricity consumption for charging a BEV at home is assumed to be about 5,700 kWh per year in 2050. As a result, the cost of electricity transport and distribution amounts to about 8.1 ct/kWh. Including transport and distribution losses, the cost of electricity for households and thus for charging a BEV amounts to 17.9 ct/kWh. The charger is installed in the vehicle and is included in the price of the vehicle.

Fast charging

The fast-charging station consists of 6 chargers ("superchargers") of 120 kW each. The charging station is connected to the medium-voltage electricity grid. A stationary electricity storage system is installed onsite at the fast charging station.

The maximum power output of the stationary storage system depends on the grid capacity at the location of the fast-charging station. At Gotthard Fast Charge, the maximum power of the battery system amounts to 50% of the charging capacity (400 kW for 800 kW of charging capacity) (Gotthard Fast Charge, 2017). It has been assumed that, in 2015, the stationary storage system consists of a battery system capable of meeting approximately 30% of the maximum power demand of the six superchargers (720 kW). The maximum power output of the battery system increases to 100% of the maximum power demand in 2050. Furthermore, the study assumes that the share of electricity supplied by the stationery storage system increases from 30% in 2015 to 50% in 2050.

According to Electrek (2016) a battery system with 100 kW and 200 kWh costs US$145,100 (battery: US$89,000; bidirectional 250 kW inverter: US$52,500; cabling and site support hardware: US$3,600). This equates to about US$726 per kWh of storage capacity. The study assumes that the storage system installed in the EU would cost €726/kWh, including power electronics, cabling and site-support hardware. According to Becker et al. (2015), the cost of electricity storage decreases to €210/kWh in 2030. It is assumed that the specific investment remains constant from 2030 to 2050.

In addition to short-term stationary electricity storage via battery, a balanced approach has been chosen for the mid- to long-term stationary electricity storage that is needed to cover the supply when both wind and solar generation are low for several consecutive days. Thus, from 2035 onwards, a hydrogen-based electricity storage system that uses an electrolyser, underground storage tubes, and fuel cells is included. The storage capacity of the stationary hydrogen system can cover two days of electricity demand. The share of electricity from stationary storage supplied by the fuel cell amounts to 50% in 2050. The capacity of the fuel cell is 720 kW. The specific investment for the stationary fuel cell is assumed to be €778/kW_e, based on data in Roland Berger (2015) and converted to hydrogen as fuel instead of natural gas (stack at 500 MW of cumulative production per manufacturer: €600/kW + 8% installation + 20% OEM and trade margins; power electronics are already available from the battery system). The electrolyser's capacity is roughly 420 kW (electricity input). The study assumes the specific investment for the electrolyser to be €445/kW_e in 2050 (the same as for onsite hydrogen generation for CGH_2 supply).

Depending on factors such as grid expansion and consumer behaviour, the required amount of stationary electricity storage for dispatchable power supply may be higher (or lower under certain conditions; see IWES, 2017). It is assumed that additional dispatchable power is covered by the power component of the grid fee.

The fast-charging station is connected to the medium-voltage grid. The electricity costs, including transport and distribution, amount to about 13.5 eurocents per kWh of electricity in 2015 and about 10.1 eurocents per kWh of electricity in 2050. Table 51 shows fast-charging cost assumptions.

	Unit	2015	2050
Key technical data			
Power output supercharger	kW_{DC}	120	120
Number of superchargers	-	6	6
Capacity, battery system	kW	200	700
Electricity storage capacity, battery system	kWh	400	1400
Capacity, stationary fuel cell system	kW	-	720
Net H_2 storage capacity	kg H_2	-	1994
Capacity, electrolysis plant	kW_e	-	423
Efficiency		88%	76%
Average electricity output	GWh/yr	1.26	1.26
Investment			
Contribution towards network costs	€ million	0.21	0.21
Superchargers	€ million	0.18	0.18
Stationary electricity storage (battery)	€ million	0.29	0.29
Stationary electricity storage (H_2 fuel cell system)	€ million	0.00	1.16
Total	€ million	0.68	1.84
Overall costs			
Electricity costs well-to-tank	€/GJ_e	58	83
	€/MWh_e	210	297

Table 51: Cost assumptions for BEV fast charging

5.5.4 Results

Figure 38 shows the costs of supplying final energy (transportation fuel) well-to-tank for 2015, expressed in litres of diesel equivalent (LHV = 35.88 MJ/l = 9.97 kWh/l). In the case of BEVs, the costs are well-to-receptacle.

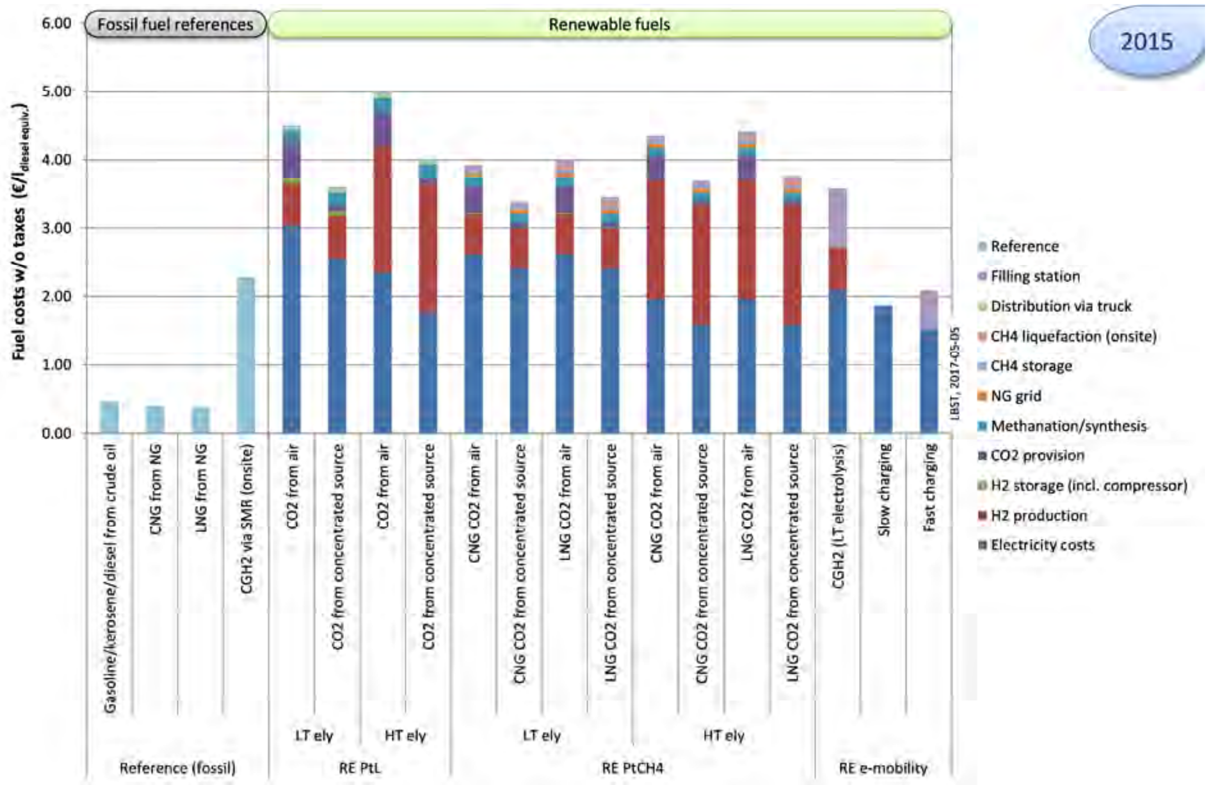


Figure 38: Costs for supplying transportation fuel, per litre of diesel equivalent in 2015

High-temperature electrolysers are still at the research and development stage, which results in high specific investments for hydrogen production. Therefore, 2015 pathways involving high-temperature electrolysers show higher costs for fuel supply than those involving low-temperature electrolysis.

The assumed reduction in specific investment for high-temperature electrolysers, combined with the high efficiency, leads to lower fuel costs than in PtL pathways employing low-temperature electrolysis in 2050. Figure 39 shows the costs of supplying final energy well-to-tank, in 2050, expressed in litres of diesel equivalent.

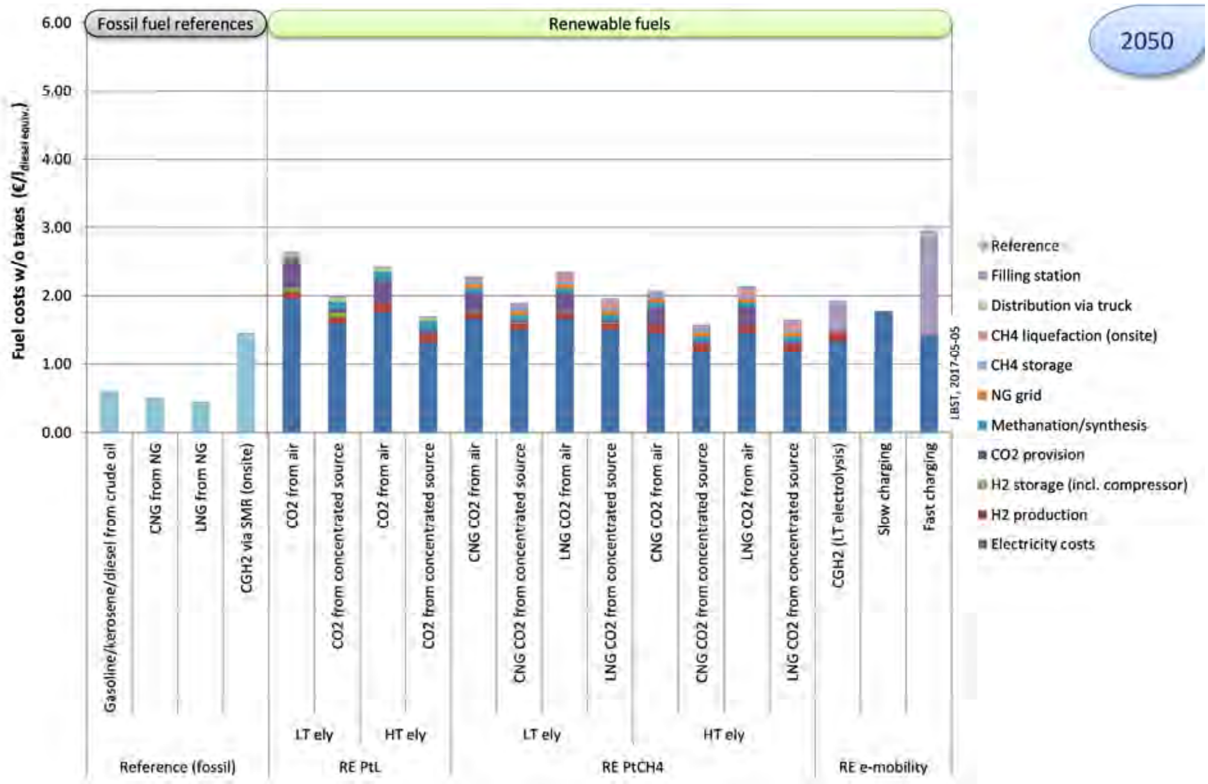


Figure 39: Costs of supplying transportation fuel per litre of diesel equivalent in 2050

While the costs for PtL and $PtCH_4$ fuels decrease in 2050, the costs of electricity for fast charging increase due to the introduction of a hydrogen-based stationary electricity storage system consisting of an electrolyser, stationary hydrogen storage, and fuel cells.

Figure 38 and Figure 39 do not take into account the different energy efficiencies of the vehicles. The combination of the final energy costs with the fuel consumption of the associated different passenger vehicle provides the costs of final energy well-to-wheel. Figure 40 shows the costs of final energy for passenger vehicles in 2015.

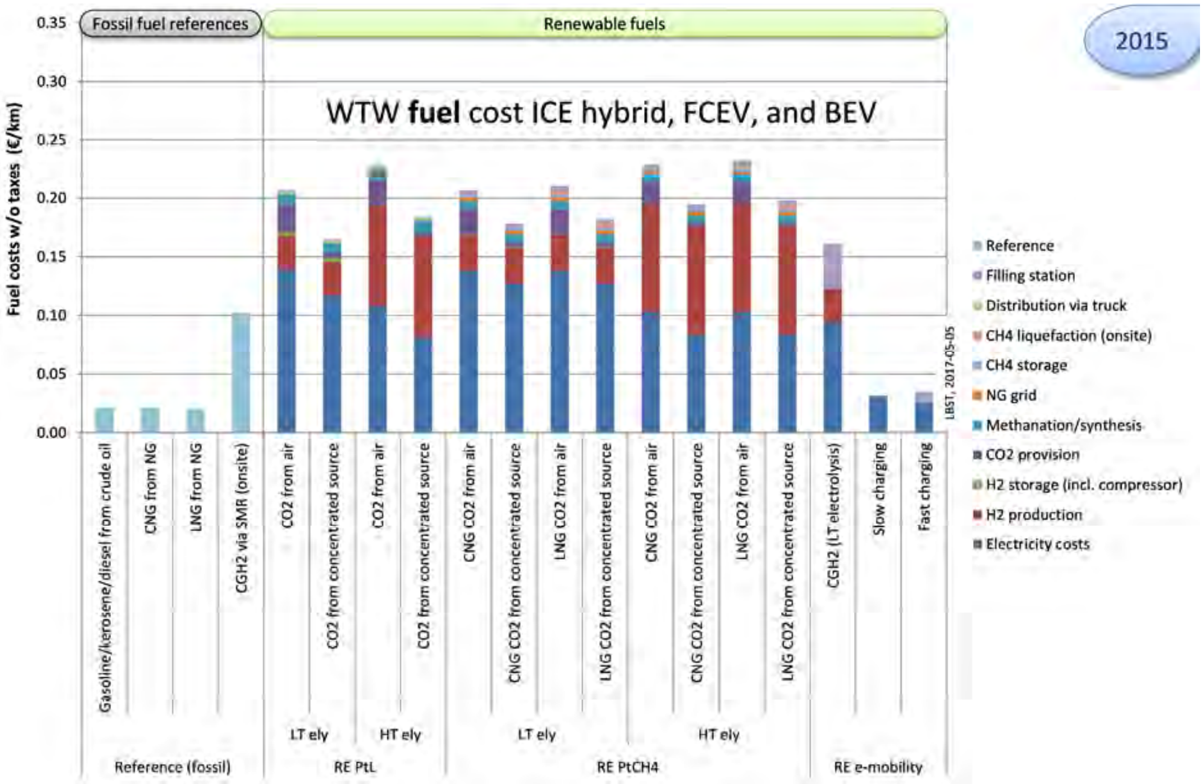


Figure 40: Fuel costs of passenger cars per km in 2015

The high efficiency of BEVs leads to low well-to-wheel final energy costs.

Figure 41 shows the costs of final energy for passenger vehicles in 2050.

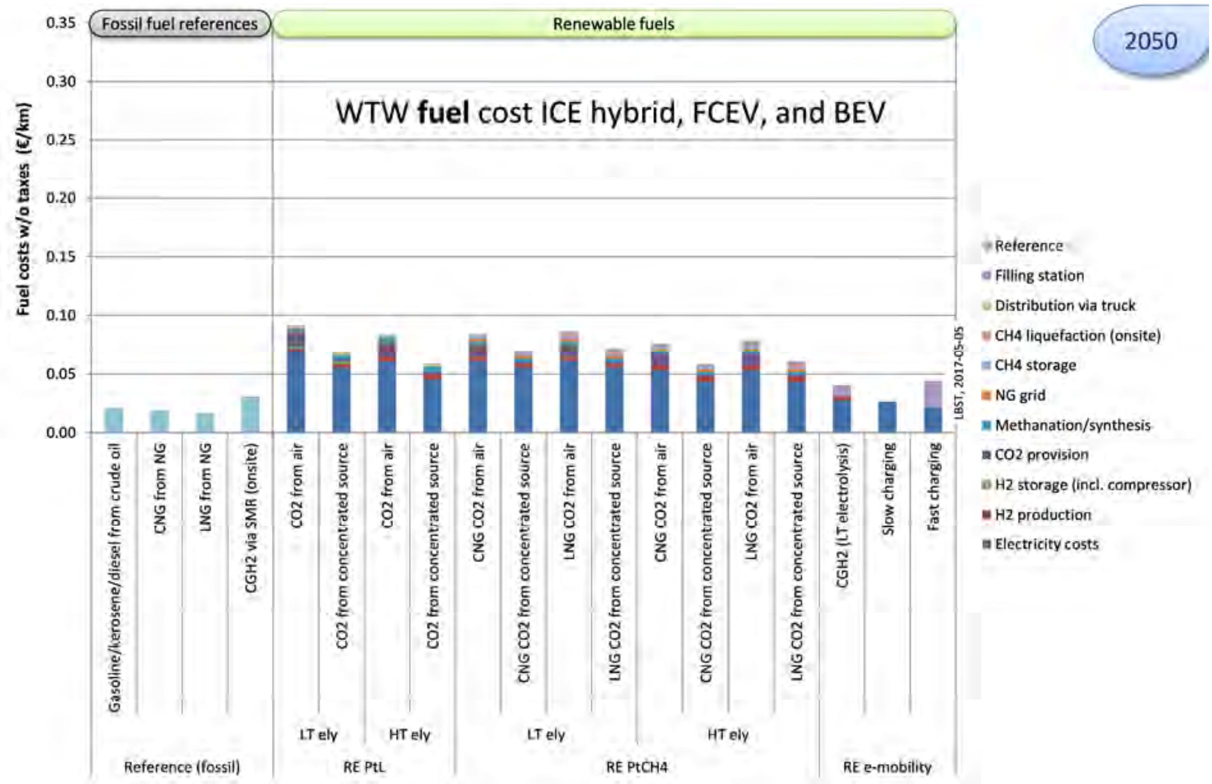


Figure 41: Fuel costs of passenger cars per km in 2050

The reduction in the required investment for renewable power plants and fuel production facilities reduces final energy supply costs and final energy costs per km driven. The high efficiency of BEVs makes up for the higher electricity supply costs for fast charging. Due to the high efficiency of FCEVs, the well-to-wheel fuel costs for hydrogen are lower than those for PtL and $PtCH_4$. The well-to-wheel final energy costs for CGH_2 from renewable electricity and for electricity for fast-charging BEVs are approximately the same.

