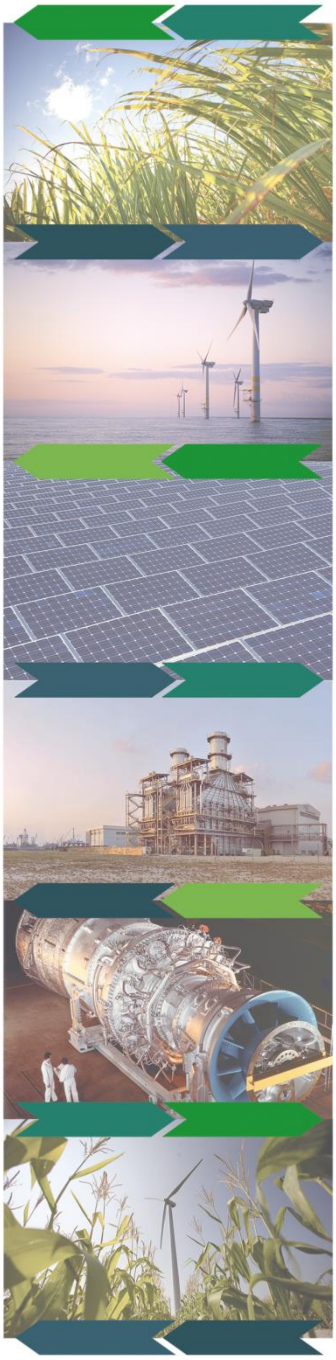
Ref. Ares(2018)3472838 - 29/06/2018

Navigating the Roadmap for Clean, Secure and Efficient Energy Innovation



Case study report on:

Ways to a cleaner and smarter transport sector

Authors: Stephanie Heitel, Michael Krail (Fraunhofer ISI)
Amela Ajanovic, Reinhard Haas (TU Wien)
Christiane Bernath, Frank Sensfuß, Benjamin Lux (Fraunhofer ISI)
Héctor Marañón-Ledesma (NTNU)

06 / 2018

A report compiled within the H2020 project SET-Nav (work package 5)

www.set-nav.eu

Project Coordinator: Technische Universität Wien (TU Wien)

Work Package Coordinator: Fraunhofer ISI

SET-Nav Strategic Energy Roadmap

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 691843 (SET-Nav).

Project coordinator:

Gustav Resch

Technische Universität Wien (TU Wien), Institute of Energy Systems and Electrical Drives, Energy Economics Group (EEG)

Address: Gusshausstrasse 25/370-3, A-1040 Vienna, Austria

Phone: +43 1 58801 370354
Fax: +43 1 58801 370397
Email: resch@eeg.tuwien.ac.at
Web: www.eeg.tuwien.ac.at

Dissemination leader:

Prof. John Psarras, Haris Doukas (Project Web)

National Technical University of Athens (NTUA-EPU)

Address: 9, Iroon Polytechniou str., 15780, Zografou, Athens, Greece

Phone: +30 210 7722083
Fax: +30 210 7723550
Email: h_doukas@epu.ntua.gr
Web: http://www.epu.ntua.gr

Lead author of this report:

Stephanie Heitel

Fraunhofer ISI

Address: Breslauer Str. 48, 76139 Karlsruhe, Germany

Phone: +49 721 6809-340
Fax: +49 721 6809-135
Email: stephanie.heitel@isi.fraunhofer.de
Web: http://www.isi.fraunhofer.de

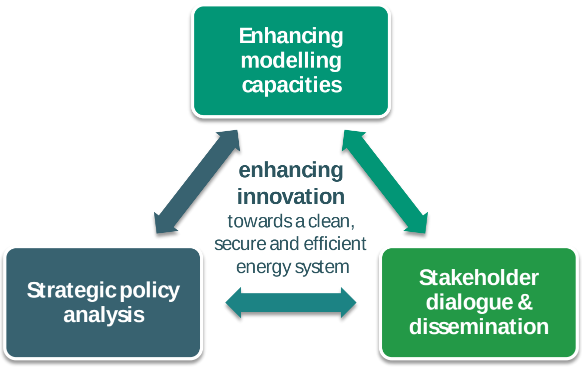
http://www.astra-model.eu

Project duration:	April 2016 – March 2019
Funding programme:	European Commission, Innovation and Networks Executive Agency (INEA), Horizon 2020 research and innovation programme, grant agreement no. 691843 (SET-Nav).
Web:	www.set-nav.eu
General contact:	contact@set-nav.eu

About the project

SET-Nav aims for supporting strategic decision making in Europe's energy sector, enhancing innovation towards a clean, secure and efficient energy system. Our research will enable the European Commission, national governments and regulators to facilitate the development of optimal technology portfolios by market actors. We will comprehensively address critical uncertainties facing technology developers and investors, and derive appropriate policy and market responses. Our findings will support the further development of the SET-Plan and its implementation by continuous stakeholder engagement.

These contributions of the SET-Nav project rest on three pillars: modelling, policy and pathway analysis, and dissemination. The call for proposals sets out a wide range of objectives and analytical challenges that can only be met by developing a broad and technically-advanced modelling portfolio. Advancing this portfolio is our first pillar. The EU's energy, innovation and climate challenges define the direction of a future EU energy system, but the specific technology pathways are policy sensitive and need careful comparative evaluation. This is our second pillar. Ensuring our research is policy-relevant while meeting the needs of diverse actors with their particular perspectives requires continuous engagement with stakeholder community. This is our third pillar.



Who we are?

The project is coordinated by Technische Universität Wien (TU Wien) and being implemented by a multinational consortium of European organisations, with partners from Austria, Germany, Norway, Greece, France, Switzerland, the United Kingdom, France, Hungary, Spain and Belgium.

The project partners come from both the research and the industrial sectors. They represent the wide range of expertise necessary for the implementation of the project: policy research, energy technology, systems modelling, and simulation.

The project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 691843
(SET-Nav).

Legal Notice:

Table of Contents

Figures

Tables

Executive Summary

Despite having a very innovative transport industry investing a lot in research and development with policies designed to foster the shift towards energy efficient and renewable energy carriers, the transport sector is still strongly based on fossil fuels. The EU Roadmap for moving to a competitive low-carbon economy sets the target to reduce emissions from transport compared to 1990 by -54% to -67% in 2050. Analyses show that transport is likely to miss this target by far without major changes in the policy framework. This report presents the main results from a modelling case study within the SET-Nav project dedicated to analysing decarbonisation options for the transport sector and their impact on the electricity system.

In this case study, ambitious policy scenarios were analysed to achieve a CO_2 emission reduction in the transport sector of 60% to 65% by 2050 compared to 1990. The major strategies for decarbonising the transport sector are (1.) shifting to more efficient transport modes, (2.) diffusion of low/zero-emission technologies, and (3.) bio & synthetic fuels. The case study differentiates two ambitious policy scenarios due to two promising technologies for road freight transport: (1.) Direct electrification achieved by hybrid-trolley trucks on motorways, and (2.) Power-to-Hydrogen based fuel cell electric vehicles. These transition scenarios include several strong policy measures.

The main model used in this case study is ASTRA (ASsessment of TRAnsport Strategies), an integrated assessment model applied since more than 20 years for strategic policy assessment in the transport and energy field. With ASTRA, policies cannot only be simulated by single transport measures but as whole transport policy bundles. Technology diffusion is based on an adapted total cost of ownership approach. New low-emission powertrain options were added within the SET-Nav project and the scope of the model was expanded to EU28 countries. ASTRA was linked to the models ALTER-MOTIVE, Enertile® and EMPIRE in order to consider technological progress of battery electric and fuel cell electric vehicles and to analyse the impact on the electricity system.

The results show that all three strategies for decarbonisation have to be combined. The shift to more efficient road modes is partly restricted by limited capacities of public transport and railways, and depends a lot on behaviour change that is hard to achieve and is influenced by various factors. The new powertrain technologies offer huge potentials for decarbonisation, however, due to high production costs at market entry level, a lack of infrastructure in many countries and low acceptance, the diffusion of these technologies has to be pushed with diverse measures including stronger R&D, subsidies, deployment of the filling and charging infrastructure and increased CO_2 emission standards. Even phase-out decisions of pure internal combustion engine vehicles should be considered. After having achieved a certain diffusion level, price decreases and range increases due to technological learning and higher acceptance due to familiarity with the alternative options are expected to accelerate the diffusion. As sustainable biomass is limited and the efficiency of synthetic fuels is low, both options should mainly be considered as supplement for transport modes for which low-emission alternatives will not be available in the upcoming decades. Technological options have also to be assessed on their flexibility potential that they provide for the electricity sector and on the overall efficiency because sector coupling is key to achieve the overall energy system transformation in a cost-efficient way. The results from the electricity system models indicate that flexibility options provided by the transport sector can significantly reduce the need for back-up capacity in the electricity system.

The analysed ambitious scenarios reflect a radical change to be achieved within three decades only. Policies need to be in place soon to drive this transition. Intensive discussions are required on the best policy mix on European and national level as well as on further required framework conditions.

1 Introduction

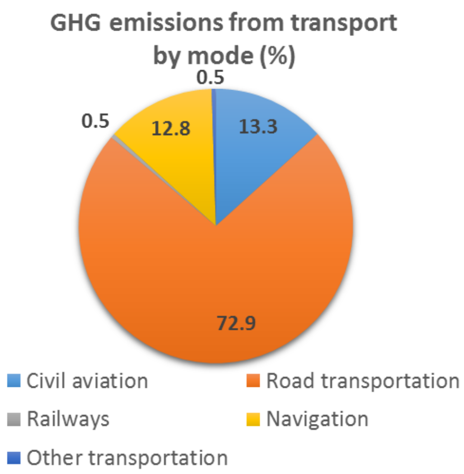
The overall objective of work package 5 of the SET-Nav project is to provide scenarios for the demand side of energy systems including buildings, industrial processes and transport. This report describes the approach and the results from case study 5.4 which is dedicated to the decarbonisation of the transport sector, the resulting final energy demand and its impact on the electricity system.

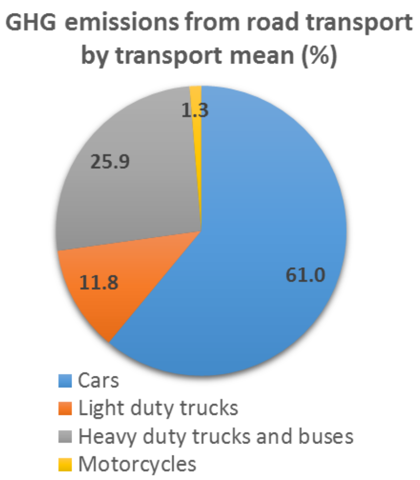
1.1 Greenhouse gas emissions in transport and reduction targets

In 2015, the transport sector accounted for around 30% of the European greenhouse gas (GHG) emissions. The EU Roadmap for moving towards a competitive low-carbon economy sets the target to reduce GHG emissions from transport[1] compared to 1990 by -54% to -67% in 2050 in order to achieve an overall reduction of 80% for all domestic emissions across sectors. Analyses show that transport is likely to miss this target by far without major changes in the policy framework and the adoption of new technologies.

Despite having a very innovative transport industry investing a lot in research and development with policies designed to foster the shift towards energy efficient and renewable energy carriers, the transport sector still strongly depends on fossil fuels. Efficiency increase of conventional technologies is countervailed by a strong increase in transport activity both for freight and for passengers due to GDP growth and higher incomes of the population. In 2005, the transport sector showed even an increase of +30% GHG emissions compared to the base year in contrast to all other sectors that were able to decrease emissions. The EU Reference Scenario 2016 shows that based on current policies the European transport sector would still be strongly fossil-fuel-based in 2050 with over 80% of final energy demand met by refined oil-products. Thus, substantial efforts are needed to reduce the use of fossil fuels in the next decades.

In 2015, European transport GHG emissions mainly stemmed from road transport (73%) and from aviation (13%). Road transport emissions are mainly caused by passenger cars (61%), by heavy duty trucks and buses (26%) and by light duty vehicles (12%). Figure 1 illustrates GHG emissions by mode and road transport mean.





Data source: European Commission (2017)

Figure 1: GHG emissions from transport (incl. international bunkers) by mode and road transport mean in 2015

[1] including international aviation, excluding international maritime shipping

The decarbonisation potential varies between transport modes. Aviation and navigation are difficult to decarbonise in particular due to the long operating life of aircrafts and ships up to 50 years with low substitution rates and lack of profound technological alternatives. Thus, heading for a 60% cut of GHG emissions in transport until the year 2050 requires land-based transport to be comprehensively decarbonised by 2050.

1.2 Objectives of the case study and research questions

The main purpose of this case study is the analysis of strategies and policy measures to accelerate the transition from a fossil fuel based towards an energy efficient and low-carbon transport sector in Europe. Due to the significance of road transport for reducing GHG emissions of the transport sector, the focus will be on required measures to achieve the transition towards low- and zero-emission road vehicles. This transition implies the electrification of transport with impacts on the electricity system due to increasing electricity demand and by providing a certain flexibility potential depending on the type of electrification. Therefore, this case study also aims at analysing the link between different options to decarbonise transport and the deployment of renewable energy sources (RES) in the electricity system.

This leads to the following key research question for the case study:

- Which measures can accelerate the transition of the transport sector from a fossil fuel based towards an energy-efficient and low-carbon system that can provide flexibility potential to the energy sector?

In particular, the following sub-questions were addressed:

- What are today's and prospective technical options of energy efficiency and alternative fuel technologies for the single transport modes?
- Which measures can help to improve the energy efficiency of the whole transport system by shifting transport from less towards more energy efficient modes?
- Which impact do different electrification options of transport demand have on the flexibility potential for the energy supply system and on the overall efficiency?

The results and findings of the case study will be the basis for future energy transition pathways to achieve European GHG reduction targets across all sectors within work package 9 of the SET-Nav project.