5.6 Cost of producing renewable power and PtL fuel in the Middle East and North Africa

The Middle East and North Africa (MENA) region has attractive locations for wind and solar energy production. The global horizontal irradiance is about double that of Central Europe. The PVGIS tool from the European Commission's Joint Research Centre shows annual PV production of about 1,800 kWh per kW_{peak} for virtually every location in the region.

Attractive wind power production sites are limited to certain locations in the region. At those locations, however, the wind speeds are similar to the most attractive wind areas in Europe.

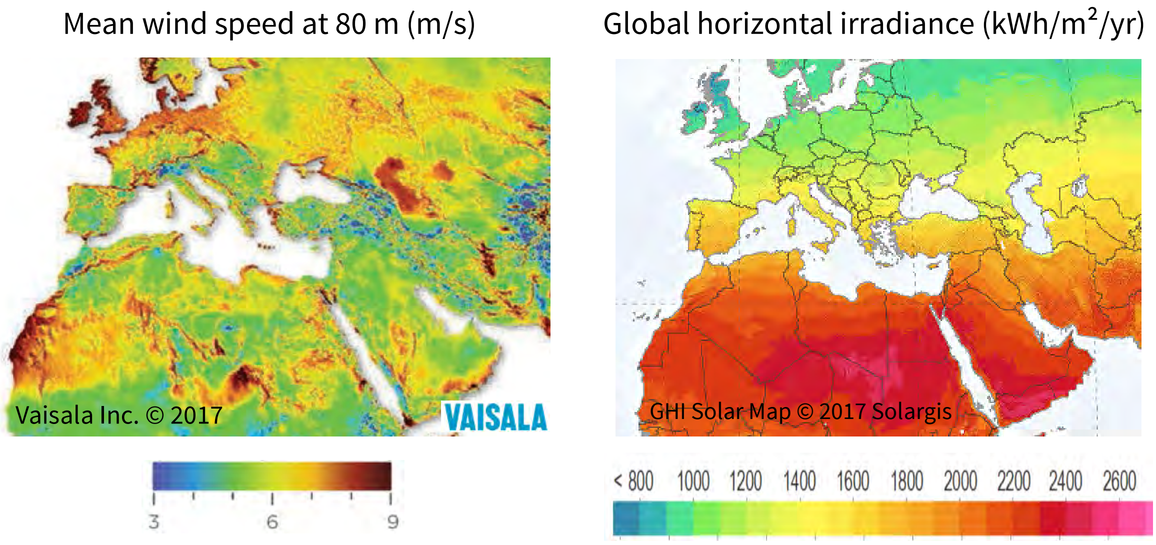


Figure 42: Mean wind speed and global horizontal irradiance in Europe and the MENA region

The most attractive locations ("sweet spots") for e-fuel plants (PtH_2, $PtCH_4$ and PtL) with dedicated renewable electricity combine both high wind speeds and high global horizontal irradiance. A source of concentrated renewable CO_2 could further increase the attractiveness of a location.

Detailed studies on renewable CO_2 sources in the MENA region are not available. However, the literature gives some indications about the very limited availability of biomass (e.g. Favero & Massetti, 2013). Al-Yousfi & Al-Karaghouli (2007) state: "Due to the semi-arid nature of MENA countries and the small amount of forest and agriculture residues, the biomass potential for MENA countries is available only from municipal waste." Thus, for the large-scale production of e-fuels, CO_2 will mainly have to be extracted from the atmosphere.

5.6.1 Power generation costs and equivalent full-load hours from hybrid PV/wind power plants in sweet spots

The costs for generating PtL, PtCH4 and PtH2 depend heavily on the price and availability of electricity. Figure 43 shows the number of annual equivalent full-load hours which can be achieved when operating a mix of wind turbines and PV systems at certain locations. For the MENA region, between 3,500 and 7,000 full-load hours can be achieved. High figures can be reached at locations with very good wind power potential.

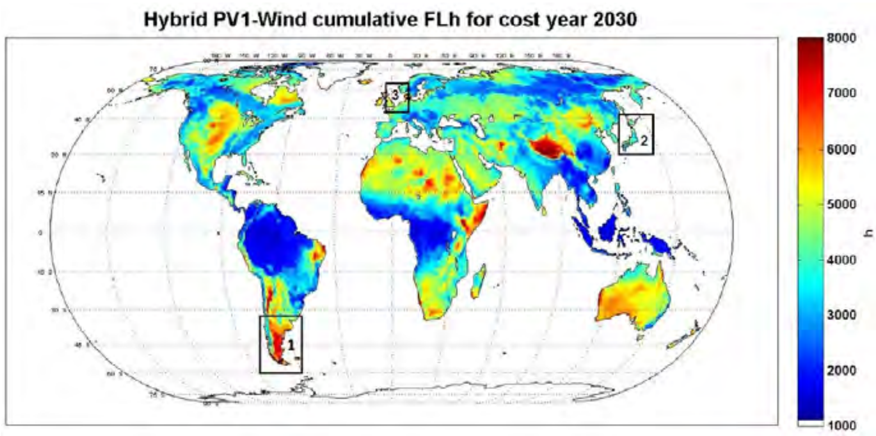


Figure 43: Achievable full-load hours with PV/wind hybrid generation (Fasihi et al., 2016a)

The costs of delivered electricity are shown in Figure 44. For the MENA region, costs vary between €30 and €60/MWh depending on the location. The lowest costs can be achieved in areas close to the coastline. In Fasihi et al. (2016a), e-fuel plants are situated close to the coast to minimise transport efforts for desalinated water (for electrolysis) and product fuel (for export). Thus, costs for electricity transmission are included in the figures presented.

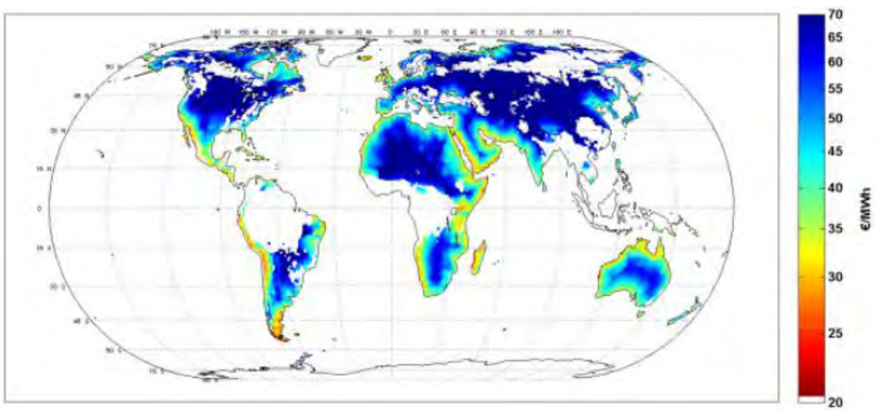


Figure 44: Levelised cost of delivered electricity, 2030 (Fasihi et al., 2016a)

Other sources arrive at similar costs for renewable electricity in the MENA region. In Aghahosseini et al. (2016), costs for renewable electricity in 2030 are between €37 and €61/MWh, depending on the scenario. Area-wide electricity trade (in the MENA region) and energy-sector coupling can achieve €37/MWh. If the country supplies itself, €61/MWh is possible. These costs include transport, curtailment, and some storage to provide a fully renewable electricity supply to the region.

5.6.2 $PtCH_4$ and PtL costs at German filling stations for imported e-fuels

The following figures show the fuel costs for producing power-to-methane and power-to-liquids outside Europe, including transport to and distribution within Europe. Fuel costs for the domestic production of electricity and e-fuels are detailed in Section 5.5.

Wind and PV electricity are complementary to a large extent. Periods of high wind speeds occur at times of low solar irradiation and vice versa. According to Fasihi et al. (2016a), many regions of the EU and other parts of the world can expect an equivalent full-load period of more than 4,000 hours per year for e-fuel plants. Some locations outside the EU can expect an equivalent full-load period of about 7,000 hours per year for e-fuel plants connected to wind turbines and PV systems. Fasihi et al. (2016b) indicates an equivalent full-load period of 6,840 hours per year. The present study assumes this figure for PtL and $PtCH_4$ plants for imported e-fuels.

According to Fasihi (2016), a hybrid PV/wind power plant with 5 GW of PV and 5 GW of wind power can supply 34,668 GWh of electricity per year. The investment has been put at €7.8 billion, based on €550/kW for a PV single-axis tracking system and €1,000/kW for a wind turbine. The investment seems to be rather optimistic, especially for plants in remote locations where components must travel long distances to reach the construction site. Low investments and high equivalent full-load periods may result in an overoptimistic estimation ("cherry picking"). Therefore, more conservative investment assumptions have been derived from other literature sources in order to be on the robust side.

The investment for the PV part is derived from a planned PV plant in Dubai with a capacity of 800 MW and an investment of US$800 million (€720 million) (Berkel, 2016). The investment for the wind turbine is assumed to be €1,400 per kW of rated power based on IWES (2015). As a result, the investment for the hybrid PV/wind power plant amounts to about €11.5 billion. The costs for operation, maintenance and repair are from IWES (2015) for wind power, and from ISE (2015b) for PV.

	Unit	Fasihi 2016, Fasihi et al. 2016b	This study
Capacity	GW	5 (PV) + 5 (wind)	5 (PV) + 5 (wind)
Electricity supplied to PtX plant	GWh/yr	34,668	34,668
Lifetime	yr	30	30
Investment	€ billion	7.8	11.5
Operation, maintenance, repair	-	1.75% of investment/yr	-
	€/(kWp*yr)	-	10 (PV) 64 (wind)
Interest rate			4%
Electricity costs	€/kWh_e	0.0229	0.0298

Table 52: Costs of electricity from hybrid PV/wind power plants in sweet spots

The e-fuel plant is located at the coast. The study assumes that high-voltage direct current (HVDC) transmission will be used to transport electricity from the PV system and wind turbine to the e-fuel plant over an average distance of 200 km. The cost data for HVDC transmission, including converters, are derived from Fasihi et al. (2016b), which results in about 0.004 kWh of electricity for electricity transport. As a result, the electricity costs at the e-fuel plant are about €0.034/kWh of electricity.

Figure 45 shows the costs for the supply of final energy well-to-tank in 2050, expressed in litres of diesel equivalent (LHV = 35.88 MJ/l = 9.97 kWh/l), if PtL and $PtCH_4$ fuels are imported. In the case of BEVs, the costs are well-to-receptacle.

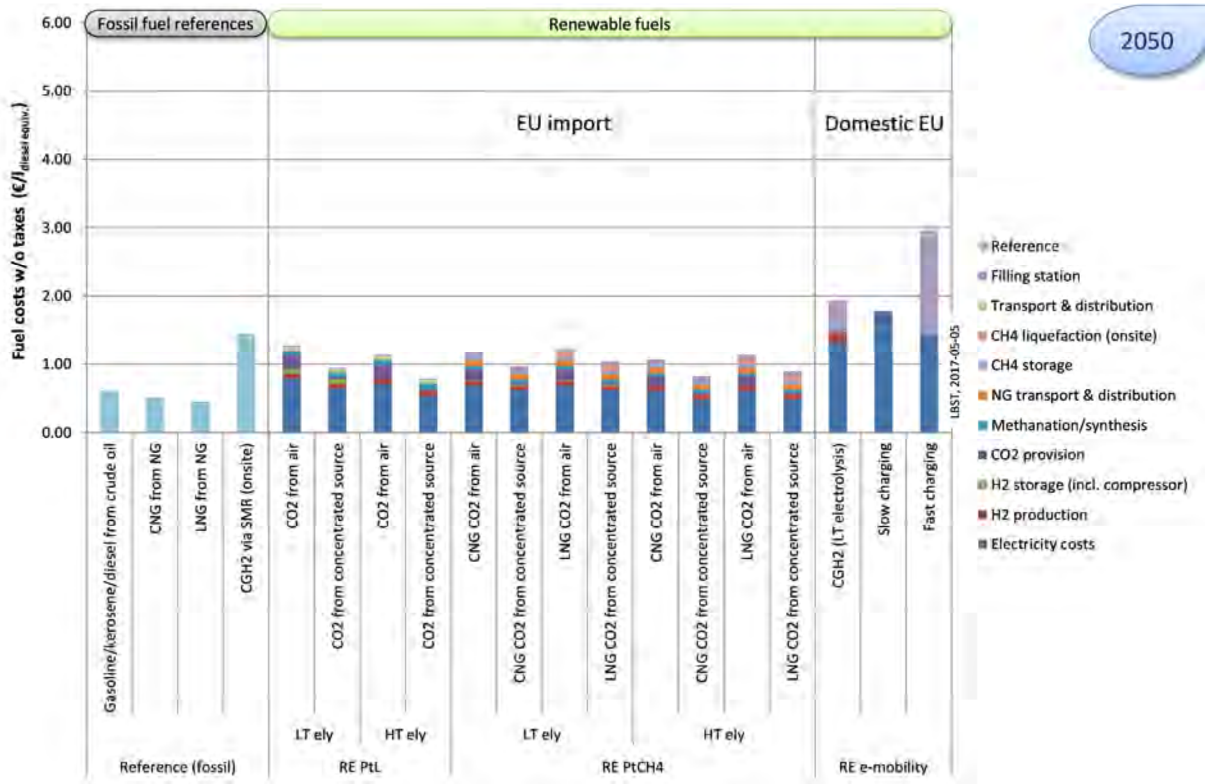


Figure 45: Costs for supplying imported transportation fuel per litre of diesel equivalent in 2050

Combining the final energy costs with the fuel consumption of the passenger vehicle gives the cost of final energy well-to-wheel. Figure 46 shows the costs of final energy for passenger vehicles in 2050 if PtL and $PtCH_4$ fuels are fully imported.

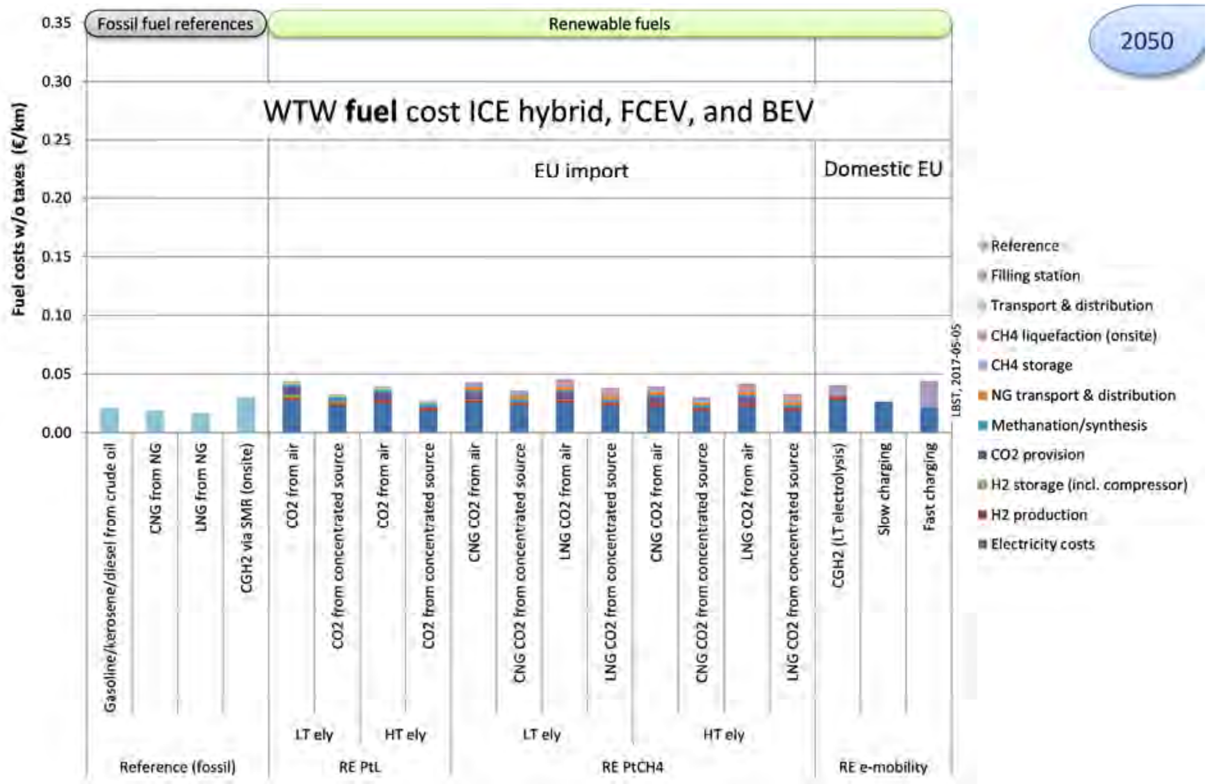


Figure 46: Fuel costs of passenger cars per km in 2050

As can be seen from Figure 46, the fuel costs in mobility converge if all PtL and PtCH4 fuels for EU transport were imported. In regions with high solar irradiation and/or wind, the availability of renewable CO_2 from biogenic sources may be rather scarce. E-fuel production pathways including CO_2 extraction from air are thus the more likely pathways for the e-fuels imported.