The report is structured as follows: Chapter 2 describes potential strategies and policy measures for the decarbonisation of the transport sector. Chapter 3 presents the scenario framework of the case study, the models applied within the case study and the main data exchange between these models. In the three following chapters results of the analysed scenarios are provided for the transport sector: In Chapter 4, the technology diffusion in the road vehicle stock is shown as well as the development of the modal split. Chapter 5 presents the GHG emissions and the final energy demand. In Chapter 6, related investments and expenditures are discussed for the scenarios. The impact on the electricity system including flexibility potential and overall efficiency is analysed in Chapter 7. Chapter 8 concludes this report with a summary of the findings and lessons learned for potential decarbonisation pathways until the year 2050.

2 Strategies and policy measures to decarbonise transport

2.1 Strategies to decarbonise transport

There are several options to reduce GHG emissions in the transport sector. They can be differentiated into technological and behavioural options. The so-called ASIF scheme originally developed by the IEA on behalf of the World Bank (Schipper et al. 2000) describes the various options in a simple equation:

GHG emissions = transport Activity (A) * modal Share (S) * energy Intensity (I) * carbon intensity of Fuel (F)

Reducing transport activity (A) in terms of vehicle-km driven is the first option in this scheme contributing to a decarbonised transport sector. Vehicle-km can be reduced by avoiding passenger trips or freight volumes, by reducing average distances of transport and by optimising load factors, empty runs and occupancy rates. Shifting (S) transport activity towards more energy efficient and less carbon intensive transport modes is the second option that can be achieved by improving the competitiveness of these transport modes. The third option consists in the improvement of energy intensity (I) of transport means. This can be achieved by optimising energy efficiency of conventional transport technologies or by a transition towards more energy efficient fuel options. Finally, reducing the carbon content of transport fuels (F) is the forth option in the ASIF scheme.

The EU Transport White Paper from 2011 (European Commission 2011) has set several targets to reduce GHG emissions from transport in the EU until 2050. According to the White Paper, the key goals or strategies to decarbonise the transport sector until the year 2050 are:

1) Shift to more efficient transport modes: More than 50% of road freight transport above 300 km distance should be shifted towards rail and ships.
2) Diffusion of low/zero-emission technologies: The share of conventionally fuelled cars in cities should be halved until 2030 and completely set to zero by 2050.
3) Alternative fuels - biomass and synthetic: Sustainable low carbon fuels for aviation should achieve a share of 40% in the year 2050.

Shifting transport towards **more efficient transport modes** like public transport, trains or non-motorised modes (cycling and walking) is difficult. The modal split in many European countries kept constant over decades or a shift towards motorised road transport was even observed. Nevertheless, there are measures and incentives to achieve such a modal shift. The combination of

- financial measures like smart pricing, road infrastructure or congestion charges in cities,
- measures to improve the infrastructure of public transport, cycling and walking pathways,
- measures to improve the accessibility and the use of multi-modal transport, bike-, car- and ridesharing services by better applying digital technologies and
- regulatory measures like lower speed limits for passenger cars, prioritised traffic flows of non-motorised modes and public transport on crossings and high parking fees

can be powerful instruments to achieve a modal shift at least in urban areas.

A powerful instrument to force efficiency increases of road vehicles is setting stricter CO_2 standards. Those standards have the potential to enforce the manufacturers and suppliers of road vehicles to further **improve fuel efficiency** of fossil fuel based drivetrains. Furthermore, they can lead to an accelerated diffusion of **alternative fuel vehicles** like battery, plug-in hybrid or fuel cell electric vehicles. Unfortunately, alternative fuel options to reduce GHG emissions do not exist for each transport mode due to technical limitations like energy capacity, range or economic limitations like high investment costs. The following list names promising alternative fuel options from a feasibility and cost-efficiency perspective by mode that could contribute to a decarbonisation of the transport sector:

- Cars and light duty vehicles: Electrification in terms of battery electric (BEV) and plug-in hybrid vehicles (PHEV) for general use as well as fuel-cell electric vehicles (FCEV) for specific uses related to long-distances like for taxis.
- Heavy duty vehicles: Electrification with FCEV or hybrid-trolley trucks for long haul transport and battery electric trucks for urban or last mile delivery.
- Buses and coaches: BEV or trolley systems for urban busses and FCEV for coaches.
- Train: Further electrification of railways.
- Ships: Improvement compared to diesel with LNG and its biofuel and synthetic fuel alternatives (PtX).
- Aviation: Bio-kerosene and synthetic kerosene.

The big advantage of biofuels and synthetic fuels is that they can be applied without the need of substantial additional investment in new vehicles and filling station infrastructure. Nevertheless, limitations exist for both options. **Biofuels** should be limited despite their renewable character due to competition with other needs of land use. Only sustainably produced biofuels should be allowed. As biomass is also used by other sectors for decarbonisation, quantitative limits have to be taken into account. What concerns **synthetic fuels**, it is foreseen that they are produced via electrolysis with electricity from renewable energy sources (RES-E). However, they will be most probably more expensive in the production than fossil fuels - even when the development of large scale production sites is assumed. Therefore, these alternative fuels could be used in particular for modes for which no promising technological alternatives are available so far. While ships might at least partly switch from diesel consumption to liquefied methane, aircrafts will continue to use kerosene at least until the year 2050. Considering also the long operating life of aircrafts and vessels, alternative fuels could be dedicated in particular to maritime and inland waterway ships as well as to aviation.

All three strategies have to be applied to a certain degree in order to achieve the GHG reduction targets of the transport sector in 2050. These strategies will only be successfully implemented, when several transport policy measures are combined.

2.2 Policies and framework conditions

Regulatory measures like setting CO_2 standards for new registered vehicles in Europe might be powerful measures to contribute to the decarbonisation of the transport sector. However, their impact strongly depends on the level of ambitiousness. The draft of the enforcement of CO_2 standards for passenger cars and light duty vehicles of the EU from November 2017 proposing a further reduction of CO_2 emissions of 30% until 2030 could lead to a stagnation of efficiency gains (Mock 2018) for internal combustion engine (ICE) vehicles. As average lifetimes of passenger cars in Europe are increasing, a significant share of inefficient ICE vehicles could still be in vehicle stocks around Europe avoiding the decarbonisation of road transport. Additionally, few transport policies address the envisaged strong modal shift for road towards rail freight transport until 2050. Even if infrastructure bottlenecks will be reduced by the implementation of the TEN-T networks until 2050, road freight transport will still be more competitive in economic terms in many cases. Similarly, the modal shift from motorized individual transport towards multi-modal, public transport and non-motorized transport requires more effort and suitable policy measures.

The following measures can support the transition to a low-carbon transport system. They intend to accelerate the penetration of low- and zero-emission vehicles while further improving the internal combustion engine in the short and medium term and to foster modal shift:

- Stricter fuel efficiency or CO_2 standards until 2030 and beyond resulting in reduced fuel consumption factors of new registered vehicles
- Subsidies for electric vehicles in early market phases to push sales and accelerate price decrease via technological learning
- Vehicle registration taxes steered via bonus-malus systems related to CO_2-emissions of the vehicle
- Increased energy taxation for conventional fuels and reduced fuel tax for electricity, biofuels, hydrogen and renewable synthetic fuels
- Spreading road charges for trucks, light duty vehicles, busses and passenger cars based on CO_2 emissions (on all roads)
- Banning fossil-fuel based cars from entry into cities
- Regulating a general phase-out of pure ICE vehicles at least for passenger cars
- Support of the development of common electronic multi-modal information platforms and seamless electronic ticketing for all public transport modes (incl. car-sharing)

2.3 Decisions required on investments and selection of alternative technologies

The intensity and the speed of diffusion of alternative fuel technologies does not only depend on related direct cost and on more soft factors like driving range, image and perceived reliability and risks, but requires also a sufficient **deployment of charging and filling infrastructure**. Studies have shown that a certain level of deployment is required for early adopters followed by a further steady ramp-up consistent with the increased vehicle diffusion in order to reduce perceived hurdles of vehicle purchasers and at the same time avoiding unprofitable infrastructure due to a lack of customers.

For **road freight transport**, battery-electric vehicles are not an option for intermediate and long-distance trucks due to the limited energy capacity and the weight of batteries. From the technical point of view, **fuel cell electric trucks** and **hybrid trolley trucks** are the most promising options to decarbonize at least long haul freight transport in Europe. Both technologies are still under development. Hybrid trolley truck systems are already tested at least in some field tests in different European countries. Overhead power lines are erected along motorways similar to those used in cities by trolley buses and trams. The system enables diesel-electric hybrid trolley trucks to operate in electric mode when connected via overhead pantographs. For distances without overhead power lines, diesel is used. Starting with diesel-electric hybrid trolley trucks, diesel could be replaced by batteries in new vehicles as of 2030 in order to achieve a complete electrification of the hybrid trolley trucks. While fuel cells and trolleys constitute promising decarbonisation options for trucks operating on long haul distances, there are several experts claiming that an introduction of both technologies in parallel would be too expensive due to the investments in two completely different infrastructure systems. It is not yet clear which technology will prevail. The decision for a deployment of a trolley infrastructure on motorways for trucks that are driving long-distances and often cross national borders might depend on a joint decision of several European countries to rely on this technology.

For **synthetic fuels**, decisions must be taken on the **expansion of production capacities** in Europe versus import agreements from Non-European countries. Synthetic fuels like Power-to-Liquid (PtL) or Power-to-Gas (PtG) can be produced using renewable electricity, water and CO_2

from the atmosphere or industrial processes in electrolysis and further synthesis processes. The production is very energy-intensive. Hence, the energy efficiency from the basic renewable electricity to the final synthetic fuel is low which would require substantial additional renewable electricity capacities in Europe. It seems improbable and not cost-efficient that additional renewable energy capacity will be installed in Europe only to produce these synthetic fuels because the demand for electricity from renewable energy sources is already high and might further increase. An option discussed among experts is the strategy to import synthetic fuels from countries with higher economic potential of renewable electricity (e.g. from Algeria with renewable wind and photovoltaics power).

As the production varies according to the fuel type, different strategies might be applied. While hydrogen is produced within one electrolysis step, the production of synthetic methane, kerosene, diesel and gasoline requires two energy-intensive steps. This implies a higher consumption of electricity for the production. In addition, the liquefaction of methane to LNG and the refinement process for kerosene, diesel and gasoline are also energy-intensive processes. Thus, the probable scenario is to produce LNG, kerosene, diesel and gasoline in non-European countries at locations where renewable electricity can be produced at lower cost due to better conditions. However, hydrogen production might be a reasonable option in Europe. Not only is its production less energy-intensive compared to other synthetic fuels, but it could also constitute an adequate flexibility potential for the renewable energy system that is challenged by fluctuations from solar and wind power generation. Hydrogen can be produced with surplus electricity in times with high renewable energy generation but low electricity consumption and can be used as electricity storage with the option of reconversion to electricity if needed.

3 Scenario definition and methodology

3.1 Scenario description for the transport sector

To identify and describe potential decarbonisation pathways towards an energy-efficient transport system largely based on renewable energy carriers by 2050, we conducted a model-based analysis of three different scenarios. For each scenario, a set of transport and energy policy packages was defined as well as a techno-economic framework setting the parameters for energy efficient and alternative fuel technologies (e.g. learning rates, infrastructure deployment).

The following three scenarios were defined:

- A **Reference scenario**, which reflects the effects of current policies and serves as a benchmark to compare the more ambitious scenarios.
- Two ambitious Policy scenarios that aim at achieving GHG emission reductions of 60% to 65% by 2050 compared to 1990 and are mainly differentiated by infrastructure decisions:
  1) **Direct electrification**: Hybrid trolley truck infrastructure is deployed in all European countries on highly-used motorways.
  2) **Hydrogen scenario**: Hydrogen fuelling infrastructure is expanded comprehensively and market entry supported.

The Reference Scenario assumes that all policy measures related to the European transport sector existing at the end of 2017 are implemented in their current form and continue to be valid until the year 2050. This comprises in particular regulations on CO_2 standards for cars and light duty vehicles and the directive on renewable energy. In addition, the directive on the deployment of alternative fuels infrastructure (AFID) is assumed to be implemented to the extent that the member states defined in their National Policy Frameworks as response to this directive. Furthermore, guidelines on the Trans-European Transport Network (TEN-T) are considered. TEN-T is a

European Commission policy directed towards the development of a Europe-wide network of roads, railway lines, inland waterways, maritime shipping routes, ports, airports and rail-road terminals. Its implementation aims also at increasing the competitiveness of railways and inland waterways. The scenario assumes that the Core Network representing the most important connections is completed by 2030, and the Comprehensive Network covering all European regions by 2050.

In the ambitious Policy scenarios, measures of the Reference Scenario were intensified and complemented by further regulations in order to achieve a stronger shift to more-efficient modes, to low- and zero-emission vehicles and to alternative fuels.

Table 1 provides an overview on the key policies and measures for the three scenarios. The interventions for the policy scenarios are considered to be additional to the existing measures in the reference case.