5.7 Excursus: Potential impacts of high shares of electric powertrains and e-fuels on car manufacturers and suppliers

A steep increase in both e-fuels and electrified powertrains (xEVs) will create major challenges within the value chain of all vehicle manufacturers, component suppliers, and energy suppliers. The changes expected for high numbers of xEVs mainly concern the following:

- Powertrains and components (batteries, fuel cell technology)
- Tank and fuel supply systems (batteries, gas storage)
- Chassis
- Power electronics and controls

On the one hand, complete electrification will reduce the complexity of powertrains and will make many components sufficient. One the other, with an increasing electrification of powertrains (hybrids, PHEVs, REEVs), the system and component base can be gradually transitioned to electrification. This transformation route is driven by local emissions aspects and efficiency considerations for cars and (light-)duty vehicles. These developments are not just driven by Europe, but also by the major global car markets of China, the US and (soon) India.

5.7.1 Challenge: New regulations in EU member states and abroad

During the past year, policymakers have made major decisions regarding the electrification of the car market. India, France and UK plan to restrict new registration of ICE to 2030, 2035 respectively 2040, and China will impose a New Electric Vehicle credit System from 2019. This trend, which is being driven by climate, air-quality and industrial concerns, looks set to create the future market framework for original equipment manufacturers (OEMs) and suppliers.

Markets such as China are of major importance for European OEMs, so it seems clear that there is a market and financial need to electrify fleets faster. On the one hand, this is very challenging as the competitive advantage of European OEMs could decrease due to lower profit margins and the added value of xEVs compared to ICEs. On the other hand, however, it offers an opportunity to become the market leader in high-quality electric vehicles. It could also provide scope for creating new markets for OEMs in the field of mobility management, which seems to be gaining in importance as the world moves towards higher levels of digitalization.

5.7.2 Challenge: Fast-changing technology within the value chain, and the "innovator's dilemma"

Rapid changes which tend to increase xEV numbers could result in losses within the value chain of the European automotive industry. Aspects that previously added value, such as motors and gears, will become less important in an electrified world. Therefore, other components will play a major role, such as:

- Drive axles with integrated electric motors
- Battery technology
- Electric controls

Therefore, the pace of the development of competitive electric powertrains is crucial. The challenge is to organise the transition of business cases in a way that avoids strong downshifts across all value chains. Therefore, a transition strategy is needed that aims to react as quickly as possible to the changing market situation, and uses current ICE revenues to invest in addressing changing market requirements in the future.

The following factors could be strategically important for automotive markets with a high share of xEVs:

- Battery technology is key to the way xEVs perform and what they cost. Solutions are needed for a variety of challenges, such as the battery capacity, charging cycle, long-term stability, availability of materials (and recycling), energy input during production, and the cost of production. For many manufacturers, the question of a ***make-or-buy strategy*** seems relevant today.

- xEVs seem to be a disruptive technology which will lead to major changes in most automotive processes. The European automotive industry must identify the advantages of a more electric or even fully electric future.
- What role can charging infrastructure and hydrogen filling stations play for business models, vehicle sales and customer loyalty?
- How will new production systems (which differ from those used in ICE production) affect the workforce? It seems plausible that shorter value chains will reduce the demand for low-skilled workers – especially if battery and fuel cell production is heavily automated. Therefore, rapid change within value chains will create a strong need for new labour qualifications and maybe less need for low-skilled work. The net effect is currently highly uncertain.

The above questions all concern the very fundamental question of how established automotive manufacturers and their tier suppliers can successfully make this transformation in an open process of changing sociotechnical systems. Since European car manufacturers were so successful in the past, they are now even more vulnerable to what Christensen (2016) calls the "innovator's dilemma".

5.8 Excursus: Renewable power demand from transport, and potential impacts/synergies in the energy sector (sector coupling)

Even in a scenario with a low demand for transportation fuels, the final energy demand from the transport sector is expected to be equal to today's electricity demand (which is mainly used for stationary applications). The future demand for electricity required to ensure the supply of transportation fuel is higher than today's electricity demand. After shifting from fossil fuels to e-fuels, the transport sector will become the main consumer of renewable electricity. Transport thus has an integral role to play (from the perspective of sector coupling) in balancing the electricity supply from (fluctuating) renewable sources and the electricity demand from transport. Figure 47 illustrates the power-balance challenge with today's electricity demand for stationary applications, possible future demand for transportation fuel, and a fluctuating electricity supply.

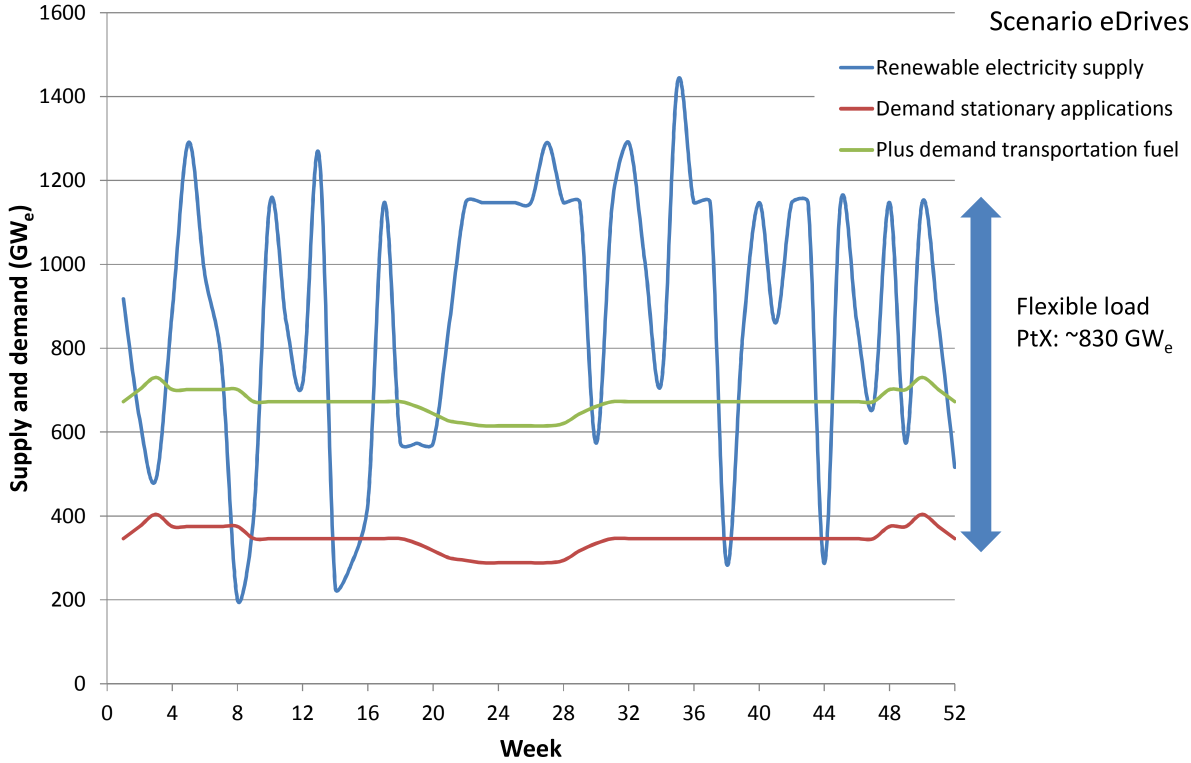


Figure 47: Sketch of current EU28 electricity demand for stationary applications, demand for transportation fuel, and fluctuating electricity supply (Source: LBST)

Due to the potentially high demand for power for transport, this sector could become a major provider of flexibility in the electricity system. In the scenario with the lowest demand for transportation fuel (eDrives), about 830 GW of flexible load from PtX plants could be provided for demand-response / demand-side management.

PtX plants for e-fuel production have the following characteristics:

- They are major electricity consumers
- They are flexible loads in the MW to GW range
- They are set to become key providers of grid services needed to stabilise grid operations, e.g. through demand-side management, electricity storage and voltage control

The type and extent of grid services needed is determined by the characteristics of electricity consumers in the transport sector (LBST/IFEU/IWES, 2016). A kind of trade-off between efficiency and the ability to integrate electricity from transport is of high importance. The more efficient the fuel/powertrain is, the stronger it is directly coupled to the electricity demand – and vice versa (see Figure 48).

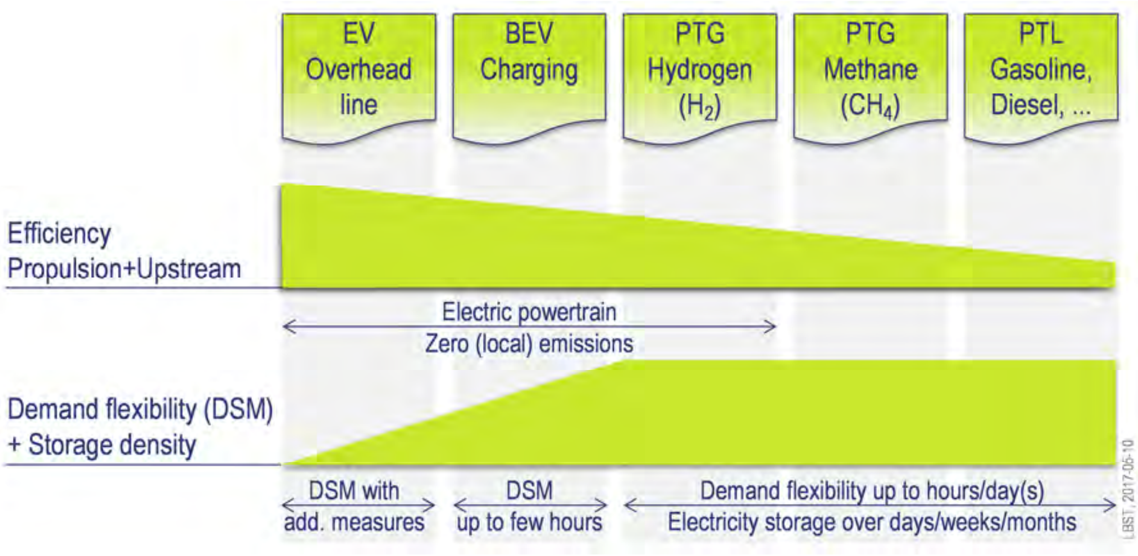


Figure 48: Trade-off between efficiency and renewable electricity integration (LBST/IFEU/IWES 2016)

The power needed to supply catenary vehicles via overhead lines and to supply fast charging for BEVs must be delivered instantaneously (or additional measures such stationary electricity storage must be in place). Fuels based on renewable electricity, such as power-to-hydrogen, power-to-methane and power-to-liquids can be stored for days, weeks and months. Electrolysers can largely be flexibly operated to follow renewable power supply. Chemical energy carriers thus facilitate renewable power integration. Power-to-hydrogen seems to be a particularly robust option, as it is a chemical energy carrier that is both produced and used efficiently. It also offers long-term energy storage and zero well-to-wheel emissions of GHGs and other pollutants.

The huge amount of renewable electricity needed for an energy transition in transport does not necessarily result in an equivalent increase in demand for electricity transportation capacities. For chemical energy carriers such as power-to-hydrogen, power-to-methane and power-to-liquids, the energy density and thus capacities for fuel storage, transport, and distribution infrastructures are significantly higher than with infrastructures for bulk electricity handling (see Figure 49).

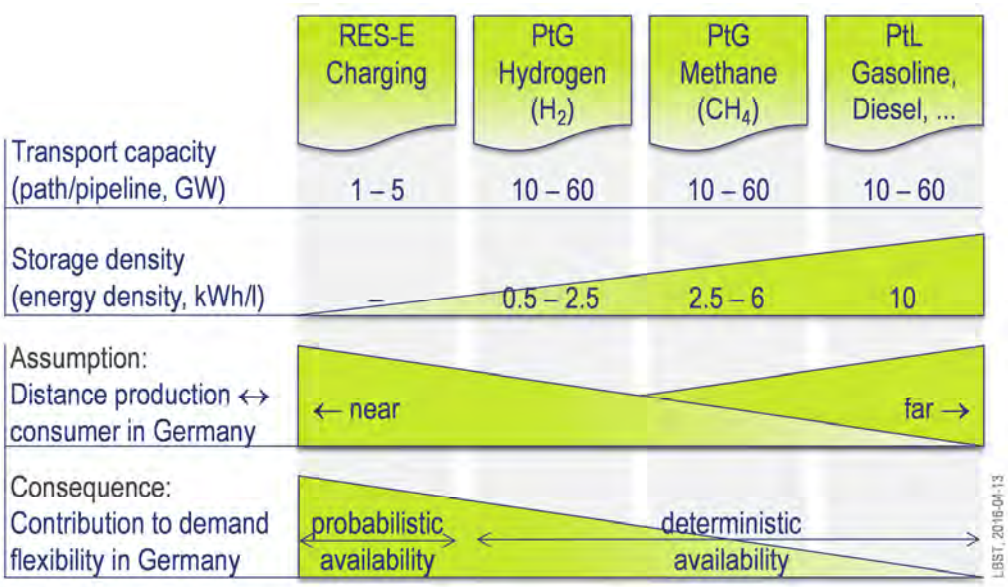


Figure 49: PtX handling characteristics provide options for domestic/international production (LBST/IFEU/IWES 2016)

Both demand flexibility and energy storage are key technology options for balancing fluctuating renewable electricity generation with electricity consumption in the various sectors, both ad-hoc (power balance) and long-term (energy balance).

Slow charging for BEVs offers a probabilistic potential for up/down regulation as it is subject to ad-hoc connectivity with the grid, the on-board battery's charge status, and consumer choice. In the case of PtX fuels, there is a planned availability of electrolyser demand response which can be scheduled in day-ahead planning. Naturally, the further away PtX production takes place (not necessarily in terms of geographical distance, but rather electrical connection), the less able it is to help stabilise the local grid.

High energy densities allow for bulk transport over long distances. Chemical energy carriers can be transported and distributed using high-capacity infrastructures such as pipelines, ships, trains and trucks. In the case of methane and liquid fuels, this infrastructure is already available both within Europe and internationally. In a changing energy landscape where renewable electricity is becoming a major energy pillar, operators of infrastructure for gases and liquids are now seeking to define what their role will be in an increasingly defossilised future energy system. Considering existing infrastructures, established supply chains and lower fuel production costs in renewable-energy-rich regions outside of Europe, it reasonable to assume that an increasing share of power-to-gas and power-to-liquid fuels could be imported into the EU.

Infrastructure and sector coupling

Increasing the use of renewable electricity in all sectors will require new renewable power plants and power-to-x conversion plants. In a sensitivity analysis, the requirement for additional energy infrastructure is explored using a worst-case scenario: Offshore wind power from northern Germany is assumed to be the sole source of transport energy consumed in southern Germany. The transport energy demand is taken from scenarios in LBST/IFEU/IWES (2016).

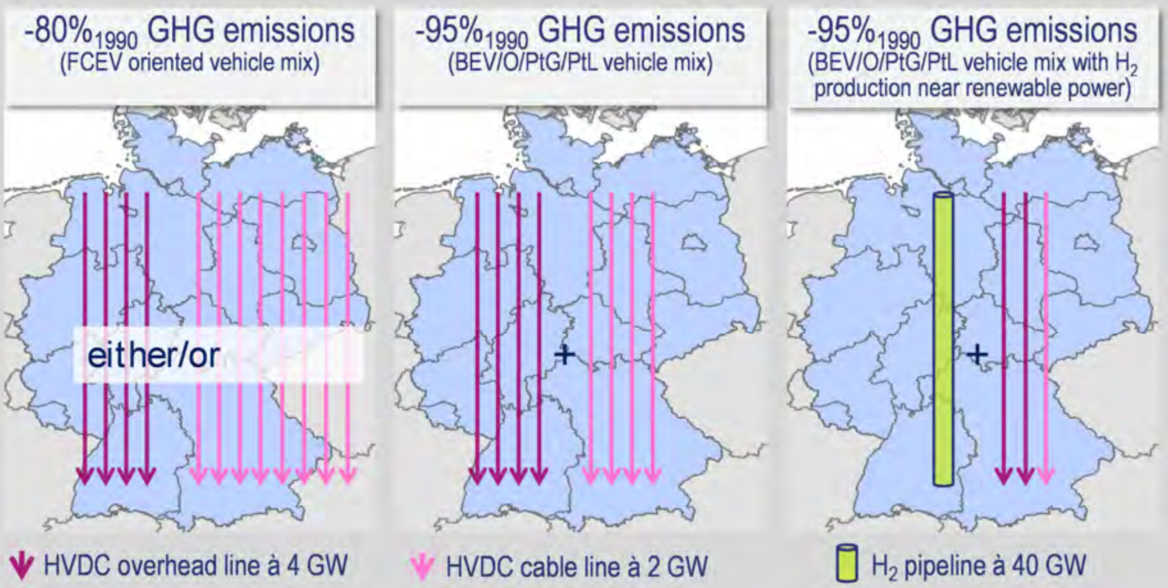


Figure 50: E-fuels reduce electricity transmission requirements; sensitivity analysis; example Germany (source: Raksha/Schmidt/ Bendig-Daniels (2016), based on scenarios derived from LBST/IFEU/IWES (2016))

The left diagram in Figure 50 shows that a worst-case scenario would either need four high-voltage direct-current (HVDC) overhead lines or eight HVDC cable lines to supply southern Germany with transport energy from offshore wind power. In the diagram in the centre, a higher GHG reduction (-95%$_{GHG\_1990}$ by 2050) and a vehicle mix with a variety of fuels/powertrains (BEVs, overhead lines, PtG, PtL) require the equivalent of four HVDC overhead lines and four cable lines. For the centre and left diagrams, it is assumed that the PtX fuel is produced in the consumption region. In the right diagram, the assumption is that only electricity for direct use in transport (BEVs, overhead lines) is transported to the south, and that hydrogen is produced in the north and transported via pipeline to the south. In this case, only three HVDC lines and one hydrogen pipeline are needed to supply energy for transport (the hydrogen pipeline capacity is not fully utilised).