Table 1: Overview on the main characteristics of the Reference and the two Policy Scenarios

<table>
<tr><th rowspan="2"></th><th rowspan="2">Reference Scenario</th><th colspan="2">Policy Scenarios</th></tr>
<tr><th>Direct Electrification</th><th>Hydrogen</th></tr>
<tr><td rowspan="7">Policies for the diffusion of low/zero-emission technologies and alternative fuels</td><td rowspan="2">Passenger car CO_2 EC regulation 443/2009</td><td colspan="2">CO_2 regulation for new buses and trucks, stricter regulation for cars and light duty vehicles</td></tr>
<tr><td colspan="2">Vehicle taxation via bonus-malus regulation related to CO_2-emissions of the vehicle</td></tr>
<tr><td rowspan="2">Van CO_2 EC regulation 510/2011</td><td colspan="2">Road charging based on emissions</td></tr>
<tr><td colspan="2">Subsidies for electric vehicles in early market phases</td></tr>
<tr><td rowspan="3">Renewable Energy Directive 2009/28/EC (10% share of renewable energy in the transport sector final energy demand)</td><td></td><td>Subsidies and R&D initiatives for market entry of FCEVs</td></tr>
<tr><td colspan="2">Increased energy taxation for conventional fuels and reduced fuel tax for electricity, biofuels, hydrogen and renewable synthetic fuels</td></tr>
<tr><td colspan="2">Phase-out of new pure internal combustion engine vehicles for urban buses as of 2030, for cars and light duty vehicles as of 2035</td></tr>
<tr><td rowspan="2">Filling and charging stations for alternative fuels</td><td rowspan="2">As defined by National Policy Frameworks provided by member states as response to the AFID directive 2014/94/EC</td><td colspan="2">Continuously increasing public charging infrastructure (1 charging point per 10 battery-electric vehicles)</td></tr>
<tr><td>-</td><td>Dense hydrogen infrastructure (1/10 of current petrol stations in 2040)</td></tr>
<tr><td>Trolley truck infrastructure</td><td>-</td><td>Hybrid Trolley-Truck infrastructure on highly-used motorways in all EU countries</td><td>-</td></tr>
<tr><td>Non-road transport</td><td rowspan="2">TEN-T guidelines (core network completed by 2030, comprehensive completed by 2050, increasing the competitive advantage of railways and inland waterways)</td><td colspan="2">Increased electrification for railways, emission standards for new aircrafts and ships, higher share of LNG for ships, higher share of bio-kerosene for aviation</td></tr>
<tr><td>Shift to more efficient transport modes</td><td colspan="2">More intensive efforts to shift traffic from cars to trains, public transport, cycling and walking, e.g. by improving local public transport</td></tr>
<tr><td>Alternative fuels</td><td></td><td colspan="2">Higher share of bio-fuels, supplemented by synthetic PtX-fuels if not enough sustainable biomass should be available</td></tr>
</table>

3.2 Methodology: model coupling and data flows

3.2.1 Coupling ASTRA with ALTER-MOTIVE, Enertile® and EMPIRE

Several models were applied for the analysis of the defined scenarios of the transport sector in order to analyse the impact on the energy system and to include simulations on technological progress. This chapter provides an overview of the models applied, the main data flows between models and the scenario set-up.

The main model used in this case study is the transport sector model ASTRA representing the energy demand side. ASTRA simulates the development of the yearly energy consumption by energy carrier for each transport mode. The impact of the transition on the electricity system is analysed by the energy supply models Enertile® and EMPIRE. The energy demand by year and mode is transferred into hourly consumption by using load profiles and day specific traffic load curves.

In addition, ASTRA was linked to the model ALTER-MOTIVE that provides the technological development of battery storage capacities and consumption factors for batteries and fuel cell stacks. Both parameters determine the development of the ranges of alternative fuel vehicles and are thus relevant for the diffusion of zero-emission vehicles.

All three defined scenarios were simulated with ASTRA. For analysing the impact on the electricity system in particular concerning the flexibility potential from transport, the Direct electrification scenario was chosen to be analysed in more detail under two different assumptions: taking battery-electric cars 1.) as unflexible load charging the battery immediately when plugged in and 2.) as flexible load assuming demand site management.

ASTRA calculates annual GHG emissions for all EU member states per mode based on the passenger and freight transport performance and the efficiency and technical composition of road and non-road vehicle fleets. This calculation takes real world emissions and not laboratory drive cycle emissions into account. ASTRA distinguishes between direct (tank-to-wheel) emissions composed out of hot and cold start emissions and indirect emissions (well-to-tank). By definition, ASTRA provides as output only direct emissions from transport activities. Emissions from electricity generation are provided by Enertile® and EMPIRE.

A schematic description of the scenario set-up, the involved models and the data exchange concept is illustrated in Figure 2.

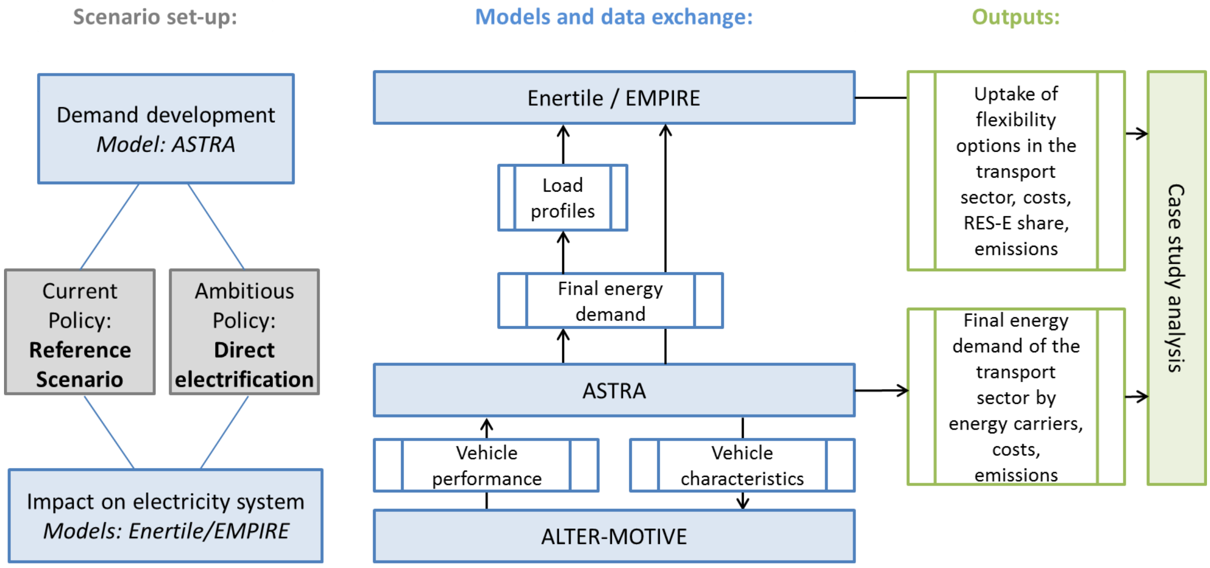


Figure 2: Scenario design, model links and data exchange concept

3.2.2 Model description ASTRA

ASTRA (ASsessment of TRAnsport Strategies) is an integrated assessment model applied since more than 20 years for strategic policy assessment in the transport and energy field. The model is based on the System Dynamics approach and built in Vensim®.

The model covers all EU28 member states plus Norway and Switzerland. A strong feature of ASTRA is the ability to simulate and test integrated policy packages and to provide indicators for the indirect effects of transport on the economic system. The ASTRA model covers the time period from 1995 until 2050. Results in terms of main indicators are available on an annual basis.

ASTRA simulates the development of passenger and freight transport per mode with an adapted classical four stage modelling approach. The model is calibrated to reproduce major indicators until 2015 such as transport performance, fuel consumption, CO_2 emissions and GDP according to the main European reference sources such as Eurostat. For future trends until 2050, the EU Reference Scenario (Capros P. et al. 2016) provides parameters like the development of GDP, population and energy prices and serves for validation of the ASTRA model behaviour (e.g. transport performance and fleet development) in the Reference scenario.

Model structure

ASTRA consists of six different modules, each related to one specific aspect, such as the economy, the transport demand or the vehicle fleet. The main modules cover the following aspects:

- Population and social structure (demographic structure and income groups)
- Economy (including input-output tables, government, employment and demand side)
- Foreign trade (within Europe and to regions in the rest of the world)
- Transport (including demand estimation, modal split, transport cost and infrastructure networks)
- Vehicle fleet (covering detailed stock models for road modes)
- Environment (including air pollutant emissions, CO_2 emissions, fuel and energy consumption, accidents)

A key feature of ASTRA as an integrated assessment model is that the modules are linked together. An overview on the modules and their main linkages is presented in the following figure. A more detailed description of the ASTRA model can be found in Schade (2005), Krail (2009), Fermi et al. (2014) or on the ASTRA website (www.astra-model.eu).

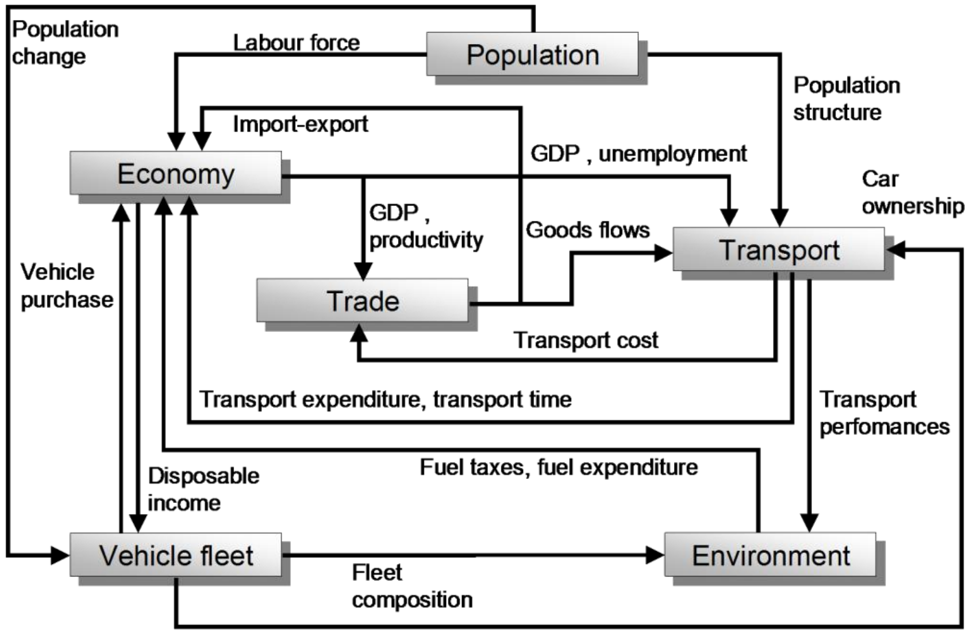


Figure 3: Model structure of ASTRA

Vehicle fleet and technology diffusion

The diffusion of alternative drive technologies in the *road vehicle fleet* is simulated separately for different vehicle categories. These categories comprise private and commercial cars, light duty vehicles, heavy duty vehicles in four gross vehicle weight categories, urban buses and coaches. Based on the technical characteristics of available fuel options today and in the future and the heterogeneous requirements of the different users, a set of fuel options is available for each vehicle category. Technologies cover gasoline, diesel, CNG, LNG, LPG, battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV), fuel cell electric vehicles (FCEV) and trolleys for urban buses and long-distance trucks. Within the SET-Nav project, new low-emission powertrain options were added in particular for the freight road modes and for buses. Technology diffusion is based on an adapted total cost of ownership (TCO) approach. Besides the associated costs, an important issue of the diffusion of new technologies is the deployment of charging and filling station infrastructure and the development of ranges of alternative fuel vehicles.

Non-road vehicle fleets like inland waterways, maritime ships, airplanes and railways are also modelled, however, in less detail due to a lack of detailed statistics, long average lifetimes, and only few renewable fuel options imaginable for the time horizon until 2050. As alternative fuel options, ASTRA considers blended kerosene with biofuels for planes, an increasing share of electrified traction for railways, and biodiesel and LNG for maritime ships and inland waterways.

Model outputs

ASTRA can produce a wide range of impact categories; in particular transport system operation, economic, environmental and social indicators. Standard outputs from ASTRA are for example:

- Transport performance
- Technology share of the vehicle stock

- Final energy consumption
- Emissions
- Investments

Results are available in several levels of detail, depending on the output e.g. by mode, by vehicle category, by energy carrier or by emission type.

3.2.3 Model description and scenario assumptions in ALTER-MOTIVE

Model description

The model ALTER-MOTIVE (A-M) was developed within the EU-funded project ALTER-MOTIVE between 2009 and 2012 and further extended afterwards. It is a dynamic model featuring historical data and has the option of modelling various features of private transport up to 2050. It starts with modelling on a yearly base service demand (S) for passenger car transport, which is kilometre driven per car and year and stock of vehicles depending on fuel prices (p), GDP and investment costs (IC) of the vehicles.

S= f (p, GDP, IC)

Finally, the model derives energy consumption by energy carrier and by type of car and calculates the GHG emissions year by year. A-M allows to model conventional technologies (petrol, diesel, CNG,) as well as battery electric vehicles (BEV), hybrids vehicles (HEV), Plug-in hybrids (PHEV)) and fuel cell vehicles (FCV). The types of cars modelled are private cars, commercial cars, different categories of light duty vehicles, busses and different categories of trucks.

Important components of electric vehicles modelled in A-M are the storages, e.g. batteries and hydrogen tank. The starting point is the current situation and the historical development of the size and weight of batteries depending on the overall capacity of the vehicles. The dynamic framework for the future considers the development of prices, investment costs, taxes, technological learning of car and battery production. It is also possible to include modelling of policies as taxes, subsidies or standards.

Model outputs for case study and scenario assumptions

Within this case study, the focus of A-M is on modelling the dynamic future development of the size of the battery including the depth-of-discharge leading to yearly gross and net values for the battery size. Over time, the cost decrease of the battery due to technological learning effects is considered leading to an increasing size of the battery capacity (QBAT) for the same power (P) of the vehicle:

QBAT (t) = f (IC(t), P(t))

Based on historical empirical data of EVs and FCVs, the development of IC and of the electricity intensity (EI) of the cars are modelled depending on the power of the vehicles and the capacity of the battery:

EI = f (P, QBAT) = a + b P + c QBAT

IC = g (P, QBAT) = d + e P + f QBAT

where a, b, c, d, e, f are coefficients obtained from econometric analyses.

The relation for the driving range (R) of the car is:

R = QBAT / EI

From this framework, QBAT and the EI are calculated as well as the driving range R, the average lifetime and the average weight of the batteries for the vehicle types described above. The service costs per km driven can be derived for every year depending on the overall electricity prices used in SET-Nav and the IC modelled in A-M.

These outputs are calculated for the two types of scenarios modelled in the case study. The major differences in assumptions are: (1.) In the reference scenario the standard assumptions for the A-M model scenarios are used with a rather moderate speed for the increase in the battery size and for the share of electricity consumption of PHEVs; (2.) In the policy scenario, the speed of the increase of the battery is faster and there is a higher share of electricity consumption of PHEVs.

3.2.4 Model description and scenario assumptions in Enertile®

Model description

Enertile® is a model for energy system optimization developed at the Fraunhofer Institute for System and Innovation Research ISI. The model strongly focuses on the power sector but also covers the interdependencies with other sectors such as the heating and transport sector. It is used for long-term scenario studies and is explicitly designed to depict the challenges and opportunities of increasing shares of renewable energies. A major advantage of the model is its high technical and temporal resolution.

Enertile conducts an integrated optimization of investment and dispatch. It optimizes the investments into all major infrastructures of the power sector, including conventional power generation, combined-heat-and-power (CHP), renewable power technologies, cross-border transmission grids, flexibility options, such as demand-side-management (DSM) and power-to-heat storage technologies. The model chooses the optimal portfolio of technologies while determining the utilization of these in all hours of each analysed year.

The model currently depicts and optimizes Europe, North Africa and the Middle East. Each country is usually represented by one node, although in some cases it is useful to aggregate smaller countries and split larger ones into several regions. Covering such a large region instead of single countries becomes increasingly necessary with high shares of renewable energy, as exchanging electricity between different weather regions is a central flexibility option. The model features a full hourly resolution: In each analysed year, 8760 hours are covered. Since real weather data is applied, the interdependencies between weather regions and renewable technologies are implicitly included.

Enertile includes a detailed picture of renewable energy potential and generation profiles for the optimization. The potential sites for renewable energy are calculated on the basis of several hundred thousand regional data points for wind and solar technologies with consideration of distance regulations and protected areas. The hourly generation profile is based on detailed regional weather data. Figure 4 shows a simplified structure of the input and output of the Enertile optimization model.

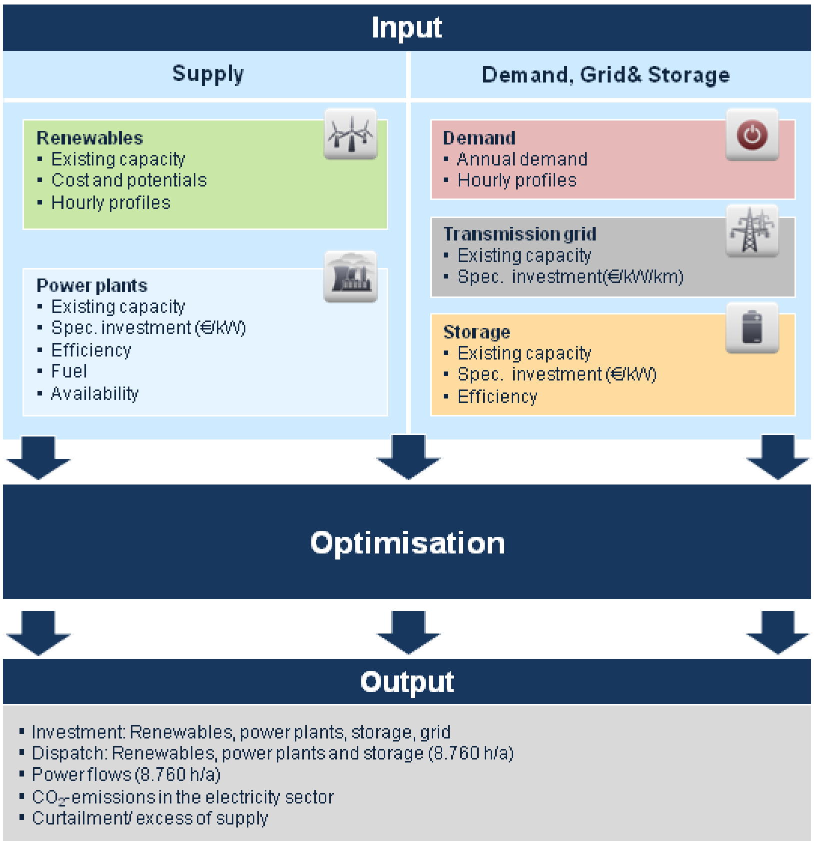


Figure 4: Simplified structure of the Enertile® optimization model

Model extensions

Enertile has a strong focus on the electricity sector in Europe and neighbouring countries. The integration of rising shares of renewable energy in the electricity sector is a crucial task for the next decades. On one hand, this can be addressed by additional flexibility within the electricity sector. On the other hand, a stronger linkage to other sectors could help to integrate renewable electricity. Within the SET-Nav project, Enertile has been expanded by several modules to integrate demand and flexibility from the transport sector.

Flexibility in the transport sector

Rising shares of electricity utilization in the transport sector increase the total electricity demand. Assuming an intelligent loading infrastructure and sufficient incentives for customers to load vehicles flexible, the additional electricity demand in the transport sector is flexible to a certain degree. The load profile of the additional demand as well as the potential flexibility in the transport sector strongly depend on driving profiles and time slots for charging. Different driving profiles for different vehicle types were used in the flexibility module for the transport sector. The profiles define charging times and necessary charging states for certain points of time. For example, many battery electric (BEV) and plug-in hybrid vehicles (PHEV) have to be charged in the morning to allow commuting to work. When they return back home in the evening, charging does not necessarily have to start immediately. If the owners are willing to participate in smart charging, the charging process can be postponed to times that are more cost efficient for the power system. The share of willing owners can be defined for each country and year.

Hydrogen

One CO_2 mitigation option in the transport sector is the usage of electrolysis-based hydrogen in fuel cell electric vehicles instead of fossil fuels. This fuel shift has two main implications for the electricity sector. On the one hand, the hydrogen production with electrolysis increases the total electricity demand. On the other hand, hydrogen has the potential to provide flexibility to the power system. Due to its long-term storage property, it can be produced in hours of small loads and high electricity generation by renewable energies. Hydrogen demands in the transport sector can be met by this storage. Furthermore, this good storage property qualifies hydrogen as a pure electricity storage. In hours of high load and small renewable generation, stored hydrogen can be fired in a gas turbine to generate emission free electricity. Therefore, the hydrogen module in Enertile consists of a formal description of three components: An electrolyser, a hydrogen storage that can meet both exogenous demands from the transport sector and endogenous demands for electricity generation, and a reconversion instance. The techno-economic parameters assumed for the electrolyser are shown in Table 1. As the reconversion instance a gas-fired power plant with a specific investment of 450 Euro/KW_{el}, a lifetime of 20 years and an electric efficiency of 40 % is implemented. The size of the hydrogen storage facility is based on the capacity of the electrolyser: It is set to 1.000 full load hours of peak hydrogen generation. The modelling approach assumes that electrolysers are installed decentralized at the fuelling stations. A hydrogen network infrastructure is not explicitly modelled. The model tends to overestimate the amounts of electricity generation by firing hydrogen in gas turbines, as transport costs from small, decentralized electrolysers and hydrogen storages to more centralized gas turbines are neglected.

Table 1: Assumed techno-economic parameters for electrolysers

	2020	2030	2040	2050
Specific Investment (€/kW)	875	750	625	500
El. efficiency (%)	68	72	76	80
Lifetime (years)	20	20	20	20

Scenario assumptions

The scenarios assumptions for this case study concerning the electricity demand in the European countries and the fossil fuel prices are based on the Primes Reference Scenario. Only the price path specified for CO_2 is higher than in the Primes Reference Scenario. Table 2 shows the CO_2-prices used in the Enertile scenarios.

Table 2: CO_2-prices in the Enertile® scenarios

	2020	2030	2040	2050
CO_2 price (€/t)	15	42	96	150

The Enertile model optimizes endogenously the expansion and deployment of conventional and renewable technologies. Nevertheless, the installed capacity of hydro, biomass and nuclear is fixed according to the values in the Primes Reference Scenario. Furthermore, the status of offshore wind energy for the year 2020 in the Primes Reference Scenario is integrated within the optimization as a minimum restriction for the calculated scenario years. In this case study, the optimization covers the scenario years 2020, 2030, 2040 and 2050. The optimal portfolio of technologies for electricity generation in the EU 28 member states plus Norway and Switzerland is determined.

Based on the results from the ASTRA model concerning the policy scenario *Direct electrification* two Enertile scenarios are designed. The electricity consumption from the transport sector modelled by ASTRA is integrated into the Enertile model. The demand from trolley trucks, trains and trolley busses are considered as inflexible demands, as we assume there is no possibility of load shifting for these categories. To derive the hourly demands from the annual demands for those categories different driving profiles for the respective categories are used. In contrast, the electricity demand from BEVs and PHEVs is considered as flexible demand. This means that battery charging is optimized within the model taking into account the restrictions considering the driving profiles and charging times. Hydrogen demands from the transport sector are taken into account within the hydrogen module in Enertile.

Within this case study, two scenarios were calculated to analyse the implications of flexibility in the transport sector on the electricity sector. In the flexible scenario we assume that all vehicle owners participate in smart charging. In accordance with the established driving profiles, electric vehicles are charged when it is most beneficial to the power system. In contrast, we assume in an inflexible scenario that none of the vehicle owners uses smart charging. This emulates the situation where electric vehicles charge with maximal charging capacity immediately when reaching a charging station, without taking into account the current state of the electricity system. In reality, the share of smart chargers will always lie between these two extreme cases. In addition, it is possible to convert hydrogen back into electricity in gas turbines in the flex scenario. This reconversion of hydrogen is not possible in the inflex scenario. These two extreme paths allow for the greatest possible differences in the results. Table 3 gives an overview of the calculated scenarios and the different properties concerning electricity and hydrogen demand from the transport sector and the available flexibilities.

Table 3: Overview of scenarios calculated with the Enertile® optimization model

Scenario	time scope	BEV & PHEV smart charging	Trolley Trucks	Trains & Trolley Buses	Hydrogen reconversion
Flex	2020 - 2050	-	Inflexible	Inflexible	-
Inflex	2020 - 2050	✓			✓

3.2.5 Model description and scenario assumptions in EMPIRE

EMPIRE is the European Model for Power Investment (with high shares of) Renewable Energy (Skar et al. 2016). It is used for assessing the mid-term and long-term generation capacity and transmission expansion in the European power system.

The model includes short-term uncertainty from load and RES and short-term dynamics for operational constraints. Long-term system dynamics is also present for various factors as for instance carbon emission price, fuel prices, technology efficiencies, technology costs and RES share targets.

The number of technologies present in the system is exhaustive: from fossil fuel plants to biomass, geothermal, hydro storage and battery storage. In the RES side, off-shore wind, on-shore wind and solar are represented with data from the EMHIRES dataset as source (SETIS 2017).

Electricity demand is represented by hourly country profiles through the ENTSO-E data for EU28 countries plus Switzerland, Norway and Balcan countries (OPSD 2017). The annual electricity demand comes from the EU reference case which is based on the outputs from the PRIMES model (Capros P. et al. 2016).

The historical data is used to create short-term stochastic scenarios which take into account the statistical properties of the inputs and their correlations.

Flexibility is represented in the model through 10 Demand Responsive (DR) loads. Seven of them concern the building sector, one represents industry and two represent transport. The two flexible load groups from the transport sector are represented in Table 4. The DR groups aggregate different types of vehicles according to their hourly profiles.

Table 4: Flexible loads represented in EMPIRE with the potential flexible capacity per flexible load in the Policy and Reference scenarios in MW

DR group	Sector	Supertype	Type	Potential EU Capacity (MW)	Initial investment cost (€/MW)
1	Residential	Cooling	Air Conditioning	43744	250
2	Residential	Hot Water	Heat Pumps	6024	20
2	Residential	Hot Water	Electric Direct Heaters	1603	
2	Residential	Hot Water	Storage Heating	676	
3	Residential	Space Heating	Heat Pumps	28004	250
4	Residential	Space Heating	Electric Direct Heaters	1785	20
4	Residential	Space Heating	Storage Heating	127	
5	Non-residen.	Cooling	Air Conditioning	46797	10
6	Non-residen.	Hot Water	Heat Pumps	961	5
6	Non-residen.	Hot Water	Electric Direct Heaters	22	
6	Non-residen.	Hot Water	Storage Heating	26	
7	Non-residen.	Space Heating	Heat Pumps	16553	20
7	Non-residen.	Space Heating	Electric Direct Heaters	147	
7	Non-residen.	Space Heating	Storage Heating	8	
8	Industry	Industry Processes	Aluminium, Chemical,…	149944	0
9	Transport	Large Electric Vehicle (EV1)	Bus, Heavy Duty Vehicle (HDV), Trolley (battery)	31707 / 1104	500[1)]
10	Transport	Electric Vehicle (EV2)	Private cars, commercial cars and Low Duty Vehicles (LDV)	170393 / 50212	500[1)]

[1)] *Investment costs are 500€/MW from 2010 to 2025 and 0 from 2030 to 2050 as the flexibility characteristics are expected to become standard by then. Variable operational costs for the 10 DR groups are: 10, 10, 10, 10, 5, 20, 10, 150, 20 and 20€/MWh respectively.*

The number of flexible load groups is the maximum affordable for the current problem size and computational available option.

The profile loads are obtained from the model Enertile, the EV charging hourly availability from the eLOAD model and annual energy demand from the ASTRA model.

Shiftable loads are modelled through three constraints. The balance constraint fixes the energy consumption of the flexible load to the original demand value in each day interval. In second place, the country load-generation balance constraints incorporate the changes by flexible loads [1]. Third, the flexible loads are constrained to take values within an interval defined by its load profile.

Generation + Imports – Exports + Discharge – Charge = Load + Flexible load – Lost load [1]

The flexible loads are allowed to time shift their demand at a given cost. From the prosumers perspective, these are the reservation prices, the minimum price at which they sell its flexibility. From the supplier's perspective, it is the maximum they would pay to consumers in order to change their demand. If the reservation price is lower than the price differential between two short-run marginal hourly costs, or inter-hour price differential, then it is optimal for the system to execute the load shifting.