This example shows how chemical energy carriers can significantly reduce grid infrastructure needs. Obviously, energy transport needs are also reduced by distributing renewable power generation more evenly.

6 Main findings

Using three scenarios with differing assumptions regarding the future development of powertrains and the fuel supply for all transport modes, this study analyses the need for future (renewable) energy to achieve an 80% or 95% reduction in GHG emissions in EU transport by 2050. In particular, the study examines the role of and need for fuels to achieve the GHG targets and the potential investment costs to guarantee a continuous energy supply for all transport modes. However, the study does not model the future development and interactions of the European electricity market. With regard to the challenges of peak loads and secure energy supply for BEVs/PHEVs/REEVs in an electricity market dominated by fluctuating renewable power, the authors assume local investments in the short term, and long-term storage to guarantee energy supply.

The following section summarises some of the main results of the study along with the factors that will influence the success of a European energy transition in transport: Renewable energy supply, energy efficiency, transport demand, and support for e-fuels.

6.1 Summary

- Reducing GHG emissions from EU transport to the level set out in the 2015 Paris Agreement will be extremely challenging and requires urgent action in terms of deploying renewable energy, improving transport efficiency, and optimising transport demand.
- Without e-fuel imports, the EU transport energy demand for renewable electricity in 2050 may exceed current EU electricity production by a factor of between 1.7 (in the eDrives/Low/95% scenario) and 3 (in the PtL/High/80% scenario).
- As well as increasing the number of electrified powertrains in road transport, e-fuels must play a major role in reducing GHG emissions from legacy road vehicles, aircraft and maritime transport.
- To greatly reduce GHG emissions from fuel supply, the rate of renewable power plant deployments and the build-up of e-fuel production capacities across Europe and abroad must increase as soon and as quickly as possible.
- The recent EU deployment rate for renewable energy use (in transport) is not sufficient. To reach appropriate volumes of renewables in the next decade, much more ambitious EU renewable energy targets and measures are needed.
- The technical renewable energy potential in the EU would be sufficient to cover current electricity and future transport energy demand. From a cost perspective, renewable fuel imports from abroad seem to be efficient, likely and necessary.
- Policymakers and industry should create an e-fuels roadmap that addresses technological development, (international) market scale-up, and efforts to set the international political agenda.

6.2 Main findings

Renewable energy demand

Irrespective of transport demand and the future pathway of driving technology the transport sector needs to achieve a much higher share of renewables. EU transport energy demand for renewable energies in 2050 will exceed current EU electricity production by a factor of between 1.7 and 3. The transport sector will thus become a major electricity market of the future. Aside from road transport, from 2030 onwards, the e-fuels demand from maritime transport and aviation will grow dramatically, resulting in a sharp increase in the demand for renewable electricity. Renewable energy must therefore be ramped up across Europe and abroad as soon and as quickly as possible. To reach an appropriate volume of renewables in at least ten years, more ambitious EU renewable energy targets are needed. At the same time, regulatory and financial instruments must be developed to incentivise investments in renewable energies, infrastructure and also e-fuels industrialisation.

Result of renewable electricity modelling (all transport modes)	Renewable electricity demand (TWh/yr)	
	2030	**2050**
PtL/High/-80%	3,253	8,459
PtL/Low/-95%	1,269	6,899
PtG/Low/-95%	768	5,582
eDrives/Low/-95%	593	4,666

Table 53: Results of renewable electricity modelling for all transport modes

The technical potential for renewable energy generation in the EU is large enough to cover the transport energy demand. But given that regions outside the EU have more favourable conditions for renewable power generation – being more sparsely populated, sunnier or windier – it will probably be more cost-effective to import e-fuels, at least to cover part of the demand.

Energy efficiency

Even in a world with a very high share of renewable power, energy efficiency will be of major importance in transport. Just as in the past, continuous powertrain efficiency improvements will also be needed in the future to offset energy demand from rising levels of freight and passenger transport. The study results also show that the scenarios with higher energy efficiency across all transport modes are more likely to achieve the EU's 2030 GHG reduction target. This is because they reduce the demand for fossil fuels (which still dominate the transport market in 2030) at a faster pace. A more energy-efficient vehicle fleet could therefore also help achieve the EU targets of reducing dependency on today's dominant fossil fuels and diversifying energy sources.

	PtL/High/-80%GHG	PtL/Low/-95%GHG	PtG/Low/-95%GHG	eDrives/Low/-95%GHG
ICE vehicle stocks in million				
ICE/hybrid cars	258	212	187	164
PHEV/REEV cars	13	10	25	29
ICE/hybrid trucks	31	40	35	34
Newly registered ICE vehicles in million				
ICE/hybrid cars	18.4	12.8	9.1	6.0
PHEV/REEV cars	1.7	1.2	3.3	3.8
ICE/hybrid trucks	2.3	3.7	2.7	2.4
Fuel demand from ICE vehicles (PJ/yr)				
E-fuels	2,871 (27%)	1,139 (12%)	648 (8%)	401 (5%)
Biofuels	376 (4%)	396 (4%)	385 (5%)	376 (5%)
Fossil fuels	7,287 (69%)	7,678 (83%)	7,410 (88%)	6,810 (90%)

Table 54: Results of achieving 2030 GHG targets for every scenario

Since the study results show an enormous renewable energy demand from future transport, energy efficiency will also play a key role in reducing total renewable energy build-up and therefore the costs of generating renewable energy and expanding the infrastructure. With regard to the upcoming competition for renewable generation locations, energy efficiency can contribute to minimise lower-performing production locations and to maintain and gain acceptance for further renewable energy installations.

Transport demand

The growing demand for transport has outweighed past progress in energy efficiency. It is now, and will be in the future, the main driver of additional GHG emissions. Scenarios with high transport growth show that the efforts and costs involved in achieving sufficient renewable energy for an 80% reduction in GHGs are much higher than for the scenarios with lower transport growth and a 95% GHG reduction. Therefore, the EU'S GHG reduction targets – especially the 2030 targets – can be achieved cost-effectively and more realistically with lower transport demand. EU and member state transport policies aligned with the 2030 and 2050 GHG targets could play a key role in successfully reducing GHGs in transport.

E-fuels demand

Irrespective of the future market share of BEVs, significant quantities of gaseous or liquefied fuels are needed to fulfil the energy demand of the existing vehicle fleet (legacy) in 2030 and beyond. Even in the eDrives scenario, more than 70% of fuel demand of all transport modes in 2050 comes from e-fuels, of which 70% are liquid fuels. Regarding the underlying assumptions, e-fuels will mainly be needed to meet the energy demand from heavy-duty vehicles and navigation (inland vessels and especially maritime transport) and aviation from 2030. However, as a side-effect, e-fuels can also support in the future a reliable energy supply of charging stations.

Conditions and framework for achieving the EU's GHG reduction targets

The study results show that we are unlikely to achieve the 2030 and 2050 GHG reduction targets by only focusing on changing one boundary condition in the transport or energy market. Instead, we should address different policy areas. A successful energy transition in transport will probably be more efficient and effective with an integrated approach that aims to increase renewable energy and energy efficiency, control transport demand, and guarantee grid stability.

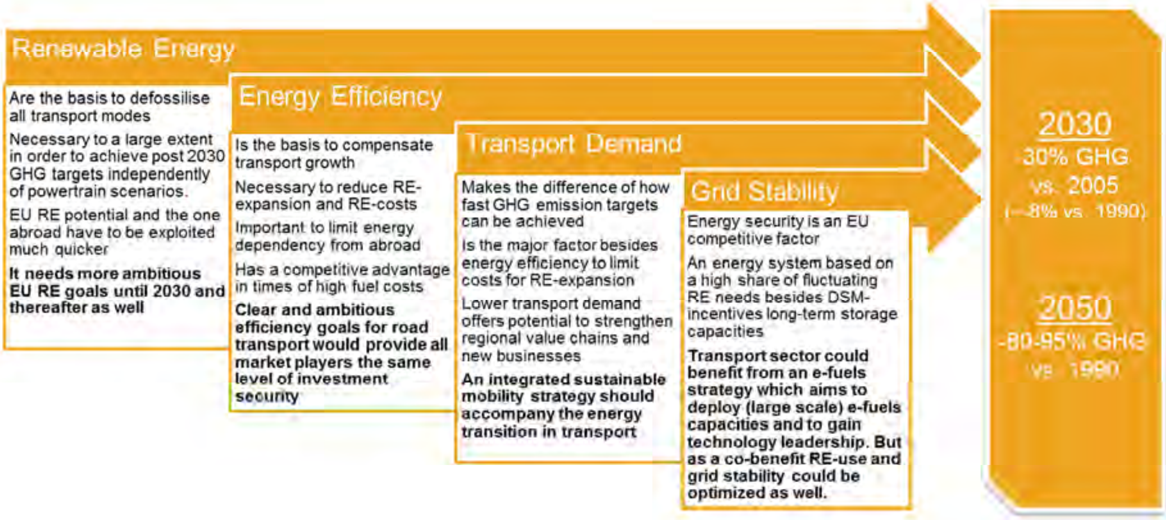


Figure 51: Pillars for a successful energy transition in transport

7 Discussion of the political framework: Next steps for ramping up the e-fuels market

7.1 Policy options for accelerating the market ramp-up of alternative powertrains

The current political and public discussion about reducing GHGs in transport focuses on regulating carbon emissions from passenger cars (see Section 2.3.3) and the market maturity of alternative fuels (particularly for BEVs). The study authors feel that this is not sufficient to substantially decrease energy demand and GHG emissions.

The main aspects that will drive more sustainable transport are as follows:

- Increase in renewable energies for transport (defossilisation)
- Increase of energy efficiency in all transport modes
- Transport behaviour of private and commercial consumers

This means that achieving the EU's GHG reduction targets is a shared responsibility between consumers, the producing industry and the energy sector. Policies must enable a transformation process and create a political framework that, in the best case, allows the most cost-efficient (technological) solutions to contribute to achieving the GHG target and gives consumers and industry a high degree of freedom. This will make it possible to foster innovation and competitiveness, and transfer them to other regions of the world to help reduce global GHG emissions. However, a political framework with low regulatory restrictions requires a binding commitment from industry that it will not continue with inefficient technologies and previously successful strategies. Equally, it must place a high level of responsibility on consumers to reduce GHGs – including by setting appropriate price signals. With its strategy for low-emission mobility, the European Commission stresses the polluter-pays principle and favours the development of stronger incentives to encourage investment in energy-efficiency solutions and renewable energies.

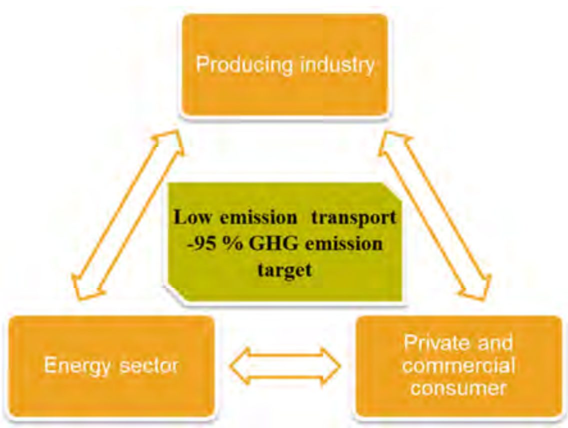


Figure 52: Responsibilities for achieving GHG targets in transport

Figure 53 shows actions which, on the one hand, are to be carried out by the three target groups to foster low-emission transport, and on the other, are instruments and measures that policymakers could use to support and incentivise consumers, the automotive industry and energy markets to achieve the GHG targets.

	Private and commercial Consumer	Producing Industry	Energy sector
Regulatory Policy	• Road tolls/charging systems • Driving permissions • (City) Environmental badges • Bans (driving, flying, …) • (Exemptions of) Restricted area access • Public environmental and pollutant standards	• Vehicle CO_2-regulation • Energy Efficiency standards • Environmental and Pollutant standards for industry • Vehicle market quota • Weight and dimension requirements (directives) • Tariff and non-tariff trade barriers	• Renewable Energy Quota • Fuel Quality Standards • Trade mechanism and detections systems/register • Levy/apportionment (*also financial Instrument) • Network charges (* also financial Instrument)
Tax and other financial instruments	• Vehicle Purchase Tax • Registration Tax (Benefits) • VAT • Ownership Tax (Benefits) • Commuter allowance • Energy Taxation • Company Car regulations/tax • Parking Fees/Rates	• Bonus-malus-systems	• Energy Tax exemption/reduction • Energy Tax differentiation
Research and public funding	• Vehicle Purchase Subsidies • Infrastructure Subsidies • Pilot project support • Research support	• Infrastructure Subsidies • Research support • Pilot project support • Investment support and credits	• (Downstream) Infrastructure Subsidies • Research support • Pilot project support • Investment support and credits • Grid development
Information and Commu-nication	• Vehicle Labeling • Product Labeling • Advertisement • Raising awareness • Education • Political strategies and public examples	• Vehicle Labeling • Product Labeling • Marketing/advertisement • Training and incentives for sales staff • Political Lobbying • Campaigns	• Political Lobbying • Campaigns

Figure 53: Instruments for fostering low-emission transport

In terms of GHG reductions, four main fields of policy instruments can be used to achieve the targets (see Figure 53). Each has advantages and disadvantages. In reality, probably all types of instruments have to be used in order to accelerate the energy transition in transport. If so, policymakers should be conscious of matching these instruments to avoid ineffectiveness and inefficiency. In terms of a common European strategy for GHG emissions reduction in transport, it would be desirable for the member states and the European Commission to be united in their choice of instruments to create a level playing field for all market players.

Taking a closer look at regulatory policy instruments which are already in place in transport markets in Europe or abroad shows that one instrument alone will most likely not be enough to overcome all environmental and climate challenges. To achieve the target of a more sustainable and low-emission transport sector, several complementary and non-discriminatory instruments are needed post-2020.

Figure 54 shows the selected target areas for policy action. It makes clear that CO_2 regulations for vehicles – of the kind currently in place in the EU, the US and China – focus on efficiency and GHG reduction. They do not directly address renewables and reducing other pollutants, but these are regulated in the RED and EU exhaust emissions standards. A well-to-wheel approach would – unlike tank-to-wheel regulation – also stress the renewable share, but not necessarily the energy efficiency of vehicles. An electric vehicle credit system (or quota) of the kind that will be introduced in 2019 in China will directly affect energy efficiency and local emissions, but only in the case of a balanced electricity mix or growing share of renewable electricity.

Instrument	Primary (secondary) policy objective				
	Energy efficiency	GHG reduction	Renewable share	Pollutant reduction	Tested / in use, e.g.
CO_2 (TtW) absolute	✓	✓	–	–	EU
CO_2 (TtW) %	✓	✓	–	–	–
GHG (WtT)	–	✓	(✓)	–	EU-FQD
GHG (WtW)	–	✓	(✓)	(✓)	–
RE Fuel Quota	–	(✓)	✓	–	EU-RED
RE Fuel Feed in Tariff	–	(✓)	✓	–	Transport none; but electricity market e.g. Germany
Electric Vehicle Quota	✓	(✓)	–	✓	California., China
Euro I - VI, ...	–	–	–	✓	EU, others

✓ Primary
(✓) Secondary / Subject to conditions
– No

Figure 54: Policy objectives of selected target areas for policy actions

Figure 55 shows that most target areas for policy actions would be a great help in achieving the targets of the scenarios in this study. However, a tank-to-wheel CO_2 regulation or electric vehicle quota would affect the PtG and eDrives scenario much more than the other scenarios because of the higher share of BEVs, FCEVs, PHEVs and REEVs. With regard to the increase of the share of renewables, an ambitious renewable energy quota (e.g. in the RED) would help all scenarios to achieve the 2030 and 2050 GHG reduction targets.

Instrument	Suitability of instruments to achieve GHG target in each scenario			
	PTL / HIGH / -80	PTL / LOW / -95	PTG / LOW / -95	eDrives / LOW / -95
CO_2 (TtW) absolute	(✓)	(✓)	✓	✓
CO_2 (TtW) %	(✓)	(✓)	✓	✓
GHG (WtT)	✓	✓	✓	✓
GHG (WtW)	✓	✓	✓	✓
RE Fuel Quota	✓	✓	✓	✓
RE Fuel Feed in Tariff	✓	✓	✓	✓
Electric Vehicle Quota	(✓)	(✓)	✓	✓
Euro I - VI, ...	–	–	–	–

✓ Primary
(✓) Secondary / Subject to conditions
– No

Figure 55: Suitability of the selected target areas for policy actions for each scenario

7.2 GHG reduction in practice: The importance of e-fuels

All study scenarios show that in the future, even in markets with a very high share of electrified vehicles, e-fuels are needed to cover energy demand from transport. This is mainly due to international aviation and maritime transport, but also to e-fuels supply for utility vehicles and passenger cars (ICEs, PHEVs, REEVs, FCEVs).

In principle, a direct use of renewable electricity in the most efficient powertrain is the most resource- and cost-effective way to reduce GHG emissions. However, if BEVs or vehicles that run on overhead lines are to be supplied with renewable energies, more efforts will be needed to match energy supply and demand However, a tank-to-wheel CO_2 regulation or electric vehicle quota would affect the PtG and eDrives scenario much more than the other scenarios because of the higher share of BEVs, FCEVs, PHEVs and REEVs. In practice, therefore, the energy transition in transport will be affected by a trade-off between the highest energy efficiency standards and the minimum requirements for ensuring a stable, renewable energy supply.

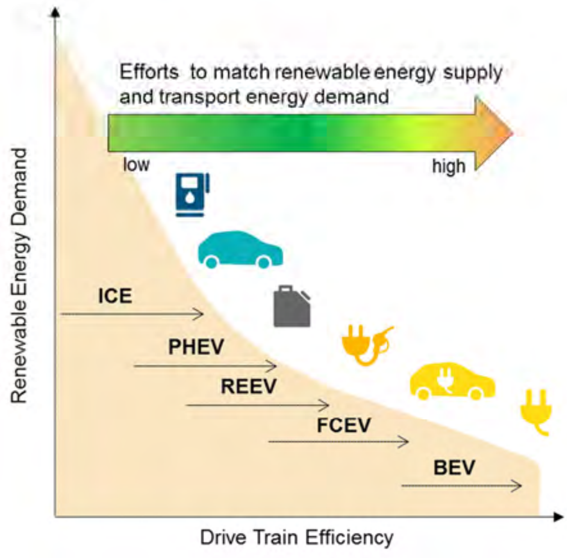


Figure 56: Interdependence of efficiency and renewable energy demand

Over the next three decades, the rate at which vehicles in maritime, aviation and road transport are replaced and renewed will vary significantly. While heavy-duty vehicles for long-haul transport are replaced in the first market every 2 to 4 years, aircraft and ships are often in the transport market for up to 40 years. This underlines the need to raise energy efficiency and increase the number of vehicles with alternative powertrains entering the market today. It also shows that there is a need for e-fuels to defossilise legacy vehicles. Thus, policy in the EU and its member states should prepare actions to simultaneously improve energy efficiency rates in transport and accelerate e-fuel deployment.

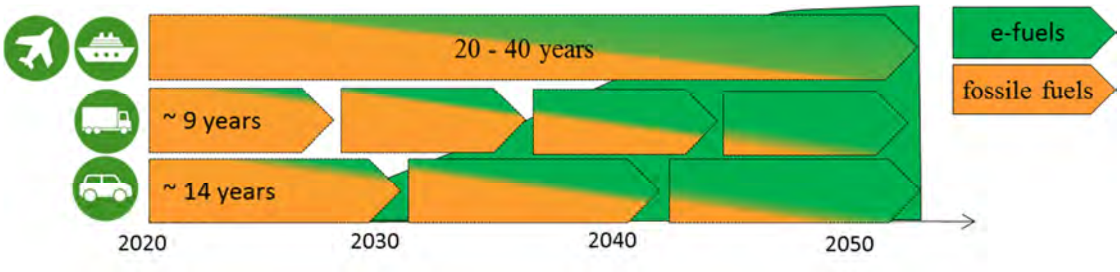


Figure 57: Lead-times in the vehicle market

From now until 2050, the need for e-fuels will steadily increase due to

- passenger car vehicle stock taking more than a decade to be replaced
- PHEV, REEV and FCEV needing e-fuels in the future to comply with GHG-emission targets
- ICE trucks and fuel cell trucks needing e-fuels from 2030 to a larger extent, and
- Long lead-times for changes in maritime and aviation propulsion technologies.

7.3 Strategies and instruments for e-fuels market ramp-up

As the results in Section 5.5 show, e-fuels today are not cost-competitive. They need larger scales, technological progress and lower renewable power costs to come closer to the current cost level of fossil fuels. This development will not be market-driven, but will require concerted efforts and actions from the transport industry, energy suppliers and policymakers.

Therefore, it is necessary to take action as soon as possible and create a framework that supports both the supply and demand of e-fuels. Table 55 shows the optional actions which would be needed to initiate an e-fuels market ramp-up. It also shows instruments which are needed for fundamental investment security.

It must be kept in mind that the impact of the instruments greatly depends on the specific design of each instrument as well as on the specific market design and political framework. Moreover, the effect of a single instrument often depends on other instruments being implemented. In principle, regulatory instruments with a clear perspective could be very effective in terms of e-fuels ramp-up and, partly, GHG emissions reduction. However, in certain market phases, they are probably more cost-intensive. Instruments such as guarantees, information exchange or (in some cases) tax incentives are less cost-intensive but will either not be especially effective, or only effective in combination with other instruments.

	Push e-fuels supply	Push e-fuels demand
Regulatory policy	• Reduced levy/apportionment for electricity used in e-fuel plants • Reduced network charges • Adapted dispenser, only useable for e-fuels • Standards concerning blending limits	• E-fuels quota • CO_2 regulation for vehicles (TtW, WtW) • Emissions reduction targets for all transport modes • Adapted filling spouts only for e-fuels • Standards concerning blending limits
Tax and other financial instruments	• Guarantees for foreign investments in e-fuels • Support for infrastructure development	• CO_2 taxation on fuels • CO_2-based vehicle tax
Research and public funding	• Funding for basic research • Co-funding for large-scale pilot projects • Support for plant location planning activities • Support for detection systems such as an e-fuels register	• Support for technical standardisation processes for e-fuels in vehicles • Support for detection systems such as an e-fuels register
Information, communication, coordination	• Support for building up an e-fuels platform • Support for international exchange and cooperation • Support for foreign policymakers • Capacity building in regional and foreign markets	• Support for building up an e-fuels platform • Support for international exchange and cooperation • Support for e-fuels in international committees (IMO, ICAO) • Awareness campaigns for e-fuels

Table 55: Instruments to increase e-fuels supply and demand

To deploy and scale up e-fuels at a European and global level, it seems to be crucial that important market players, policymakers and experts from the research sector cooperate and coordinate future activities within an e-fuels platform with shared strategic aims. This platform could, for example, support international exchange and knowledge transfer, as well as campaigns to raise awareness for e-fuels. Furthermore, it could also be responsible for dialogue processes regarding standardisation, funding schemes and political instruments, which are presented in Table 55.

The political support for e-fuels will also differ with the market development and market maturity levels of e-fuels. In the current phase, e-fuel technologies still have to be improved and optimised on a research level. But at the same time, there are already technology leaders in the market who need support to help them scale up production to gain experiences in these processes and reduce production costs. It also seems important to investigate the short- and long-term social impacts of e-fuels deployment – especially in foreign countries with better conditions for large-scale production, which may serve as exporters to supply to European demands. In the early market phase, it will be important to develop a market environment which leads to a steady rise in demand, while the phase of commercialisation policy should guarantee a stable framework for long-term investments in a competitive environment.

Figure 58: E-fuels market maturity and political support

What could be the next steps to raise awareness of e-fuels, highlight their importance for transport and create a foundation for market ramp-up?

From today's perspective, the political framework is not ambitious enough to create enough incentives to invest in large-scale production sites (or in regional, small or medium-sized sites). At the EU level, the RED could trigger such incentives and create new investments. With an increasing share of fluctuating renewables, it is becoming harder to match electricity demand and supply. In particular, when distribution network performance is low at the national and local level, it becomes important to find solutions using renewable energies instead of rewarding renewable power plant deactivation.

In order to foster strategic national and international agenda-setting, knowledge sharing and to create a common roadmap for e-fuels market development the authors recommend to establish an e-fuels platform with partners from the policy sphere and R&D sector. This platform would get the ball rolling for an e-fuels market ramp-up and for the continuous defossilisation of transport, and of other sectors such as industry and heating.

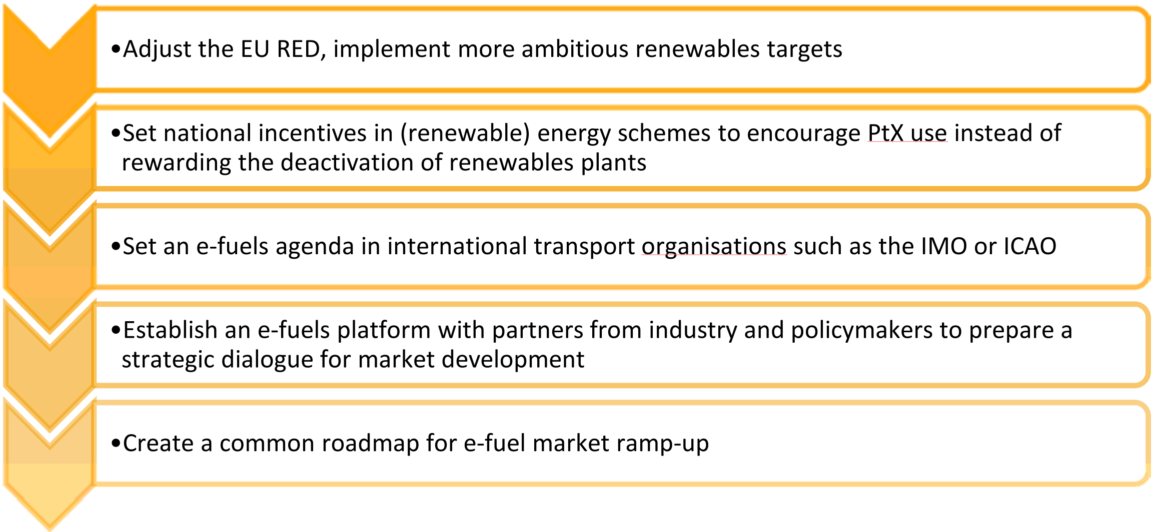


Figure 59: Next steps for e-fuel market ramp-up

7.4 Study results and recent EU policy framework

The policy framework is of major importance when it comes to accelerating innovation and new technologies, providing planning and investment security, increasing the share of renewables, and thus defossilising transport. The following section briefly describes whether current EU strategies and directions (set out in Section 2.3) will help achieve the EU's GHG reduction targets.

7.4.1 European strategy for low-emission mobility

The study results underpin the EU strategy for low-emission mobility, which aims to do the following:

- Improve the efficiency of the transport system
- Integrate low-emission alternative energy in transport
- Foster low- and zero-emissions vehicles

The study assessed the cost of transforming transport from a sector dependent on fossil fuels to one based on renewables. It shows that the transformation is challenging, but feasible. The EU strategy for low-emission mobility contains actions such as a road-charging system to help lower transport demand and promote low-emission vehicles. Distance-based charging systems can strengthen the user-pays principle. However, data handling could be an issue. Appropriately adapted company car tax seems to be a very effective instrument for the market integration of alternative and energy-efficient powertrains. Financing can be designed as cost-neutral because less efficient company cars pay a higher tax. Adapting fuel tax regimes in all EU countries would be an important step to increase the competitiveness of alternative fuels. Therefore, an ambitious, EU-wide minimum taxation for all fuels based on the specific CO_2 emissions would be preferable to avoid disadvantages for certain stakeholders facing international competition (such as logistics providers).

7.4.2 CO_2 regulation of passenger cars and light-duty vehicles: 2009/443/EG

Vehicle CO_2 regulation has proven so far to be the most important instrument in strengthening vehicle efficiency and reducing energy demand from transport. The study results show that future electricity demand for passenger car fuels can be around 1,200 TWh lower if the energy efficiency of passenger vehicles increases. The current regulation design lacks public confidence because measured values in the New European Driving Cycle and "on-road tests" have been steadily widening in recent years. A test which is closer to the potential reality of on-road fuel consumption (such as the Worldwide Harmonised Light Vehicles Test Procedure) can improve consumer confidence in OEMs and policymakers. Directive 2009/443/EG is currently a hybrid that combines efficiency and CO_2 regulation. It prefers vehicle efficiency (BEVs, H_2, REEVs, PHEVs), but it sets a CO_2 limit for OEMs.
For reasons of consistency, policymakers should consider two options for developing CO_2 regulation from 2020.

- Directive 2009/443/EG as an efficiency regulation could focus on efficiency topics only (and not CO_2); CO_2 matters could be dealt with in the RED and/or the greenhouse gas footprint regulations (FQD) for fuels.
- Directive 2009/443/EG as a CO_2 regulation is so far not fully consistent because it does not create any incentives for using fuels with a low carbon-intensity. To be consistent, in terms of a well-to-wheel approach, it could reward the traceable use of renewable energies in ICE powertrains – in addition to an ambitious renewable energy quota.

From a competition point of view, two main factors are important for implementing a successful regulation: time to prepare for the new regulation, and a level playing field to achieve the long-term binding targets. Post-2020 regulation should provide all market players with a competitive framework, including ambitious CO_2 targets that ensure planning and investment security, and contribute to the post-2030 GHG reduction pathway.

Even today, 2009/443/EG as a CO_2 regulation allows one to take the used fuel of each car into account – but only for BEVs, PHEVs and FCEVs. Providing an additional credit for e-fuels (e.g. ICE), if approved and implemented beyond the RED-quota into the fuel market, could be an option to incentivize e-fuels investments. However, the system is complex and creates more uncertainty for OEMs.

Taking a post-2020 CO_2 regulation into account with the option of crediting emissions from fuels (well-to-tank) and a higher market share of BEVs and PHEVs, CO_2 targets will not only depend on the technical powertrain efficiency potential, but also on the fuel's emissions. Therefore, stable and ambitious mid-term and long-term CO_2 targets are recommended to improve powertrain efficiency in ICEs and PHEVs/REEVs, to support the market integration of vehicles with alternative powertrains, to achieve the 2030 and post-2030 GHG targets, and to encourage e-fuel development.

7.4.3 The Renewable Energy Directive (RED)

Looking at the RED proposals currently under discussion, the aims seem to be too moderate to introduce sufficient amounts of renewable energies into transport considering the following:

- GHG reduction targets for transport in 2030/2050
- Legacy fuel demand from ICEs dominating passenger cars and light/heavy-duty vehicles in 2030

The study results show a high renewables demand at the very beginning of the 2030s to defossilise all transport modes. A quick and extensive build-up of renewable energies to the required degree across Europe and abroad seems unfeasible if the implementation is late. With regard to the transport energy demand analysed in the study, much more ambitious renewable targets are needed to ensure a steady build-up of renewable capacities from today.

Investments in such capacities need trust and planning security. This implies the following:

- Quotas for renewable fuels should be more ambitious in the RED proposal in the short-term, but also for the mid-term 2030 targets.
- The biofuel contribution to the post-2020 targets is uncertain. E-fuels could provide a robust alternative.
- Sustainability safeguards should be developed for e-fuels, i.e. robust, verifiable and reportable sustainability criteria. Biofuel certification schemes could be used as a basis for this.
- A stop-and-go policy, as seen with biofuels, should be avoided.