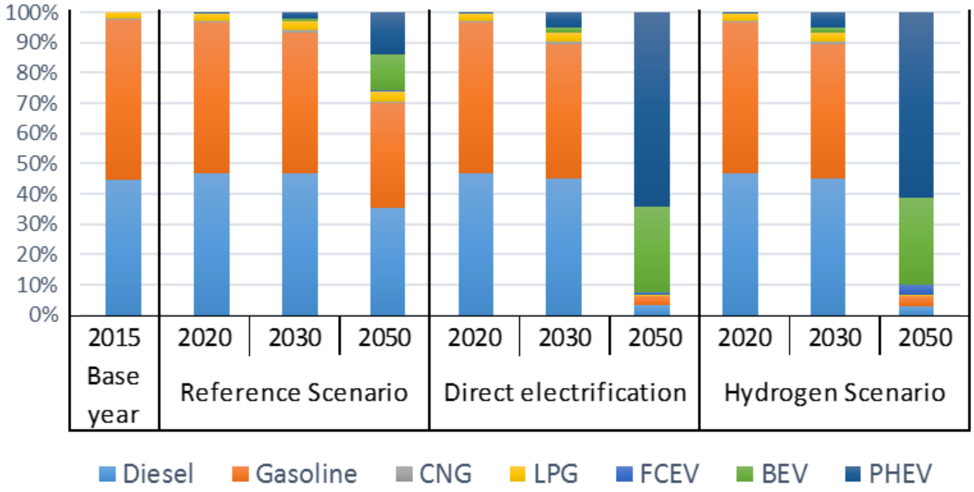
Flexible loads expansion is modelled through strategic decision variables with investment costs given in Table 4. The difference with conventional generation expansion is that flexible loads are limited by their corresponding energy demands, given by the ASTRA model. Reference and ambitious scenario, differing in energy demand from the transport sector, allow different amounts of flexible potential.

The model assumes a diffusion of flexible EV charging for each country proportional to their 2050 potential. This proportion is uniform for all the countries and is based on the energy demand of each EV group in each country.

4 Results on technology diffusion in the vehicle stock and on the development of the modal split

4.1.1 Development of the share of alternative fuel vehicles in the vehicle stock

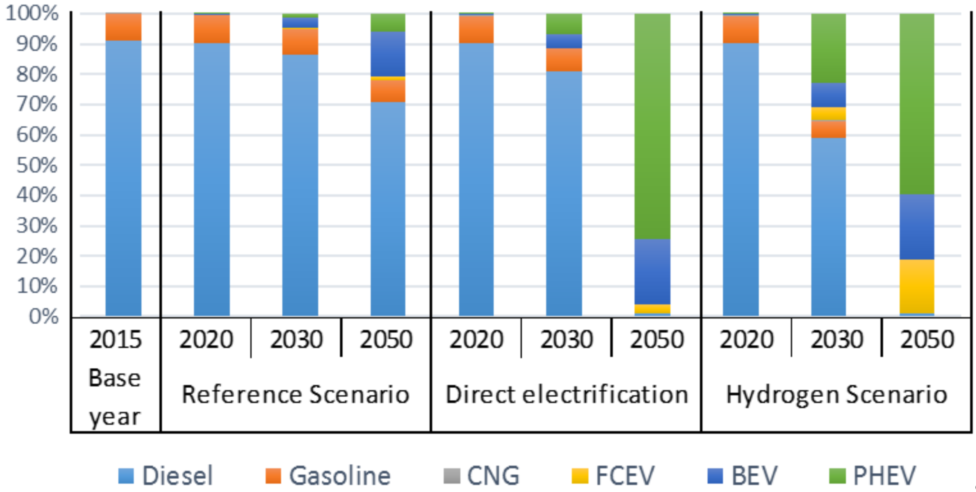
Figure 5 shows the development of the powertrain technologies in the European car fleet for the three scenarios. In the Reference scenario, pure diesel and gasoline-fuelled vehicles still constitute around 70% of the European car fleet in 2050, while battery electric cars (BEV, PHEV) represent a quarter of the fleet. The development is driven by a planned increase in charging stations as well as by decreasing prices and longer ranges due to technological learning. Learning effects in the first years result mainly from countries like Norway, the Netherlands and China where electric cars already have a remarkable market share today. In the Policy scenarios, pure gasoline, diesel, LPG and CNG cars were phased out as of 2035. This leads to more than 90% electric cars in 2050, therein around 30% pure battery-electric vehicles. The two Policy scenarios show only minor differences for the car fleet. In the Hydrogen policy scenario, the fleet constitutes of some more fuel cell electric vehicles (FCEV) that substitute PHEVs for cars driving long-distances in comparison to the Direct electrification scenario.



Source: ASTRA

Figure 5: Car fleet composition by technologies in EU28 until 2050

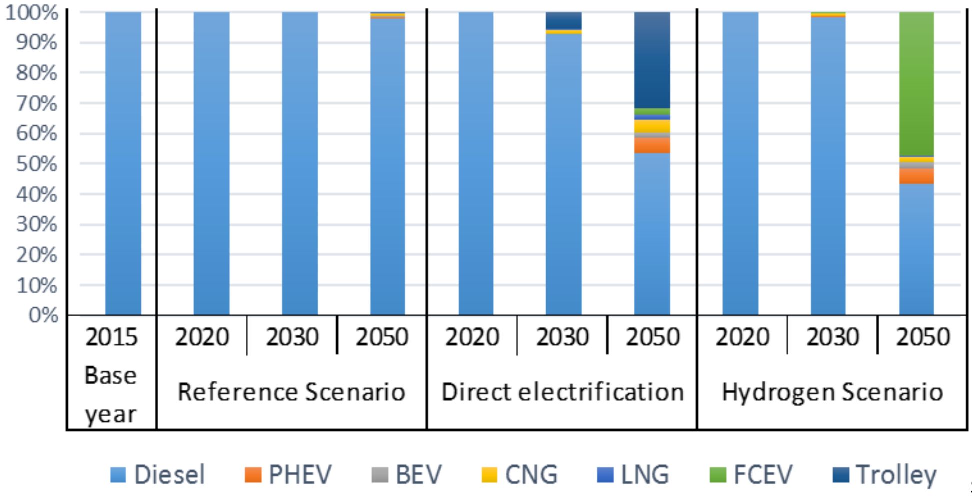
Figure 6 depicts the fleet composition of the light duty vehicles (LDV). In the Reference scenario, BEVs diffuse continuously to around 15% by 2050 mainly driven by the increasing fleet of CEP (courier, express mail and parcels) operators delivering parcels in cities. In the Policy scenarios that incorporate also a phase-out of pure gasoline, diesel and CNG LDVs as of 2035, the share of BEVs and PHEVs increases to more than 95% in the Direct electrification scenario in 2050. In the Hydrogen scenario, the BEV and PHEV share is lower with both representing together ~80% of the LDV fleet in 2050, but are supplemented by a significantly higher diffusion of FCEVs.



Source: ASTRA

Figure 6: Light Duty Vehicle (LDV) fleet composition by technologies in EU28 until 2050

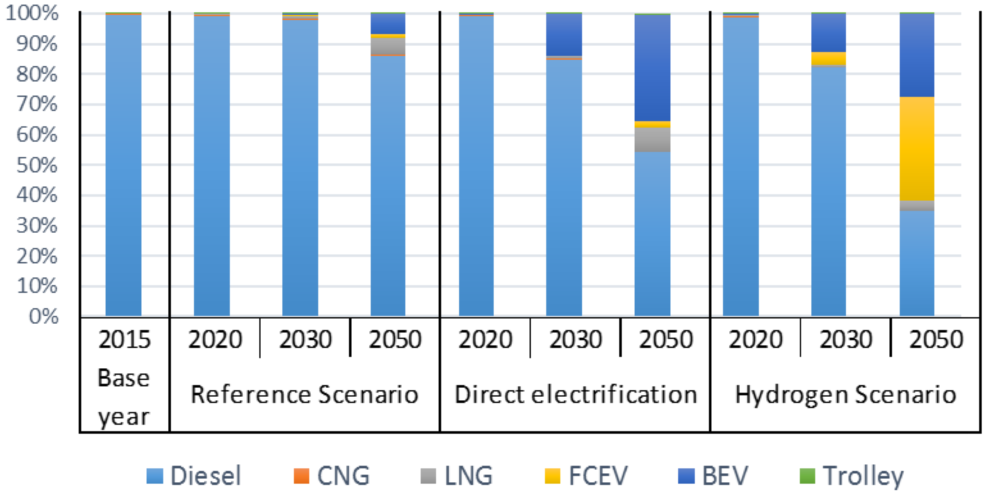
Figure 7 shows the technology diffusion in the truck fleet over time. While diesel trucks dominate in the Reference Scenario with less than 3% alternative powertrains in 2050, diesel trucks decrease in the Direct electrification scenario to a share of 53% in the fleet and in the Hydrogen scenario to even 44%. Assuming a deployment of the trolley truck overhead cable infrastructure as of 2020 in the direct electrification scenario, trolley technology starts diffusing from this time onwards for the road tractors and long-distance trucks. Market penetration of fuel cell electric trucks in the Hydrogen scenario starts later due to challenges related to the technology, the hydrogen production and its distribution to refuelling stations. Despite this later start, the fleet composition shows a higher share of FCEVs in 2050 compared to trolley trucks in the Direct electrification scenario because fuel cell technology is used for all truck weight classes not only for the long-distance trucks.



Source: ASTRA

Figure 7: Truck fleet composition by technologies in EU28 until 2050

The bus fleet presented in Figure 8 comprises urban buses and coaches. Diesel stays the main technology in the bus fleet of the Reference Scenario because the CNG technology does not seem to provide emission-related advantages anymore and alternative options are much more expensive and require high investments. BEVs are mainly chosen by cities that aim at reducing their high emission levels. Ambitious policies including a phase-out of internal combustion engine buses in cities lead to a higher share of BEVs in the bus fleet in the policy scenarios. In addition, the number of urban trolley buses increases in the Direct electrification scenario in particular based on infrastructure extensions and for bus lines with high demand; however, their share in the urban bus fleet stays minor compared to other technologies due to lower acceptance of the required infrastructure within the cities and higher initial investments. With a deployment of overhead power lines on motorways for trolley trucks, trolleys might become also an option for coaches. In contrast, the Hydrogen scenario results in a third of the bus fleet being FCEVs due to technological learning and due to an extension of the hydrogen fueling infrastructure that is important for coaches.

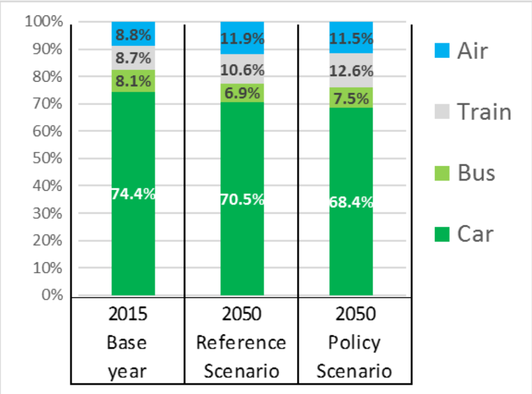


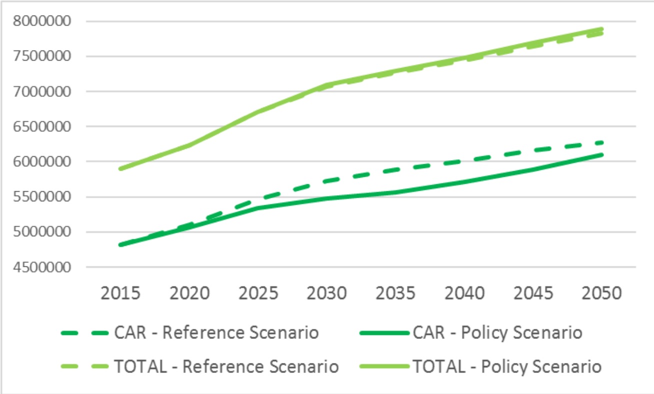
Source: ASTRA

Figure 8: Bus fleet composition by technologies in EU28 until 2050

4.1.2 Development of transport performance and modal split

Current measures in the Reference scenario already result in a shift from car use to trains for passenger transport. In the Policy scenarios an even stronger shift is achieved assuming further improvements in public transport in combination with higher costs for driving a car due to policies like higher taxes on conventional fossil fuels (see Figure 9).





Source: ASTRA

Figure 9: Modal split of passenger transport and development of passenger land transport in Mio. passenger kilometres in EU28 until 2050

For freight transport, only a slight modal shift was achieved as elasticities are lower and modal shifts even more difficult to obtain.

4.1.3 Limitations of the scenarios

Besides uncertainties in the prediction of cost developments and the effectiveness of policies, the policy scenarios have further limitations:

Changes in behaviour that are not mainly cost-driven are hard to achieve and predict and might depend on other factors including societal trends and the perceived attractiveness of more efficient alternatives. In order to shift to other more efficient modes, the perceived benefits must exceed the disadvantages and sense of loss. For example, car-sharing users have currently a distinctive socio-economic profile (mainly well-educated, male, young adults, middle/upper income ...). Upscaling car-sharing usage to further groups might also depend on the degree of development towards a sharing-economy and/or the perceived benefits like flexibility and reduced effort for car maintenance compared to owning an individual car. Reduction of transport activity via complete avoidance of certain trips is not considered in the policy scenarios.

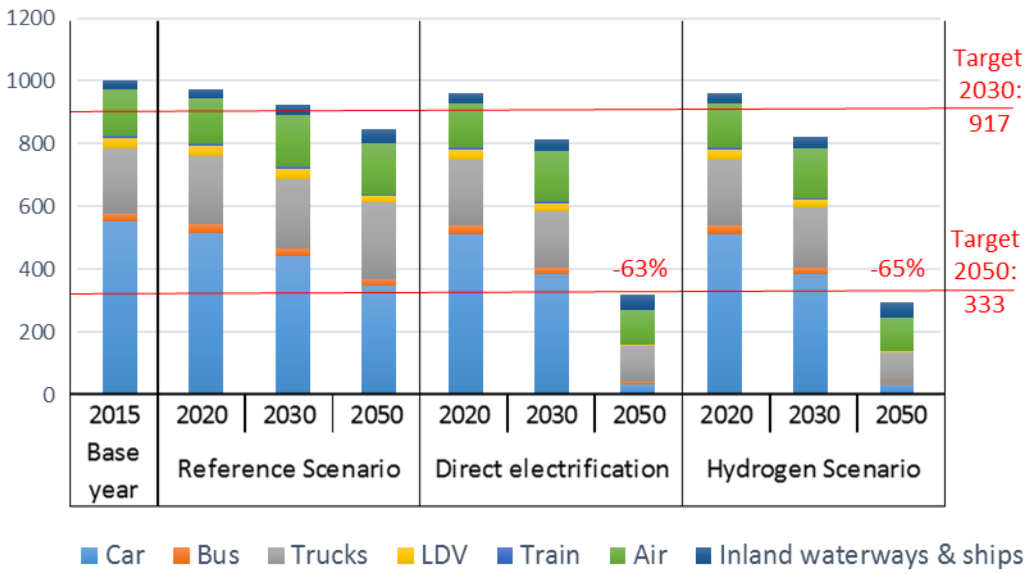
Fully automated vehicles were also not included in the scenarios. Their market entry is not expected before 2035 (Krail et al. 2018). According to recent studies their share in private vehicle fleets will still be low due to high production costs until 2050. Fully automated vehicles have a higher fuel efficiency of 15-18%. However, overall effects on emissions will depend a lot on related regulations. As part of public transport bridging the 'last-mile' in particular in less-urban regions, public transport could gain users and increase overall transport efficiency. In contrast, fully automated cars in individual private ownership could increase transport activity strongly due to additional empty trips when driving family members to their various destinations and due to increased travelling as driving time can be used for other activities. Fully automated trucks and busses might diffuse faster after market entry due to higher savings with the elimination of driver cost and increased fuel efficiency gains.

5 Results on GHG emissions and final energy demand

5.1 Development of GHG emissions until 2050 by scenario

The development of the CO_2 emissions for the three scenarios is depicted in Figure 10. The Policy Scenarios exceed the current European reduction targets for the transport sector in 2030 and in 2050 and meet the aimed reduction range of 60% to 65%.

As described in the previous chapter, the two main drivers of the achieved CO_2 emission reduction are the diffusion of alternative fuel vehicles for road transport and mode shifts in particular for passengers. In 2015, road transport accounted for ~80% of CO_2 emission from transport. While this share decreases only slightly to 75% in the Reference Scenario in 2050, a share of less than 50% is achieved in the Policy scenarios. Due to limited options for decarbonisation for aircrafts and ships, these modes represent around half of the emissions in 2050 in the Policy scenarios.



Source: ASTRA

Figure 10: CO_2 emissions by transport mode in EU28 until 2050 in Mt CO_2-equivalent

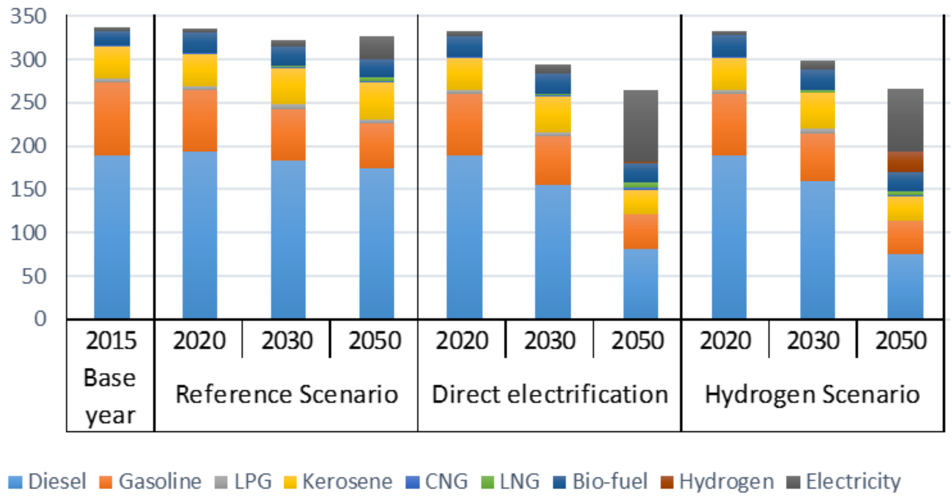
5.2 Development of final energy demand until 2050 by scenario

5.2.1 Development of final energy demand for transport in total

5.2.1.1 Final energy demand by energy carrier

Figure 11 depicts the composition of the final energy demand for the transport sector by energy carrier. In the Reference Scenario, 85% of the final energy demand is still provided by oil-based fuels in 2050, only 15% by the renewable energy carriers electricity, hydrogen and bio-fuels. In the Direct electrification scenario, the share of renewable energy increases to 40% in 2050, in the Hydrogen Scenario to 44%. The relatively low share of electricity despite a strong electrification of the road fleet is due to higher efficiency factors of battery electric vehicles and trolley trucks compared to ICE vehicles.

In the Reference Scenario, final energy demand decreases until 2030 due to efficiency improvements, but increases again towards 2050 as transport activity is assumed to grow continuously. In contrast, the policy scenarios achieve a stronger reduction of final energy demand that decreases until 2050.



Source: ASTRA

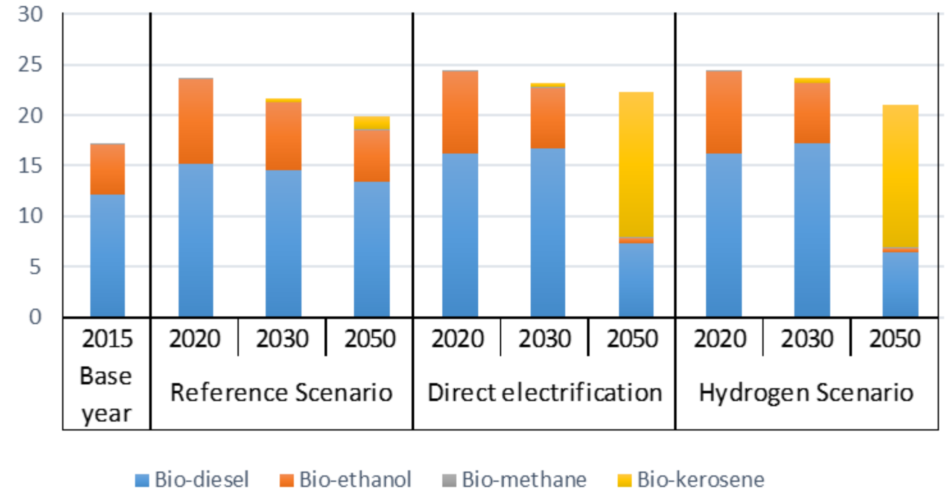
Figure 11: Composition of the final energy demand of the transport sector (excluding intercontinental shipping) by energy carrier in Mtoe in EU28 until 2050

5.2.1.2 Details on bio-fuel consumption

Details on electricity and hydrogen consumption are illustrated in chapter 7.2 when impacts of transport on the electricity system are discussed. In the following, the development of bio-fuel demand is further investigated as sustainable produced bio-mass is limited and also used by other sectors for decarbonization.

Figure 12 shows the development of bio-fuel demand. While bio-kerosene consumption increases strongly over time because no other decarbonization options are assumed to be available for aviation until 2050, the consumption of bio-diesel and bio-ethanol decreases due to electrification of road transport, in particular in the policy scenarios because of the phase-out of these technologies for cars, LDV and buses. In 2050, around 65% of bio-fuel consumption is bio-kerosene used by aviation.

The strategy for using bio-fuels has to be closely aligned with decarbonisation strategies of other sectors like buildings and industry. If sustainable biomass is not available in a sufficient quantity, strategies on the production of synthetic fuels have to be developed.

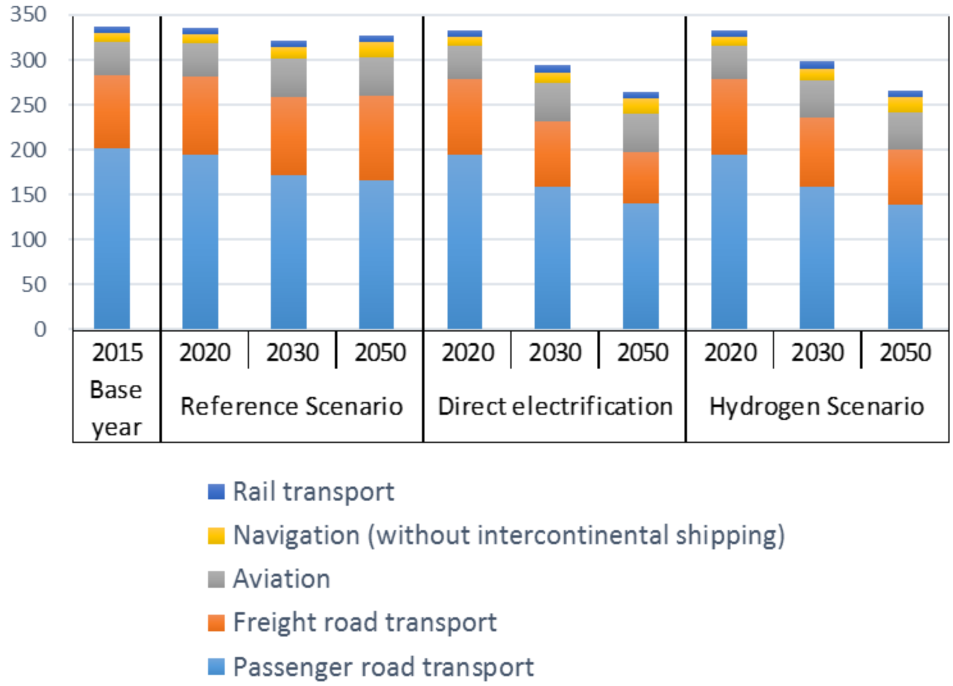


Source: ASTRA

Figure 12: Bio-fuel demand of the transport sector by type in Mtoe in EU28 until 2050

5.2.1.3 Final energy demand by mode

Figure 13 illustrates the development of the final energy demand by transport mode. Due to the electrification of road transport and further efficiency improvements, final energy demand decreases for road transport over time. For non-road modes, final energy demand increases due to higher transport activity that cannot be compensated by efficiency improvements within the existing technologies, in particular for aviation and navigation. In the following two chapters, energy demand for road vehicles and for non-road modes are depicted in more detail.

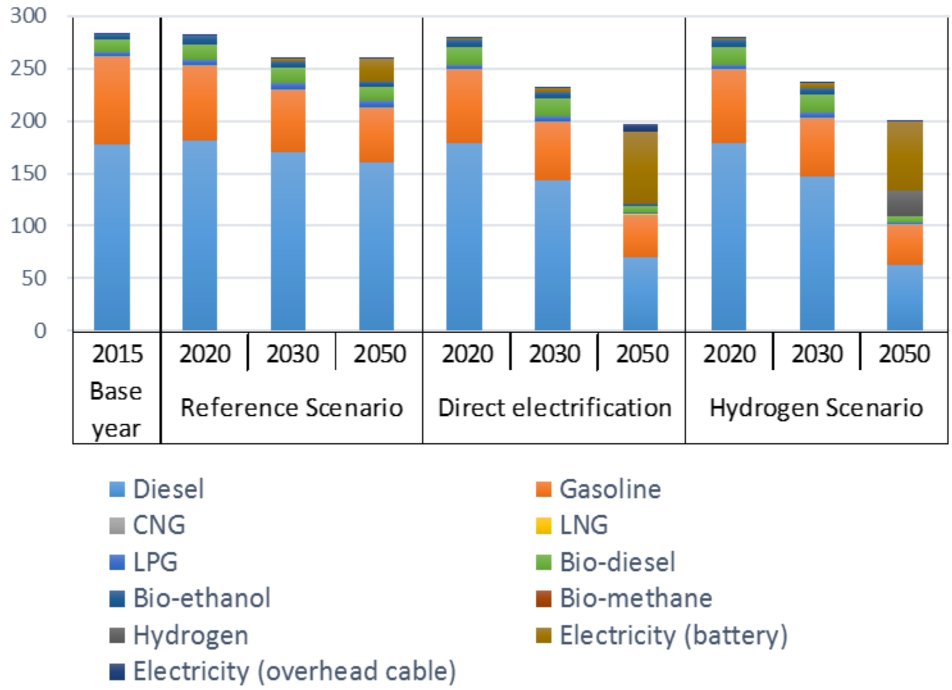


Source: ASTRA

Figure 13: Final energy demand by transport mode in Mtoe in EU28 until 2050

5.2.2 Development of final energy demand for road vehicles

Figure 14 illustrates the development of the absolute final energy demand for road vehicles and its composition. Despite an increase in transport activity for passengers and freight, the final energy demand decreases in the policy scenarios because electrification by batteries and overhead cables is more efficient than using combustion engines and due to general efficiency improvements.

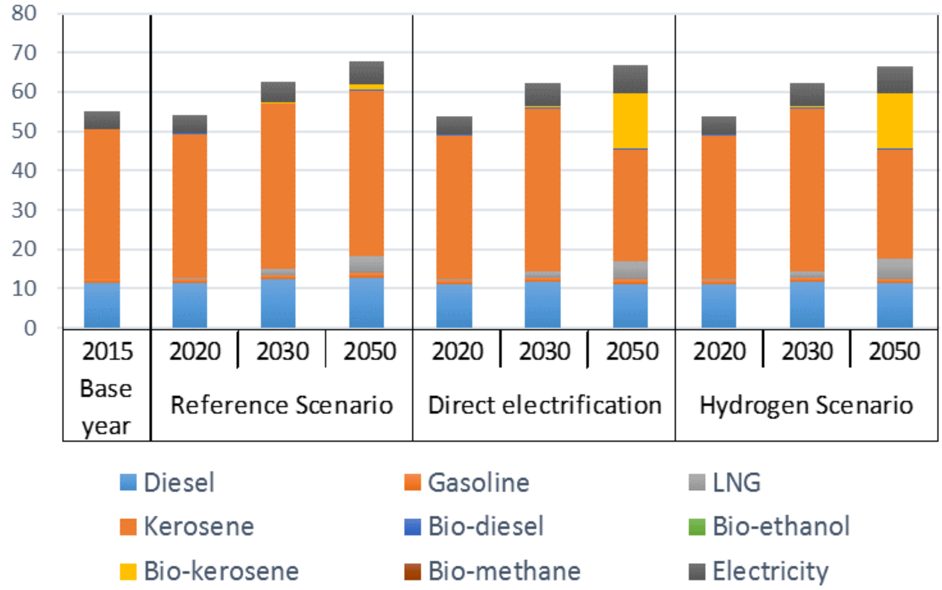


Source: ASTRA

Figure 14: Composition of the final energy demand of road vehicles by energy carrier in Mtoe in EU28 until 2050

5.2.3 Development of final energy demand for non-road modes

In contrast, final energy demand of non-road modes is increasing over time as the transport activity is increasing for all modes - aviation, navigation and rail transport. While energy demand of trains only increases slightly due to further electrification of railways, technological alternatives with higher efficiency are not available for aircrafts. Even though LNG partly substitutes diesel for navigation and enables the reduction of diverse emissions, there is no significant effect on the amount of the final energy demand. Therefore, bio-fuels play an important role for non-road modes in order to achieve the GHG emission reduction targets. Together with electricity demand, one third of the final energy demand consists of renewable energy in 2050 in the policy scenarios. Figure 15 shows the development of final energy demand for non-road modes for the scenarios by 2050.