8 Tables

9 Figures

10 Literature

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11 Acronyms and abbreviations

BEV	Battery Electric Vehicle
BtL	Biomass-to-Liquid (fuel)
CCGT	Combined cycle gas turbine
CGH_2	Compressed Gaseous Hydrogen (fuel)
CH_4	Methane (fuel, greenhouse gas)
CNG	Compressed Natural Gas (fuel)
CO	Carbon monoxide (criteria pollutant)
CO_2	Carbon dioxide (PtX feedstock, greenhouse gas)
CO_{2eq}	Carbon dioxide equivalents (global warming potential)
dena	Deutsche Energie-Agentur
eDrives	Electric mobility oriented fuel/powertrain scenario (this study)
EV	Electric Vehicles, e.g. battery- or fuel cell-electric vehicles
FCEV	Fuel Cell Electric Vehicle
FT	Fischer-Tropsch (synthesis process)
G/D	Gasoline/Diesel
GHG	Greenhouse Gas
H_2	Hydrogen
HDV	Heavy-Duty Vehicle
HEV	Hybrid Electric Vehicle
HIGH	High transportation demand scenario (this study)
HVDC	High voltage direct current
ICE	Internal Combustion Engine
LBST	Ludwig-Bölkow-Systemtechnik
LCA	Life-Cycle Assessment (methodology to determine the environmental performance)
LDV	Light-duty vehicle
LH_2	Liquefied Hydrogen
LNG	Liquefied Natural Gas
LOW	Low transportation demand scenario (this study)
MEA	Monoethanolamine

MeOH	Methanol
MJ	Megajoule
Mtoe	Million tonnes oil-equivalents
N	Nitrogen
n. d. a.	no data available
NEDC	New European Driving Cycle
NG	Natural Gas (feedstock)
OHL	Overhead Lines, e.g. for trains
PHEV	Plug-in Hybrid Electric Vehicle
PJ	Petajoule (1000 PJ = 278 TWh)
pkm	person-kilometre (unit)
PM	Particulate Matter (criteria pollutant; often clustered into size classes: PM10, PM2.5)
$PtCH_4$	Power-to-methane (fuel)
PtG	Power-to-Gas (fuel), e.g. power-to-hydrogen (PtH_2), power-to-methane ($PtCH_4$)
PTG	Power-to-gas dominated fuel/powertrain scenario (this study)
PtH_2	Power-to-hydrogen (fuel)
PtL	Power-to-Liquids (fuel), e.g. PtL gasoline/kerosene/diesel, PtL methanol
PTL	Power-to-liquids dominated fuel/powertrain scenario (this study)
PtX	Power-to-anything, e.g. power-to-gas, power-to-liquids
PV	Photovoltaic
REEV	Range Extender Electric Vehicle
SOEC	Solid Oxide Electrolyser (high temperature)
tkm	tonne-kilometre (unit)
TtW	Tank-to-Wheel (assessment boundary)
TWh	Terawatthours (1000 TWh = 3600 PJ)
VDA	Verband der Automobilindustrie
WLTP	Worldwide harmonized Light vehicles Test Procedure
WtT	Well-to-Tank (assessment boundary)
WtW	Well-to-Wheel (assessment boundary)
yr	Year

12 Glossary

Term	Definition and use in this study
Decarbonisation	Progressing towards an increasingly sustainable world in which **hydro-carbon** fuels (methane, gasoline, kerosene, diesel, etc.) are substituted for **electricity and hydrogen**.
Defossilisation	Progressing towards an increasingly sustainable world in which **fossil** fuels (e.g. natural gas, oil, coal) are substituted for **renewable** energies (wind, solar, etc.).
e-fuels (well-to-tank)	Electricity-based fuels, i.e. **chemical** energy carriers whose primary energy basis is predominantly **electricity**, e.g. power-to-gas (H_2, CH_4) or power-to-liquids (methanol, gasoline, etc). Electricity for battery-electric vehicles (BEV) is typically not considered an 'e-fuel'.
electric vehicle (EV)	Electric vehicles may be differentiated into ▪ **full-electric** propulsion (i.e. without combustion engines), e.g. battery-electric (BEV) and fuel cell-electric (FCEV) vehicles; and ▪ **more-electric** propulsion (i.e. incorporating a combustion engine without mechanical coupling), e.g. range extender (REEV) and some plug-in hybrid (PHEV) vehicles.
Emissions	Emissions from motorized transportation e.g. include greenhouse gases, criteria pollutants, and noise emissions. In this study 'emissions' refers to **greenhouse gas emissions** (unless stated otherwise).
e-mobility (tank-to-wheel)	The term stands for 'electric mobility' and is used synonym with **electric propulsion** in this study. E-mobility is thus given if one or more electric motors are used in the powertrain for vehicle propulsion. See the definition of the term 'electric vehicle' for a differentiation between full- and more-electric systems for vehicle propulsion.
synthetic fuels (well-to-tank)	**Hydro-carbon** fuels produced via **catalytic synthesis** of hydrogen and carbons (CO, CO_2). Power-to-hydrogen does hence not belong to the group of synthetic fuels. Synthetic fuels may be derived from electricity, biomass and fossil sources, see e.g. e-fuels, biomass-to-liquids and gas-to-liquids, respectively.

13 ANNEX

13.1 Transport demand scenario assumptions

For the calculation of the demand of transportation fuel and the associated greenhouse gas emissions the total aviation passenger transport demand and the total shipping freight transport demand have been taken into account. 'Total' comprises both EU domestic and international transportation. In case of international aviation all EU-outgoing flights until first touch-down are considered.

Table 56 summarises the scenario assumptions for the **HIGH scenario passenger transport**.

- The data for the motorised individual transport for all years are taken from 'EU Reference Scenario 2016' (Capros et al., 2016).
- The data for public road transport for all years are taken from 'EU Reference Scenario 2016' (Capros et al., 2016).
- The data for city rail/tram transport (tram or subway) are included in short distance rail transport.
- The data for rail transport (short and long distance) for all years are taken from 'EU Reference Scenario 2016' (Capros et al., 2016).
- The disaggregation of rail transport in short and long distance is based on a constant share between 2010 and 2050 of 40:60 for the two modes (LBST assumption).
- The passenger air transport demand in EU-28 for all years is taken from EU Reference Scenario 2016 (Capros et al., 2016). The passenger air transport demand to all destinations is taken from scenario bau-a from 'EU Transport GHG: Routes to 2050' (Hill, Nikolas et al., 2012).

HIGH (billion pkm)	2015	2020	2030	2040	2050
Motorised individual transport	4,871	5,125	5,546	6,873	6,149
Bus	546	560	620	680	750
Short distance train	218	236	277	315	351
Long distance train	328	355	416	473	527
Aircraft	1,308	1,483	1,884	2,175	2,465
Hereof intra-EU28 aviation	*608*	*693*	*860*	*1,031*	*1,177*

Table 56: Passenger transport demand – scenario HIGH (EU28)

Table 57 summarises the scenario assumptions for the **HIGH scenario freight transport**.

- The scenario data for van and medium trucks for all years are taken from scenario bau-a from 'EU Transport: Routes to 2050' (Hill, Nikolas et al., 2012). The transport volume for heavy trucks is calculated from EU Reference Scenario 2016 (Capros et al., 2016), subtracting van and medium truck activities from totals.

- The data for rail transport for all years are taken from EU Reference Scenario 2016 (Capros et al., 2016)
- The data for inland water ways for all years are extrapolated by LBST, taking historical data between 1995 and 2015 as base line.
- The data for international shipping for all years are taken from scenario bau-a from 'EU Transport GHG: Routes to 2050' (Hill, Nikolas et al., 2012).

HIGH (billion tkm)	2015	2020	2030	2040	2050
Van	45	45	45	55	60
Medium truck	180	190	220	240	250
Heavy duty truck	1,690	1,874	2,181	2,377	2,525
Train	428	482	580	662	724
Inland ship	151	161	181	195	206
Maritime ship	11,070	12,650	15,000	17,350	19,500

Table 57: Freight transport demand – scenario HIGH (EU28)

Table 58 summarises the scenario assumptions for the **LOW scenario passenger transport**.

- The data for the motorised individual transport for all years are taken from scenario C5-b from 'EU Transport GHG: Routes to 2050' (Hill, Nikolas et al., 2012).
- The data for public road transport for all years are taken from scenario C5-b from 'EU Transport GHG: Routes to 2050' (Hill, Nikolas et al., 2012).
- The data for city rail transport (tram or subway) are neglected as their contribution to total transport energy demand is small and seen as negligible in the context of the present report.
- The data for rail transport (short and long distance) for all years are taken from scenario C5-b from 'EU Transport GHG: Routes to 2050' (Hill, Nikolas et al., 2012).
- The disaggregation of rail transport in short and long distance is based on a constant share between 2010 and 2050 of 40:60 for the two modes (LBST assumption).
- The passenger air transport demand for all years is taken from scenario C5-b from 'EU Transport GHG: Routes to 2050' (Hill, Nikolas et al., 2012). However, as real intra-EU28 data for 2015 with 608 billion pkm are far above the 2015 scenario data as seen in 2012 (397 billion pkm) the whole time series was adapted in order to smoothly approach the 2050 scenario data.

LOW (billion pkm)	2015	2020	2030	2040	2050
Motorized individual transport	4,871	4,850	4,550	4,250	4,080
Bus	546	581	665	776	879
Short distance train	218	249	322	419	514
Long distance train	328	374	483	629	771
Aircraft	1,308	1,310	1,300	1,290	1,274
Hereof intra-EU28 aviation	*608*	*600*	*550*	*500*	*452*

Table 58: Passenger transport demand – scenario LOW (EU28)

Table 59 summarizes the scenario assumptions for the **LOW scenario freight transport**. The data for road, rail, inland waterway and international shipping are taken from scenario C5-b from 'EU Transport: Routes to 2050' (Hill, Nikolas et al., 2012). The disaggregation into different truck classes is already performed within the original scenario.

LOW (billion tkm)	2010	2020	2030	2040	2050
Van	45	59	65	71	74,4
Medium truck	170	182.5	196	209	218
Heavy duty truck	1,594	1,744	1,819	1,855	1,824
Train	394	546	648	764	893
Inland ship	156	150	182	220	264
Maritime ship	11,070	11,303	12,282	14,542	16,792

Table 59: Freight transport demand – scenario LOW (EU28)

13.2 Vehicle parameter assumptions

In this chapter, vehicle parameters are documented, such as the annual driving mileage or number of passengers per trips. For vehicle fuel consumption of road vehicles, see chapter 4.4.

13.2.1 Passenger vehicles

The data shown in Table 60 are derived from the following considerations.

- **Motorized individual transport:** The travelled passenger-kilometres are converted into car-km by the average occupation number. Though the model is prepared to vary the occupation over time, for the present context it is appropriate to keep it fixed with 1.4 persons per vehicle. This matches with the empirical fuel consumption for 2015 when motorized cycles are not counted separately.
  Empirical data indicate annual driving volumes to be fuel-specific for gasoline and diesel powered cars

with 10,900 km and 20,300 km, respectively in Germany in 2015 (DIW, 2016, p.309). The car life-time varies correspondingly with about 14 years for gasoline and 9 years for diesel cars. However, in the present context – which has its focus on the switch from conventional fossil to alternative non-fossil fuels – the difference between gasoline and diesel is neglected. A 'unit car' is used with an average lifetime of 13.9 years and average driving volume of 14,000 km/a. The lifetime influences the substitution speed of elder cars to new (more efficient or alternative) cars and therefore alters the date during the intermediate status marginally. However, in the long-term, its influence is negligible. This justifies the use of a 'unit car' in favour of simplicity and model transparency.

- **Buses:** For public road transport a generic bus is assumed in this study as further complexity in terms of numbers of assumptions does not give added value to the results because of buses' overall low share in fuel demand (and correspondingly GHG emissions). Hence, the study authors refrained from a disaggregation into city busses and long distance busses. Instead, the average occupation number is calculated from published pkm and the number of busses with 23 passengers per vehicle. This number is kept constant over the whole period. Annual average driving volume is 43,000 km/bus. For studies analysing pollutant emissions and that do not assume pure electric powertrains (battery, fuel cell), disaggregation is recommended.
- **Short distance trains:** The typical train size was chosen from TR 423 and TR 430 which have 184, respectively 192 seats. Other multiple units used for short distance transport other than suburban trains typical have 120 seats. Though also larger trains (with locomotive) and smaller trains (diesel and motor coaches) exist, the typical average size of 120 seats is chosen. According to different editions of the environmental report of DB the average utilisation of short distance trains varied over the period 2000-2005 between19.5 – 21.8%. In (Knörr, W. et al., 2011) the occupancy for 2009 is indicated with 23.1% based on data from Deutsche Bahn AG (DB). According to statistics from the German Federal Statistical Agency, the utilisation rate of short distance rail transport increased between 2008 and 2013 continuous from 24.1% to 26.7%, when the number of passenger-km is divided by the number of seat-km (Genesis, 2015). For the calculations a rise of the utilisation rate from 23.1% in 2010 to 30% in 2050 is assumed. In contrast, inner city tramway has a lower utilisation rate of about 19% which almost did not change over the last decade. The annual driving volume for S-Bahn Munich in 2012 was about 85,000 km/train. For the scenarios a typical driving volume of 120,000 km/yr is chosen, justified by the fact that short distance trains include regional trains with much larger activity radius that- S-Bahn. The operation time is estimated with 30 years. For the scenario calculation a share of 80% of Pkm are performed with electrical driven railcars (multiple units), 20% by diesel fuelled rail cars.
- **Long distance trains:** The typical vehicle size is a unit of the German 'Intercity-Express' (ICE) which is a high speed train similar as the French 'train à grande vitesse' (TGV). Actually DB operates three types of ICE (BR 403, BR 406, BR 407). Based on published statistics the average train-unit has a capacity of about 430 seats (calculation based on (DB, 2014)). About 70% of long distance transport is performed by ICE. The occupancy between 2000 and 2004 increased from 40.2 to 42.6%, according to various editions of DB Environmental reports. In (Knörr, W. et al, 2011) for 2009 the occupancy is indicated with 48.6% also based on data from the DB. For the scenario calculations occupancy slightly increasing from 45% (2015) to 48.6% (2050) is chosen. The annual driving volume is estimated with 200,000 km/train. The operation train is estimated with 25 years.

- **Passenger air transport:** The average aircraft size at Deutsche Lufthansa between 2011 and 2013 was 170 seats. This was chosen for the calculations. As the fuel consumption per aircraft was calculated from the specific fuel consumption per passenger-km, the aircraft size must be kept constant over the whole scenario period in order to avoid double counting of fuel improvements. According to Lufthansa, the utilisation rate in 2013 was 82.3% (LH, 2014). For the calculations the utilisation rate of 82% was kept constant until 2050. The annual driving volume is calculated from (LH, 2014) with 2.5 million km/aircraft. This is almost identical with updated report for the year 2015 (LH, 2016). The operation time is estimated with 15 years.

13.2.2 Freight vehicles

The data shown in Table 61 are derived from the following considerations. The detailed analysis was primarily based on German statistical data as these are available at a very detailed level. Finally, the data were adapted in order to meet aggregated statistical data for European transport energy consumption from past years.

- **Trucks <3.5t:** There exist no reliable data on the transport volume of commercial small trucks with less than 3.5 tons total weight. In many statistics they are neglected or summarized under passenger cars and vans. But as these offer the largest potential for alternative fuel strategies, they are discussed separately in these scenario calculations. These small trucks are by far the largest group with almost 2.1 million registered vehicles in Germany at end 2013 – a share of 80% of all trucks (KBA, 2014). According to (DIW, 2005) in 2002 their annual driving volume was between 16,000-21,000 km. However the old classification scheme was for trucks < 3.5 t load, while the present class restriction is 3.5 t total weight. (Zimmer et al., 2009) chose 19,489 km annual driving range for this class. For the present calculation load capacity and the share of empty driving volume was adapted in order to meet statistical fuel consumption data for 2010 and 2015. The average operation time is chosen as 12 years, which is about 50% above the average age of the fleet (Own calculation based on statistics from (KBA, 2014)).
- **Trucks 3.5-12t:** From (KBA, 2013) follows that the total driving volume of trucks <12t in 2013 was 1.68 billion vehicle-km with about 50% usage of load capacity and about 0.46 billion deadload-kilometre in Germany. The total transport volume was about 4.47 billion tkm. From these date the average load is calculated with 2.7 t/vehicle.
  Combined with registration statistics from (KBA, 2014) (334,883 vehicles between 3.5-12t) average annual driving volume is calculated with about 6,500 km/yr. Restricting the analysis on trucks between 7.5-12 t increases the driving volume to about 25,000 km/yr. (Zimmer et al., 2009) chose the annual average driving volume for trucks between 3.5-7.5t with 22,458 km and for trucks 7.5-12t with 32,744 km. This gives a weighted average driving volume of 24,420 km, which is close to our number. However, in order to adapt the these German statistics data to realistic fuel consumption for Europe for the years 2010 and 2015, the average load of 2 t/vehicle and empty trip-km of 30% are chosen. The operation time is chosen with 15 years, which is about 50% above average age of the fleet. The assumptions are based on own calculations using statistics from (KBA, 2014).
- **Trucks >12t and trailer trucks:** In 2013 the trucks >12t without trailer trucks had a driving volume of 8.21 billion vehicle km at 47% load and additional 2 billion deadload-km. With 84.4 billion tkm this results in an average load of 10.1 t for the 194,450 registered trucks. From these data the average annual driving volume

is calculated with 42,700 km.
Trailer trucks exhibited 13 billion vehicle-km with load and 3.57 billion deadload-km. From 216 billion tkm the average load of 16.7 t is calculated. The 181,998 registered trailer truck engines therefore have an average driving volume of 91,000 km/yr.
As the fuel consumption and driving patterns of large trucks and trailer trucks are pretty close, they are combined to one group. The thus calculated average load of 13.5t, 10% dead-load km and average driving volume of 75,000 km/yr, again, are adapted to European fuel statistics. Finally this resulted in an average load of 12.5 t, 20% dead-load km and 75,000 km/yr average driving volume. The average operation time is chosen with 8 years, which derived from average age of large trucks of 6.8 years and of trailer trucks with 4.4 years. The assumptions are based on own calculations using statistics from (KBA, 2014).

- **Trains:** From (DB, 2013) the typical load per train in 2013 was 531.9 t/train, about 2% more than in 2012. For the calculations 532 t/train are chosen. As the specific energy consumption per tkm already includes deadload-km, these are not explicitly used. The annual average driving volume per train is estimated with 100,000 km/yr. The operation time with 39 years, assumed from the average age of cargo locomotives of about 26 years (Planco, 2007).
- **Inland barges:** The average capacity of cargo barges is calculated from the number of ships, lighters and dumb barges with 1290 tons (BVB, 2013/14). From the typical return load of 13 different routes and cargo types (Planco, 2007) an average return load of 60% can be calculated which is translated into 20% of empty trips (dead-load-km). The total ship driving volume with load is calculated from 17.7 billion tkm of German inland barges and the total load capacity (1290 tons) as 13.7 million ship-km. The division by the number of registered motor barges (1253 motor barges) results in the average driving volume of 10,900 km per ship. The addition of 20% empty trips gives the estimate for the total annual driving volume of 13,700 km/yr per motor barge. The average age of the fleet is about 52 years (Planco, 2007). For the calculation 60 years of average operation age of motor barges is used.
- **Oversea freight vessels:** The typical load capacity is 53,000 tons for oil tankers and 32,000 tons for other freight ships (own calculation with data from (RMT, 2014)). For the calculation an average load of 32,000 t is assumed. The deadload-km are estimated with 40%, as by far the largest transport volume are ores (pred. iron ore) and fuels (coal and mineral oil) which have an empty-return-trip share close to 50%. The annual driving volume is estimated with 145,000 km (derived from 20 km/h average speed at 300 days, while 65 days are calculated for docking and loading/unloading). The average age of all ships in industrialized countries is about 9 years. The average age of demolished ships is close to 30 years which is chosen as typical operation time (RMT, 2014).