Source: ASTRA

Figure 15: Composition of the final energy demand of non-road modes (excluding intercontinental shipping) by energy carrier in Mtoe in EU28 until 2050

6 Related investments and expenditures

Required investments for the deployment of infrastructure for new technologies can only be roughly estimated based on available studies within this case study.

The Direct electrification scenario assumes that a cost-efficient deployment of trolley truck infrastructure is achieved when a third of the European motorways is provided with overhead cables for trucks. This third of motorway roads should be the distances that are most highly frequented and thus represent towards 2/3 of the distances driven on motorways by the trucks. This assumption is based on a study for deploying motorways in Germany with a sufficient trolley infrastructure (Wietschel et al. 2017). Assuming a required infrastructure investment of 2 Mio EUR per kilometer, total investments would add up to 51 billion Euros for EU28.

Setting up a hydrogen filling station infrastructure including a hydrogen distribution network as assumed in the Hydrogen scenario would be costly as well. Investments for the filling stations depend on the foreseen size of the single stations and on the decision if hydrogen is produced in larger production sites or directly at the filling stations. Different strategies on combining various sizes of filling stations during ramp-up and for the final set-up are discussed. The strategies have an impact on the investment cost, the utilization rate and future investments required for replacement and expansions. According to experts, investments for smaller hydrogen filling stations would be around 1 million Euro. Due to the different tank capacities of passenger cars and long-haul trucks, hydrogen filling stations for trucks could require investments of 10 to 20 million Euro per filling station. In this case, the deployment of a European network of 2.500 up to 5.000 hydrogen filling stations would lead to similar infrastructure investments of around 50 billion Euros. According to Gnann et al. (2017) there are still some open issues on the hydrogen distribution network to be considered as the distribution of hydrogen via semitrailer trucks from the production site to the filling station would not be sufficient for large and frequently visited hydrogen filling stations by long-haul trucks. According to Robinius et al. (2018), trailer-based hydrogen supply is appropriate during the market introduction phase while pipeline-based transportation seems preferable from an economical and ecological point of view for high penetration rates of FCEVs.

Thus, additional investments could be necessary. Research projects currently investigate if existing natural gas pipelines could be used for the distribution of hydrogen.

Financing solutions for the infrastructure have to be discussed. Investments by the private sector might be preferable, only supported by governmental subsidies where needed. Decisions and regulations on national and European level towards a specific technology and infrastructure would reduce investment risks and thus support private investments.

While costs for the zero- and low-emission vehicles are higher at first, lower energy prices and lower maintenance cost in addition with policy-driven advantages, like lower registration taxes and road charges, will partly compensate higher vehicle prices over time. In addition, vehicle prices of new technologies decrease with higher production numbers and technological learning.

Governmental subsidies and tax reductions, e.g. for supporting R&D and reducing alternative fuel prices, seem required for the market penetration of low-emission vehicles.

To conclude, a mix of governmental and private investments and expenditures is needed to achieve the decarbonisation according to the two analysed policy scenarios.

7 Impact on the electricity system and the role of flexibility provided by the transport sector

7.1 Link to the electricity system and overall efficiency

The investigated decarbonisation options for transport are strongly linked to the power sector. First, the real emission reduction potential through low-emission technologies and synthetic fuels depends strongly on the share of renewable electricity in the European grids. Secondly, alternative fuel technologies provide further flexibility options for an energy supply system that depends to a large degree on volatile renewable energy sources. In this chapter, the development of electricity demand from transport is illustrated and results of the electricity system models Enertile and EMPIRE are presented focusing on the value of provided flexibility.

The flexibility potential is determined by the electrification type and the acceptance of load shifting. While trains, trolley trucks and trolley busses that are powered by overhead wires will increase electricity consumption directly at the time when the transport activity takes place, BEV, PHEV and the production of hydrogen via electrolysis as PtG provide a certain flexibility potential due to their storage options.

Load shifting of BEV and PHEV can be incentivised by a reduced electricity price but might also depend on familiarity with demand side management from other sectors like home appliances. What concerns the flexibility potential of synthetic fuel production, it is dependent on where the fuels will be produced. Most probably, only the less-energy-intensive PtG-Hydrogen production will be available as flexibility option in Europe while the other fuels might be imported (see arguments for decisions in chapter 2.3).

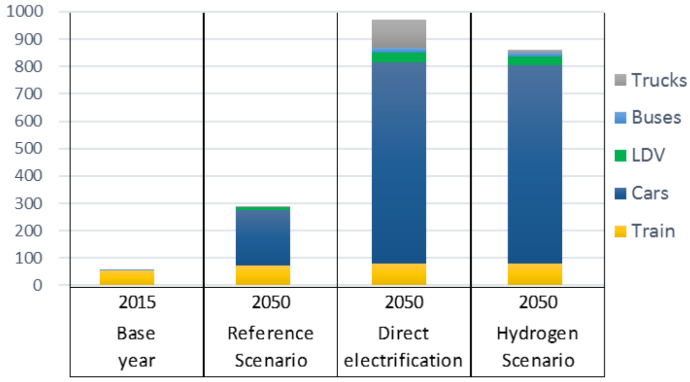
There is a tendency that the higher the flexibility potential the lower the overall efficiency: The best overall efficiency can be achieved by direct electrification with power generation from renewable energy sources either as battery-electric vehicles or as powered overhead-cable solutions. BEVs can achieve an overall efficiency factor of more than 70%, FCEVs achieve only around 30%. For a cross-sector optimisation, flexibility should only be a relevant criteria as long as it supports a secure and cost-efficient energy system, but above this level, overall efficiency should be a main decision criteria.

7.2 Development of electricity demand in the transport sector

The electricity demand from transport is expected to increase strongly compared to today if electrification is chosen as solution for the decarbonization of the transport sector. In the Policy scenarios, electricity consumption constitutes around 30% of the final energy demand of transport in 2050 (see chapter 5.2.1.1).

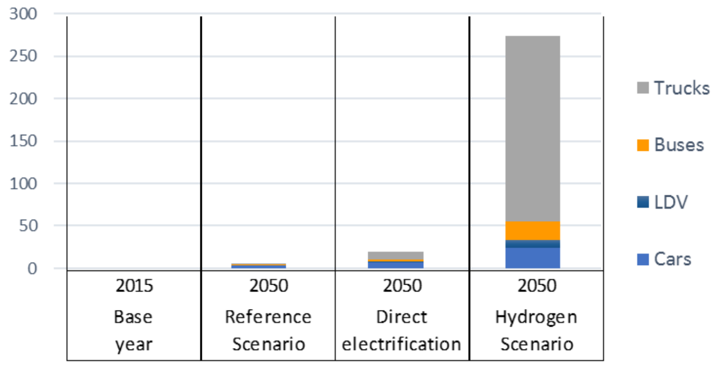
While trains consume more than 99% of the electricity consumption from transport in 2015, cars will constitute the main electricity demand by 2050 in all scenarios due to the diffusion of battery-electric vehicles. In the Direct electrification scenario, hybrid trolley trucks will consume electricity in a more or less comparable quantity like trains, both offering no flexibility options. In the Hydrogen scenario instead, around 270 TWh Hydrogen are needed in 2050 and have to be produced via electrolysis, ideally in times of electricity oversupply.

Figure 16 and Figure 17 show the electricity and hydrogen consumption by scenario. The respective quantities provide also an indication on the higher efficiency in the Direct electrification scenario and the higher flexibility potential in the Hydrogen scenario.



Source: ASTRA

Figure 16: Electricity consumption in TWh in EU28 in 2050 by scenario and mode



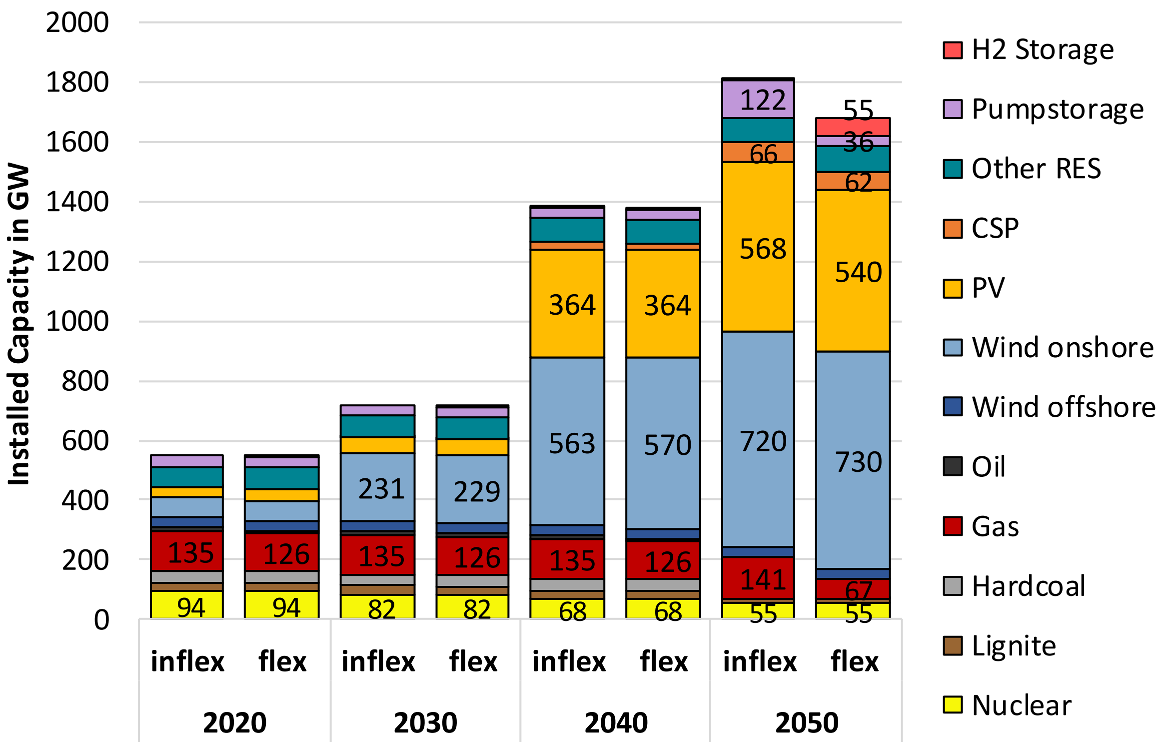
Source: ASTRA

Figure 17: Hydrogen consumption in TWh in EU28 in 2050 by scenario and mode

7.3 Results from the electricity system model Enertile®

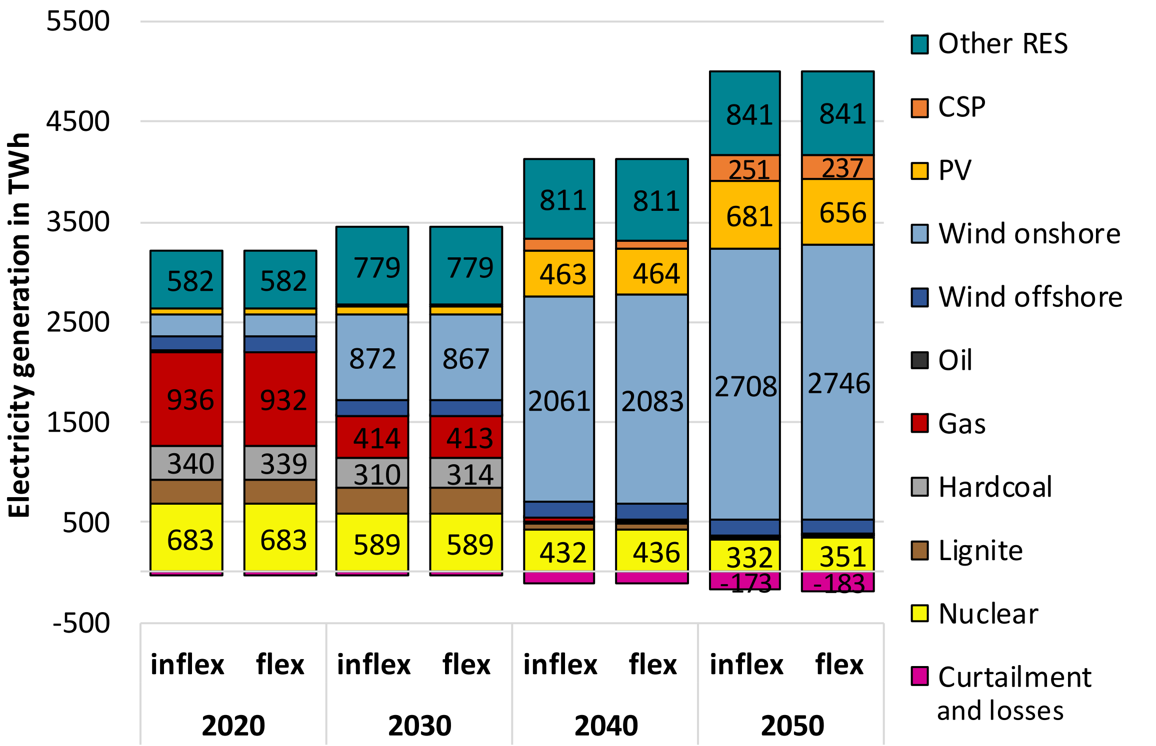
As described in section 3.2.4, two different scenarios are calculated using the Enertile® optimization model (cf. Table 3). A flexible and an inflexible scenario are defined based on the *Direct electrification* scenario results by the model ASTRA. The difference between these respective scenarios is the rate of smart charging participants with BEVs and PHEVs and the availability of hydrogen reconversion. In the following, the scenario results are analysed with regard to the electricity mix in the power sector, the emerging CO_2 emissions and the utilization of other flexibility options, i.e. exports and imports in the European power grid and the utilization of electricity storage facilities.