13.3 Fleet modelling assumptions

13.3.1 Passenger vehicle fleets

The following assumptions are used in the transport fleet model for calculating the number of new vehicles required to satisfy passenger transport demand (pkm):

- **Passenger car:** The passenger car-km are calculated from passenger-km with a fixed car occupation of 1.4 passengers/car.

The number of required passenger cars is calculated from total car-km. The assumed annual driving range is 14,000 km/car/yr. This driving range is kept constant for all scenarios. There is no distinction between different drive-trains or fuel-systems. The difference between last year's fleet minus abandoned cars and required cars is calculated as number of newly registered cars. This driving range is kept constant in all scenarios and for all bus driving systems. The assumed average car utilisation time is 13.9 years.

- **Bus:** The bus-km are calculated from passenger-km with a fixed car occupation of 23 passengers/car. The assumed annual driving range is 43,000 km/bus/yr. The assumed average bus utilisation time is 14 years.
- **Regional train:** The train-km for short-distance regional trains are calculated with a fixed occupation capacity of 120 passengers/train. The utilized capacity was 23% in 2010, and 23% between 2020 and 2050. The assumed annual driving range is 120,000 km/train/yr. The assumed average short-distance train utilisation time is 30 years.
- **Long-distance train:** The train-km for long-distance trains are calculated with a fixed occupation capacity of 430 passengers/trans. The utilised capacity was 48.6% for all years. The assumed annual driving range is 200,000 km/train/yr. The assumed average long-distance train utilisation time is 25 years.
- **Aircraft:** The aircraft-km are calculated with a fixed occupation capacity of 170 seats/aircraft. In order to avoid double counting, the average aircraft size is kept constant over time as fuel efficiency improvements – though expressed in MJ/aircraft – originally are based on fuel consumption per pkm, but translated into fuel consumption per aircraft for a fixed aircraft size and occupation. The utilized capacity was 82% between 2015 and 2050. The assumed annual driving range is 2.5 million km/aircraft. The assumed average aircraft utilisation time is 15 years.

13.3.2 Freight vehicle fleets

The following assumptions are used in the transport fleet model for calculating the number of new vehicles required to satisfy freight transport demand (tkm):

- **Van <3.5t:** The vehicle-km are calculated from capacity utilisation of 0.28 t/van and 35% idle driving-km. The assumed annual driving range is 10,000 km/van/yr. The assumed average van utilisation time is 12 years.
- **Truck 3.5-12t:** The vehicle-km are calculated from capacity utilisation of 2 t/truck and 30% idle driving-km. The assumed annual driving range is 25,000 km/truck/yr. The assumed average van utilisation time is 15 years.
- **Truck <12t:** The vehicle-km are calculated from capacity utilisation of 12.5 t/truck and 20% idle driving-km. The assumed annual driving range is 75,000 km/truck/yr. The assumed average van utilisation time is 10 years.
- **Train:** The train-km are calculated from average capacity utilisation of 532 t/train. The assumed annual driving range is 100,000 km/train/yr. The assumed average train utilisation time is 39 years.
- **Inland vessel:** The vessel-km are calculated from capacity utilisation of 1290 t/vessel and 20% idle shipping-km. The assumed annual shipping range is 13,700 km/vessel/yr. The assumed average vessel utilisation time is 60 years.

- **Sea vessel:** The vessel-km are calculated from capacity utilisation of 35,000 t/vessel and 40% idle shipping-km. The assumed annual shipping range is 145,000 km/vessel/yr. The assumed average vessel utilisation time is 30 years.

13.4 Fleet modelling results

In the following tables, the modelled fleet of cars and trucks are depicted in absolute vehicle numbers for the four scenario routes.

13.4.1 BAU-moderate (PTL / HIGH / -80%$_{GHG}$)

BAU-mod Car stock (million units)	2015	2020	2030	2040	2050
G/D ICE	244	247	222	176	132.8
CH_4 ICE	0.7	1.3	1.6	0.1	0.0
G/D HEV	2.6	8.0	33.1	66.1	89.1
CH_4 HEV	0.0	0.0	1.2	1.7	0.1
G/D PHEV/REEV	0.6	2.2	12.5	28.0	42.0
CH_4 PHEV/REEV	0.0	0.0	0.1	1.2	3.0
BEV	0.2	1.7	9.0	19.4	33.8
FCEV	0.1	0.9	3.9	7.1	12.9
TOTAL	**248.5**	**261.5**	**283.0**	**299.6**	**313.7**

Table 60: Passenger car fleet composition for BAU-moderate (PTL / HIGH / -80%$_{GHG}$)

BAU-mod Truck stock (million units)	**2015**	**2020**	**2030**	**2040**	**2050**
Truck <3.5 t	**24.7**	**24.7**	**24.7**	**30.2**	**33.0**
Diesel	24.7	24.5	22.2	22.8	21.5
BEV	0.0	0.1	1.3	3.7	5.7
FCEV	0.0	0.1	1.3	3.7	5.7
Truck 3.5-12 t	**5.1**	**5.4**	**6.3**	**6.9**	**7.1**
Diesel	5.1	5.4	5.9	5.6	5.1
Methane	0.0	0.0	0.2	0.4	0.8
BEV	0.0	0.0	0.3	0.8	1.2
Truck >12 t	**2.3**	**2.5**	**2.9**	**3.2**	**3.4**
Diesel	2.2	2.5	2.8	2.9	2.9
Methane	0.0	0.0	0.1	0.2	0.4
FCEV	0.0	0.0	0.0	0.0	0.0
TOTAL	**32.1**	**32.7**	**33.9**	**40.2**	**43.5**

Table 61: Truck fleet composition BAU-moderate (PTL / HIGH / -80%$_{GHG}$)

13.4.2 BAU-ambition (PTL / LOW / -95%$_{GHG}$)

BAU-amb Car stock (million units)	2015	2020	2030	2040	2050
G/D ICE	244	235	182	128	88.9
CH_4 ICE	0.7	1.2	1.3	0.1	0.0
G/D HEV	2.6	7.2	26.9	47.3	59.0
CH_4 HEV	0.0	0.0	1.0	1.2	0.1
G/D PHEV/REEV	0.6	2.0	10.1	20.0	27.6
CH_4 PHEV/REEV	0.0	0.0	0.0	0.9	2.0
BEV	0.2	1.5	7.3	13.8	22.1
FCEV	0.1	0.7	3.2	5.1	8.4
TOTAL	**248.5**	**247.4**	**232.1**	**216.8**	**208.2**

Table 62: Passenger car fleet composition for BAU-ambition (PTL / LOW / -95%$_{GHG}$)

BAU-amb Truck stock (million units)	**2015**	**2020**	**2030**	**2040**	**2050**
Truck <3.5 t	**24.7**	**32.4**	**35.9**	**38.9**	**40.9**
Diesel	24.7	32.0	32.1	29.5	26.9
BEV	0.0	0.2	1.9	4.7	7.0
FCEV	0.0	0.2	1.9	4.7	7.0
Truck 3.5-12 t	**5.1**	**5.2**	**5.6**	**6.0**	**6.2**
Diesel	5.1	5.2	5.2	4.9	4.5
Methane	0.0	0.0	0.1	0.4	0.7
BEV	0.0	0.0	0.2	0.7	1.0
Truck >12 t	**2.3**	**2.3**	**2.4**	**2.5**	**2.4**
Diesel	2.2	2.3	2.4	2.3	2.1
Methane	0.0	0.0	0.1	0.2	0.3
FCEV	0.0	0.0	0.0	0.0	0.0
TOTAL	**32.1**	**39.9**	**44.0**	**47.3**	**49.5**

Table 63: Truck fleet composition BAU-ambition (PTL / LOW / -95%$_{GHG}$)

13.4.3 Progressed-mix (PTG / LOW / -95%$_{GHG}$)

Progressed-mix Car stock (million units)	**2015**	**2020**	**2030**	**2040**	**2050**
G/D ICE	241	224	115	24	5.8
CH_4 ICE	3.4	9.8	22.2	16.7	5.8
G/D HEV	0.5	0.5	0.0	0.0	0.0
CH_4 HEV	2.7	8.6	49.3	66.8	32.1
G/D PHEV/REEV	0.0	0.1	0.0	0.0	0.0
CH_4 PHEV/REEV	0.3	2.3	24.6	60.5	78.0
BEV	0.2	1.5	8.2	17.5	34.2
FCEV	0.1	0.7	12.6	31.4	52.2
TOTAL	**248.5**	**247.4**	**232.1**	**216.8**	**208.2**

Table 64: Passenger car fleet composition for Progressed-mix (PTG / LOW / -95%$_{GHG}$)

Progressed-mix Truck stock (million units)	**2015**	**2020**	**2030**	**2040**	**2050**
Truck <3.5 t	**24.7**	**32.4**	**35.9**	**38.9**	**40.9**
Diesel	24.7	32.0	27.8	17.4	8.9
BEV	0.0	0.2	5.4	13.2	18.1
FCEV	0.0	0.2	2.8	8.3	14.0
Truck 3.5-12 t	**5.1**	**5.2**	**5.6**	**6.0**	**6.2**
Diesel	5.1	5.1	4.6	3.2	1.8
Methane	0.0	0.1	0.8	2.0	3.0
BEV	0.0	0.0	0.2	0.8	1.4
Truck >12 t	**2.3**	**2.3**	**2.4**	**2.5**	**2.4**
Diesel	2.2	2.2	1.9	1.3	0.6
Methane	0.0	0.1	0.4	0.9	1.3
FCEV	0.0	0.0	0.1	0.3	0.6
TOTAL	**32.1**	**39.9**	**44.0**	**47.3**	**49.5**

Table 65: Truck fleet composition for Progressed-mix (PTG / LOW / -95%$_{GHG}$)

13.4.4 More-electric (eDrives / LOW / -95%$_{GHG}$)

More-electric Car stock (million units)	**2015**	**2020**	**2030**	**2040**	**2050**
G/D ICE	241	224	125	33	1.7
CH_4 ICE	0.4	0.3	0.0	0.0	0.0
G/D HEV	5.3	15.7	39.4	30.5	8.0
CH_4 HEV	0.0	0.0	0.0	0.0	0.0
G/D PHEV/REEV	1.2	3.9	28.7	51.9	40.8
CH_4 PHEV/REEV	0.0	0.0	0.0	0.0	0.0
BEV	0.4	3.0	33.4	87.0	129.8
FCEV	0.1	0.7	6.0	14.5	27.9
TOTAL	**248.6**	**247.4**	**232.1**	**216.8**	**208.2**

Table 66: Passenger car fleet composition for More-electric (eDrives / LOW / -95%$_{GHG}$)

More-electric Truck stock (million units)	2015	2020	2030	2040	2050
Truck <3.5 t	**24.7**	**32.4**	**35.9**	**38.9**	**40.9**
Diesel	24.6	31.5	26.4	14.6	4.8
BEV	0.1	0.7	7.7	18.8	26.2
FCEV	0.0	0.2	1.9	5.5	9.9
Truck 3.5-12 t	**5.1**	**5.2**	**5.6**	**6.0**	**6.2**
Diesel	5.1	5.1	4.8	3.1	0.8
Methane	0.0	0.0	0.1	0.4	0.7
BEV	0.0	0.1	0.7	2.5	4.7
Truck >12 t	**2.3**	**2.3**	**2.4**	**2.5**	**2.4**
Diesel	2.2	2.3	2.2	1.5	0.6
Methane	0.0	0.0	0.1	0.2	0.3
FCEV	0.0	0.0	0.2	0.8	1.5
TOTAL	**32.1**	**39.9**	**44.0**	**47.3**	**49.5**

Table 67: Truck fleet composition for More-electric (eDrives / LOW / -95%$_{GHG}$)

13.5 Transport final energy demand

13.5.1 BAU-moderate (PTL / HIGH / -80%$_{GHG}$)

BAU-mod (PJ/a)	**2010**	**2020**	**2030**	**2040**	**2050**
Passenger vehicles	8,521	7,982	7,124	6,146	5,547
Buses	365	364	358	361	375
Rail (passenger)	216	226	243	270	291
Rail (freight)	86	98	112	122	131
Trucks	3,598	3,748	3,689	3,757	3,850
Ships (freight)	2,361	2,834	3,107	3,402	3,767
Aviation	2,096	2,368	2,775	3,067	3,441
Total	**17,242**	**17,621**	**17,407**	**17,123**	**17,402**

Table 68: Final energy demand by transport mode for BAU-moderate (PTL / HIGH / -80%$_{GHG}$)

BAU-mod (PJ/a)	**2010**	**2020**	**2030**	**2040**	**2050**
Liquid fuels (fossil)	16,434	14,914	11,489	3,913	419
Liquid fuels (renewable)	557	2,321	5,121	11,843	14,991
Methane	12	76	217	402	626
Electricity (0.4 kV)	0	35	200	448	701
Electricity (train)	239	255	282	314	342
H_2	0	20	98	205	323
Total	**17,242**	**17,621**	**17,407**	**17,123**	**17,402**

Table 69: Final energy demand by fuel for BAU-moderate (PTL / HIGH / -80%$_{GHG}$)

13.5.2 BAU-ambition (PTL / LOW / -95%$_{GHG}$)

BAU-amb (PJ/a)	2010	2020	2030	2040	2050
Passenger vehicles	8,521	7,584	5,858	4,469	3,691
Buses	365	377	384	412	438
Rail (passenger)	216	238	281	358	426
Rail (freight)	86	110	124	141	162
Trucks	3,598	3,859	3,615	3,435	3,363
Ships (freight)	2,361	2,326	2,361	2,646	3,039
Aviation	2096	2,105	1,930	1,825	1,779
Total	**17,242**	**16,600**	**14,553**	**13,284**	**12,897**

Table 70: Final energy demand by transport mode for BAU-ambition (PTL / LOW / -95%$_{GHG}$)

BAU-amb (PJ/a)	2010	2020	2030	2040	2050
Liquid fuels (fossil)	16,434	14,911	11,474	3,918	446
Liquid fuels (renewable)	557	1,298	2,295	8,066	10,647
Methane	12	67	181	332	488
Electricity (0.4 kV)	0	32	176	356	522
Electricity (train)	239	272	323	402	479
H_2	0	19	104	210	315
Total	**17,242**	**16,600**	**14,553**	**13,284**	**12,897**

Table 71: Final energy demand by fuel for BAU-ambition (PTL / LOW / -95%$_{GHG}$)

13.5.3 Progressed-mix (PTG / LOW / -95%$_{GHG}$)

Progressed-mix (PJ/a)	2010	2020	2030	2040	2050
Passenger vehicles	8,521	7,605	5,429	3,519	2,554
Buses	365	378	397	452	510
Rail (passenger)	216	237	279	352	414
Rail (freight)	86	109	122	135	154
Trucks	3,598	3,879	3,613	3,386	3,244
Ships (freight)	2,361	2,326	2,361	2,646	3,039
Aviation	2,096	2,105	1,929	1,821	1,769
Total	**17,242**	**16,640**	**14,131**	**12,312**	**11,683**

Table 72: Final energy demand by transport mode for Progressed-mix (PTG / LOW / -95%$_{GHG}$)

Progressed-mix (PJ/a)	2010	2020	2030	2040	2050
Liquid fuels (fossil)	16,434	14,428	9,456	2,691	253
Liquid fuels (renewable)	557	1,187	1,235	3,812	4,610
Methane	12	688	2,482	3,860	3,908
Electricity (0.4 kV)	0	35	339	778	1,105
Electricity (train)	239	272	323	402	479
H_2	0	29	295	768	1,327
Total	**17,242**	**16,640**	**14,131**	**12,312**	**11,683**

Table 73: Final energy demand by fuel for Progressed-mix (PTG / LOW / -95%$_{GHG}$)

13.5.4 More-electric (eDrives / LOW / -95%$_{GHG}$)

More-electric (PJ/a)	2010	2020	2030	2040	2050
Passenger vehicles	8,524	7,454	4,995	2,834	1,905
Buses	365	377	387	430	469
Rail (passenger)	216	237	279	352	414
Rail (freight)	86	109	122	135	154
Trucks	3,598	3,840	3,446	2,962	2,553
Ships (freight)	2,361	2,326	2,361	2,647	3,039
Aviation	2,096	2,104	1,924	1,803	1,734
Total	**17,246**	**16,448**	**13,514**	**11,163**	**10,268**

Table 74: Final energy demand by transport mode for More-electric (eDrives / LOW / -95%$_{GHG}$)

More-electric (PJ/a)	2010	2020	2030	2040	2050
Liquid fuels (fossil)	16,438	14,873	10,863	3,068	331
Liquid fuels (renewable)	557	1,163	1,238	4,852	5,016
Methane	12	34	130	324	522
Electricity (0.4 kV)	0	71	629	1,437	1,910
Electricity (train)	239	272	323	402	479
H_2	0	34	330	1,080	2,011
Total	**17,246**	**16,448**	**13,514**	**11,163**	**10,268**

Table 75: Final energy demand by fuel for More-electric (eDrives / LOW / -95%$_{GHG}$)

13.6 Transport electricity demand (direct and for PtX fuel)

13.6.1 BAU-moderate (PTL / HIGH / -80%$_{GHG}$)

BAU-mod (TWh/a)	2010	2020	2030	2040	2050	Share 2050 (energy-%)
Passenger vehicles	3	566	1,326	2,320	2,673	*32%*
Buses	0	26	67	136	178	*2%*
Rail (passenger)	9	19	30	68	105	*1%*
Rail (freight)	3	8	15	34	51	*1%*
Trucks	1	271	697	1,427	1,858	*22%*
Ships (freight)	1	205	590	1,319	1,874	*22%*
Aviation	1	171	527	1,192	1,719	*20%*
TOTAL	**18**	**1,267**	**3,253**	**6,496**	**8,459**	**100%**

Table 76: Transport electricity demand by transport mode for BAU-moderate (PTL / HIGH / -80%$_{GHG}$)

BAU-mod (TWh/a)	2010	2020	2030	2040	2050	Share 2050 (energy-%)
PtL production	5	1,234	3,141	6,571	7,691	*91%*
CH_4 production	0	6	40	170	271	*3%*
Electricity direct	12	25	56	231	373	*4%*
H_2	0	2	16	78	124	*1%*
Methanol production	0	0	0	0	0	*0%*
TOTAL	**18**	**1,267**	**3,253**	**7,050**	**8,459**	**100%**

Table 77: Transport electricity demand by fuel for BAU-moderate (PTL / HIGH / -80%$_{GHG}$)

13.6.2 BAU-ambition (PTL / LOW / -95%$_{GHG}$)

BAU-amb (TWh/a)	2010	2020	2030	2040	2050	Share 2050 (energy-%)
Passenger vehicles	3	232	503	1,665	1,969	29%
Buses	0	12	34	153	232	3%
Rail (passenger)	9	18	31	89	157	2%
Rail (freight)	3	8	13	39	66	1%
Trucks	1	123	316	1,285	1,797	26%
Ships (freight)	1	74	205	1,012	1,686	24%
Aviation	1	67	168	700	991	14%
TOTAL	**18**	**535**	**1,269**	**4,943**	**6,899**	**100%**

Table 78: Transport electricity demand by transport mode for BAU-ambition (PTL / LOW / -95%$_{GHG}$)

BAU-amb (TWh/a)	2010	2020	2030	2040	2050	Share 2050 (energy-%)
PtL production	5	504	1,184	4,587	6,175	90%
CH_4 production	0	3	17	112	235	3%
Electricity direct	12	26	58	178	355	5%
H_2	0	1	10	65	134	2%
Methanol production	0	0	0	0	0	0%
TOTAL	**18**	**535**	**1,269**	**4,943**	**6,899**	**100%**

Table 79: Transport electricity demand by fuel for BAU-ambition (PTL / LOW / -95%$_{GHG}$)

13.6.3 Progressed-mix (PTG / LOW / -95%$_{GHG}$)

Progressed-mix (TWh/a)	2010	2020	2030	2040	2050	Share 2050 (energy-%)
Passenger vehicles	3	218	300	1,010	1,102	20%
Buses	0	11	21	138	243	4%
Rail (passenger)	9	18	29	84	148	3%
Rail (freight)	3	7	12	34	59	1%
Trucks	1	114	192	1,031	1,521	27%
Ships (freight)	1	67	118	835	1,566	28%
Aviation	1	61	95	589	943	17%
TOTAL	**18**	**497**	**768**	**3,722**	**5,582**	**100%**

Table 80: Transport electricity demand by transport mode for Progressed-mix (PTG / LOW / -95%$_{GHG}$)

Progressed-mix (TWh/a)	2010	2020	2030	2040	2050	Share 2050 (energy-%)
PtL production	5	441	521	2,107	2,623	47%
CH_4 production	0	28	146	1,110	1,833	33%
Electricity direct	12	26	78	281	567	10%
H_2	0	2	23	224	559	10%
Methanol production	0	0	0	0	0	0%
TOTAL	**18**	**497**	**768**	**3,722**	**5,582**	**100%**

Table 81: Transport electricity demand by fuel for Progressed-mix (PTG / LOW / -95%$_{GHG}$)

13.6.4 More-electric (eDrives / LOW / -95%$_{GHG}$)

More-electric (TWh/a)	2010	2020	2030	2040	2050	Share 2050 (energy-%)
Passenger vehicles	3	187	223	835	762	16%
Buses	0	10	16	131	201	4%
Rail (passenger)	9	18	29	84	147	3%
Rail (freight)	3	7	11	34	58	1%
Trucks	1	102	149	910	1,090	23%
Ships (freight)	1	61	91	886	1,570	34%
Aviation	1	55	74	584	837	18%
TOTAL	**18**	**440**	**593**	**3,465**	**4,666**	**100%**

Table 82: Transport electricity demand by transport mode for More-electric (eDrives / LOW / -95%$_{GHG}$)

More-electric (TWh/a)	2010	2020	2030	2040	2050	Share 2050 (energy-%)
PtL production	5	407	444	2,420	2,254	48%
CH_4 production	0	1	7	95	229	5%
Electricity direct	12	30	113	441	861	18%
H_2	0	2	23	308	837	18%
Methanol production	0	0	6	200	484	10%
TOTAL	**18**	**440**	**593**	**3,465**	**4,666**	**100%**

Table 83: Transport electricity demand by fuel for More-electric (eDrives / LOW / -95%$_{GHG}$)

13.7 Fuel costs

Fuel costs w/o taxes (€/l$_{Diesel\text{-}eq.}$)	**Reference (fossil)**			**RE PtL**				**RE PtCH$_4$**				**RE e-mobility**		
				LT electrolyser		**HT electrolyser**		**LT electrolyser**		**HT electrolyser**				
	Gasoline/diesel from crude oil	**CNG from NG**	**CGH_2 via SMR**	**CO_2 from air**	**CO_2 from concentrated source**	**CO_2 from air**	**CO2 from concentrated source**	**CO_2 from air**	**CO_2 from concentrated source**	**CO_2 from air**	**CO_2 from concentrated source**	**CGH_2 (LT electrolysis)**	**Slow charging**	**Fast charging**
Electricity costs				3.03	2.55	2.35	1.77	2.61	2.40	1.95	1.59	2.09	1.87	1.53
H_2 production				0.63	0.63	1.87	1.87	0.59	0.59	1.75	1.75	0.63	0.00	0.00
H_2 storage, compressor				0.07	0.07	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00
CO_2 provision				0.51	0.09	0.47	0.08	0.39	0.07	0.36	0.06	0.00	0.00	0.00
Methanation, synthesis				0.19	0.19	0.23	0.23	0.14	0.14	0.12	0.12	0.00	0.00	0.00
NG grid				0.00	0.00	0.00	0.00	0.06	0.06	0.06	0.06	0.00	0.00	0.00
CH4 storage				0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.04	0.00	0.00	0.00
CH_4liquefaction onsite				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Distribution via truck				0.03	0.03	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Refueling station				0.02	0.02	0.02	0.02	0.08	0.08	0.08	0.08	0.86	0.00	0.56
Total	**0.4**	**0.4**	**2.2**	**4.48**	**3.58**	**4.97**	**4.00**	**3.92**	**3.38**	**4.35**	**3.69**	**3.5**	**1.8**	**2.09**

Table 84: Fuel Cost €/l$_{Diesel\text{-}eq.}$ 2015 (EU domestic energy supply)

Powertrain	Fuel	MJ/km
ICE hybrid	G/D	1.65
	CNG	1.89
FCEV	Hydrogen	1.61
BEV	Electricity	0.60

Table 85: Passenger cars consumption 2015 assumed for fuel cost calculations

Fuel costs w/o taxes (ct/km)	**Reference (fossil)**			**RE PtL**				**RE PtCH$_4$**				**RE e-mobility**		
				LT electrolyser		**HT electrolyser**		**LT electrolyser**		**HT electrolyser**				
	Gasoline/diesel from crude oil	**CNG from NG**	**CGH$_2$ via SMR**	**CO$_2$ from air**	**CO$_2$ from concentrated source**	**CO$_2$ from air**	**CO2 from concentrated source**	**CO$_2$ from air**	**CO$_2$ from concentrated source**	**CO$_2$ from air**	**CO$_2$ from concentrated source**	**CGH$_2$ (LT electrolysis)**	**Slow charging**	**Fast charging**
Electricity costs				13.9	11.7	10.8	8.1	13.8	12.7	10.3	8.4	9.4	3.1	2.6
H$_2$ production				2.9	2.9	8.6	8.6	3.1	3.1	9.2	9.2	2.8	0.0	0.0
H$_2$ storage, compressor				0.3	0.3	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
CO$_2$ provision				2.4	0.4	2.2	0.4	2.1	0.4	1.9	0.3	0.0	0.0	0.0
Methanation, synthesis				0.9	0.9	1.0	1.0	0.7	0.7	0.6	0.6	0.0	0.0	0.0
NG grid				0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.3	0.0	0.0	0.0
CH$_4$ storage				0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.0	0.0	0.0
CH$_4$ liquefaction onsite				0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Distribution via truck				0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refueling station				0.1	0.1	0.1	0.1	0.4	0.4	0.4	0.4	3.9	0.0	0.9
Total	**2.1**	**2.1**	**10.2**	**20.6**	**16.4**	**22.8**	**18.3**	**20.7**	**17.8**	**22.9**	**19.4**	**16.1**	**3.1**	**3.5**

Table 86: Fuel costs per passenger car kilometre 2015 (EU domestic energy supply)

Fuel costs w/o taxes (€/l$_{Diesel-eq.}$)	**Reference (fossil)**			**RE PtL**				**RE $PtCH_4$**				**RE e-mobility**		
				LT electrolyser		**HT electrolyser**		**LT electrolyser**		**HT electrolyser**				
	Gasoline/diesel from crude oil	**CNG from NG**	**CGH_2 via SMR**	**CO_2 from air**	**CO_2 from concentrated source**	**CO_2 from air**	**CO2 from concentrated source**	**CO_2 from air**	**CO_2 from concentrated source**	**CO_2 from air**	**CO_2 from concentrated source**	**CGH_2 (LT electrolysis)**	**Slow charging**	**Fast charging**
Electricity costs				1.96	1.60	1.76	1.32	1.67	1.51	1.46	1.18	1.33	1.78	1.43
H_2 production				0.09	0.09	0.13	0.13	0.08	0.08	0.12	0.12	0.15	0.00	0.00
H_2 storage, compressor				0.07	0.07	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00
CO_2 provision				0.35	0.05	0.33	0.05	0.27	0.04	0.25	0.04	0.00	0.00	0.00
Methanation, synthesis				0.11	0.11	0.14	0.14	0.08	0.08	0.07	0.07	0.00	0.00	0.00
NG grid				0.00	0.00	0.00	0.00	0.06	0.06	0.06	0.06	0.00	0.00	0.00
CH4 storage				0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.04	0.00	0.00	0.00
CH_4liquefaction onsite				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Distribution via truck				0.03	0.03	0.03	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Refueling station				0.02	0.02	0.02	0.02	0.08	0.08	0.08	0.08	0.45	0.00	1.53
Total	**0.61**	**0.51**	**1.45**	**2.63**	**1.97**	**2.41**	**1.68**	**2.28**	**1.90**	**2.07**	**1.58**	**1.93**	**1.78**	**2.96**

Table 87: Fuel Cost €/l$_{Diesel-eq.}$ 2050 (EU domestic energy supply)

Fuel costs w/o taxes (€/l$_{Diesel-eq.}$)	**Reference (fossil)**			**RE PtL**				**RE $PtCH_4$**				**RE e-mobility**		
				LT electrolyser		**HT electrolyser**		**LT electrolyser**		**HT electrolyser**				
	Gasoline/diesel from crude oil	**CNG from NG**	**CGH_2 via SMR**	**CO_2 from air**	**CO_2 from concentrated source**	**CO_2 from air**	**CO2 from concentrated source**	**CO_2 from air**	**CO_2 from concentrated source**	**CO_2 from air**	**CO_2 from concentrated source**	**CGH_2 (LT electrolysis)**	**Slow charging**	**Fast charging**
Electricity costs				0.79	0.64	0.71	0.53	0.69	0.62	0.60	0.49	1.33	1.78	1.43
H_2 production				0.07	0.07	0.08	0.08	0.06	0.06	0.07	0.07	0.15	0.00	0.00
H_2 storage, compressor				0.07	0.07	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00
CO_2 provision				0.20	0.03	0.19	0.03	0.16	0.02	0.15	0.02	0.00	0.00	0.00
Methanation, synthesis				0.06	0.06	0.08	0.08	0.05	0.05	0.04	0.04	0.00	0.00	0.00
NG grid				0.00	0.00	0.00	0.00	0.09	0.09	0.09	0.09	0.00	0.00	0.00
CH4 storage				0.00	0.00	0.00	0.00	0.04	0.04	0.04	0.04	0.00	0.00	0.00
CH_4liquefaction onsite				0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Distribution via truck				0.04	0.03	0.04	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Refueling station				0.02	0.02	0.02	0.02	0.08	0.08	0.08	0.08	0.45	0.00	1.53
Total	**0.61**	**0.51**	**1.45**	**1.26**	**0.93**	**1.12**	**0.77**	**1.17**	**0.97**	**1.07**	**0.83**	**1.93**	**1.78**	**2.96**

Table 88: Fuel Cost €/l$_{Diesel-eq.}$ 2050 (sensitivity analyses: all $PtCH_4$ and PtL fuels are imported)

Powertrain	Fuel	MJ/km
ICE hybrid	G/D	1.24
	CNG	1.32
FCEV	Hydrogen	0.75
BEV	Electricity	0.53

Table 89: Passenger cars consumption 2050 assumed for fuel cost calculations

Fuel costs w/o taxes (ct/km)	**Reference (fossil)**			**RE PtL**				**RE PtCH$_4$**				**RE e-mobility**		
				LT electrolyser		**HT electrolyser**		**LT electrolyser**		**HT electrolyser**				
	Gasoline/diesel from crude oil	**CNG from NG**	**CGH$_2$ via SMR**	**CO_2 from air**	**CO_2 from concentrated source**	**CO_2 from air**	**CO2 from concentrated source**	**CO_2 from air**	**CO_2 from concentrated source**	**CO_2 from air**	**CO_2 from concentrated source**	**CGH$_2$ (LT electrolysis)**	**Slow charging**	**Fast charging**
Electricity costs				6.8	5.5	6.1	4.5	6.1	5.5	5.4	4.3	2.8	2.6	2.1
H_2 production				0.3	0.3	0.4	0.4	0.3	0.3	0.4	0.4	0.3	0.0	0.0
H_2 storage, compressor				0.2	0.2	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
CO_2 provision				1.2	0.2	1.1	0.2	1.0	0.1	0.9	0.1	0.0	0.0	0.0
Methanation, synthesis				0.4	0.4	0.5	0.5	0.3	0.3	0.3	0.3	0.0	0.0	0.0
NG grid				0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.0	0.0	0.0
CH_4 storage				0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0
CH_4 liquefaction onsite				0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Distribution via truck				0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refueling station				0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3	0.9	0.0	2.3
Total	**2.1**	**1.9**	**3.0**	**9.1**	**6.8**	**8.3**	**5.8**	**8.4**	**7.0**	**7.6**	**5.8**	**4.1**	**2.6**	**4.4**

Table 90: Fuel costs per passenger car kilometre 2050 (EU domestic energy supply)

Fuel costs w/o taxes (ct/km)	**Reference (fossil)**			**RE PtL**				**RE $PtCH_4$**				**RE e-mobility**		
				LT electrolyser		**HT electrolyser**		**LT electrolyser**		**HT electrolyser**				
	Gasoline/diesel from crude oil	**CNG from NG**	**CGH_2 via SMR**	**CO_2 from air**	**CO_2 from concentrated source**	**CO_2 from air**	**CO2 from concentrated source**	**CO_2 from air**	**CO_2 from concentrated source**	**CO_2 from air**	**CO_2 from concentrated source**	**CGH_2 (LT electrolysis)**	**Slow charging**	**Fast charging**
Electricity costs				2.7	2.2	2.5	1.8	2.5	2.3	2.2	1.8	2.8	2.6	2.1
H_2 production				0.2	0.2	0.3	0.3	0.2	0.2	0.3	0.3	0.3	0.0	0.0
H_2 storage, compressor				0.2	0.2	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0
CO_2 provision				0.7	0.1	0.7	0.1	0.6	0.1	0.6	0.1	0.0	0.0	0.0
Methanation, synthesis				0.2	0.2	0.3	0.3	0.2	0.2	0.2	0.2	0.0	0.0	0.0
NG grid				0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.3	0.0	0.0	0.0
CH_4 storage				0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0	0.0	0.0
CH_4 liquefaction, onsite				0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Distribution via truck				0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Refueling station				0.1	0.1	0.1	0.1	0.3	0.3	0.3	0.3	0.9	0.0	2.3
Total	**2.1**	**1.9**	**3.0**	**4.3**	**3.2**	**3.9**	**2.7**	**4.3**	**3.6**	**3.9**	**3.0**	**4.1**	**2.6**	**4.4**

Table 91: Fuel costs per passenger car kilometre 2050 (sensitivity analyses: all $PtCH_4$ and PtL fuels are imported)

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