The following figures display the installed capacities (Figure 18) and the electricity generation (Figure 19) in both scenarios.



Source: Enertile®

Figure 18: Comparison of installed capacity in the inflex and flex scenario from Enertile



Source: Enertile®

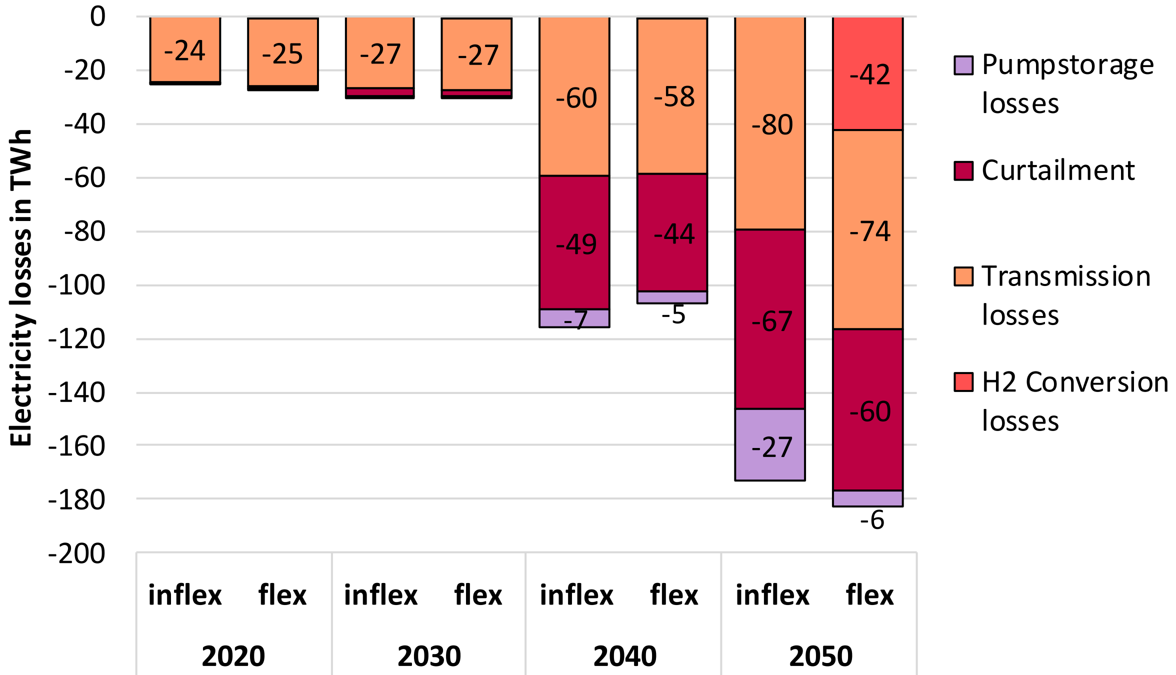
Figure 19: Comparison of electricity generation in the inflex and flex scenario from Enertile

In the scenario years between 2020 and 2040, the electricity mix is approximately the same in both scenarios. As the greatest differences between both scenarios arise in the scenario year 2050, the following analysis concentrates on installed capacities and electricity generation in 2050.

The optimization results show that in 2050 renewable energies are predominant in the European electricity generation. In both scenarios only about 8% of the electricity demand is provided by conventional energy sources. Nuclear and gas power plants are the only conventional generation technologies in use. At a CO_2 price of 150 €/t_{CO2} lignite and hard coal fired power plants cannot compete with other, less carbon-intensive generation technologies and are phased out. Providing the model with flexibility options in the transport sector (flex scenario) the installed gas turbine capacity is reduced by more than 50% compared to the inflex scenario. Gas fired power plants mainly provide peak generation in times of high residual load: In hours with a high electricity demand and low availability of renewable energies, gas fired power plants provide flexibility to the electricity system. In the flex scenario this natural gas based flexibility is substituted in parts (6 TWh) by shifting peak loads through smart charging and the emission free reconversion of hydrogen in gas turbines. By definition, there is the same installed nuclear capacity in both scenarios. The optimization results show that the model uses the flexibility options in the transport sector to increase the utilisation of the given capacities: In the flex scenario the electricity generation by nuclear power increases by 6%.

The most important renewable generation technology in 2050 is onshore wind power. With installed capacities of 720 GW in the inflex scenario and 730 GW in the flex scenario, it covers about 56 % and 57% of the annual European electricity demand. The additional flexibility options in the transport sector in the flex scenario lead to a decrease of concentrated solar power (CSP) generation by around 5% compared to the inflex scenario. Although CSP power plants are more expensive than photovoltaic (PV) power plants, they offer the advantage of a short-term power storage and thus a flexibility option for the power system. In the flex scenario this flexibility provided by CSP is substituted in parts by the flexibility options in the transport sector. A further comparison between the flex and the inflex scenario shows an exchange of electricity generation by onshore wind power and PV: The generation by onshore wind is higher (38 TWh) in the flex scenario and the generation of PV is higher (25 TWh) in the inflex scenario. A possible explanation of the exchange between these two technologies could be that the generation profile of PV matches the inflexible demand profile of electric vehicles better than the generation profile of wind generation.

Figure 20 displays curtailment, transmission losses and conversion losses in power storage systems. These figures can be interpreted as proxies for the utilization of flexibility options in the two scenarios. Scenario year 2050 shows the greatest difference in these figures between the flex and inflex scenario. Hydrogen reconversion is only possible in the flex scenario. Figure 20 indicates that the presence of load shifting options and the possibility of hydrogen reconversion in the flex scenario reduces the utilization of pump storages, the electricity exchange between countries and the amount of curtailed renewable power.



Source: Enertile®

Figure 20: Comparison of electricity losses and curtailment in the inflex and flex scenario from Enertile

Table 5 lists the resulting CO_2-emissions in the electricity sector per year for both Enertile scenarios. The utilization of flexibility options in the transport sector reduces the annual CO_2-emissions by up to 16% in the year 2050. This reduction can be almost entirely attributed to the lower gas-fired electricity generation in the flex scenario.

Table 5: CO_2-emissions per scenario year in the inflex and flex scenario from Enertile

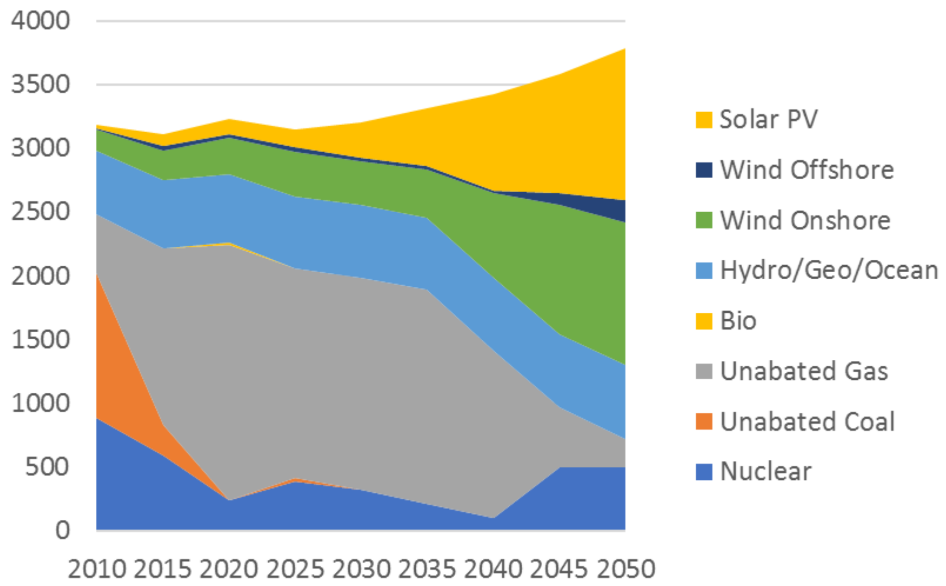
CO_2-emissions in Mt CO_2	2020	2030	2040	2050
Flex	883.15	664.72	65.83	16.23
Inflex	885.98	663.04	74.67	18.89

7.4 Results from the electricity system model EMPIRE

The electricity system model EMPIRE provides insights on the development of the electricity generation mix until 2050 and the potential uptake of flexibility options from transport in the Reference scenario and the Direct electrification scenario based on the changes in electricity demand due to the diffusion of battery-electric vehicles. As described in section 3.2.5 the uptake of flexibility options is based on cost assumptions for investments for passenger and freight transport to control loads and resulting temporal cost differences (hourly resolution) due to the variability of electricity supply and demand.

7.4.1 Development of the electricity generation mix

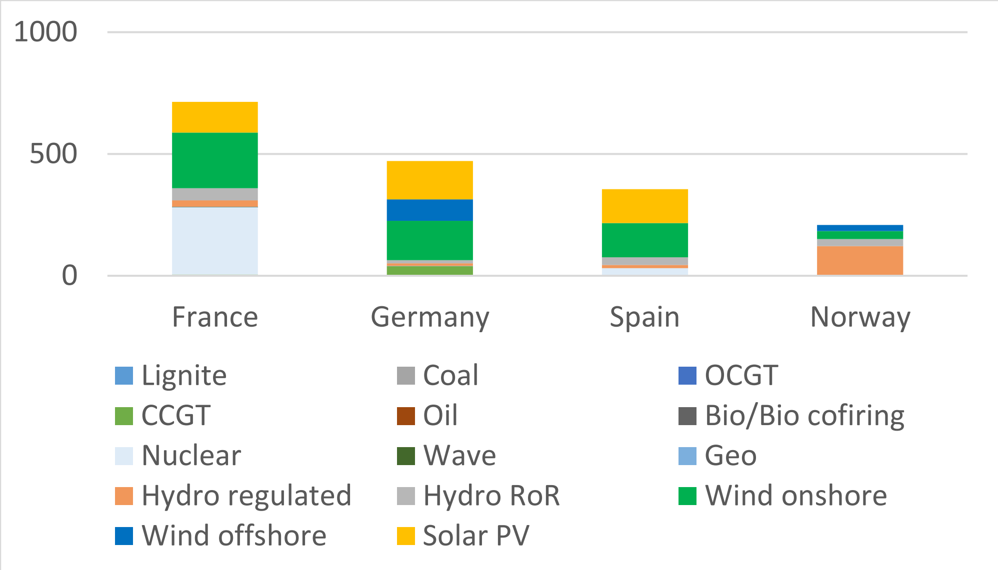
Figure 21 illustrates the generation mix resulting from the policy scenario implemented for this case study in the EMPIRE model. Also total system costs do not deviate significantly between the scenarios. Note that in contrast to the scenarios calculated by the Enertile® model no difference in CO_2 prices or emission reduction targets where assumed. Also note that due to the stochastic nature of the model, the results are less sensitive to rather small changes in electricity demands. Therefore, the differences in electricity demand from transport, heating and cooling between the scenarios result in very similar results for the optimal generation mix. In both scenarios the aggregated generation mix (Figure 21) is characterized by a strong uptake of electricity generation from PV and onshore Wind. Electricity production from coal is phased out and also electricity production from nuclear power plants decreases significantly until 2040, but its backup capacity is required between 2045 and 2050. While electricity generation from natural gas increases in a transition phase, by 2050 natural gas is also strongly reduced mainly serving as backup for hours with low feed-in from variable renewable energy sources. Figure 22 illustrates the resulting electricity generation mix per technology in 2050 for selected countries.



Source: EMPIRE

The development is characterized by a substitution of coal by gas until 2025 and a substantial uptake of solar PV from 2035 to 2050. The generation mix is very similar to the reference scenario which is why only the results for the current policy scenario is shown.

Figure 21: Aggregated generation mix evolution in Europe in TWh from EMPIRE



Source: EMPIRE

Figure 22: Generation mix by technology in selected countries in the reference scenario in TWh

7.4.2 Uptake of flexibility options from the transport sector

Under the assumptions on investment costs for flexible loads presented in section 3.2.5 the EMPIRE model estimates a strong uptake of flexible EV charging to be optimal from a system's cost perspective. Note that non-economic barriers are not included in this analysis. It is assumed that the technologies needed to control EV charging based on price or other signals are available for end users. It is also assumed that end users or other intermediaries are operating decentral EV charging in a cost optimal way, although still under the load shifting restrictions implemented in the model.

Under those assumptions, the installed flexible loads in the transport sector in 2050 are: 170 GW in EV group 2 and 32 GW in EV group 1 for the policy scenario, and 50 GW and 1 GW respectively in the reference scenario (Figure 23). The total investment costs for all flexible loads from 2015 to 2050 in flexible loads amounts to 5.5 bn€/2015 in the policy case and 5.6 bn€/2015 in the reference case. The difference between the two cases and the two EV groups is explained by the amount of energy consumed in each case.

The estimated evolution of Demand Response (DR) capacities illustrated in Figure 23 is directly linked to the electricity generation mix. The model estimates strong increases from 2035 to 2050 as flexible EV charging investment costs are zero in this period and due to a massive intake of solar and wind capacity (see Figure 21).

Considering the peak loads of European electricity demand between 400 GW and 450 GW, the total installed flexible loads of more than 200 GW (in the policy case) indicate a substantial flexibility potential to balance the supply of renewables[2].

[2] Note however that the hourly availability of flexible loads and also the energy shifting potential of each flexibility source varies significantly, which was considered in the model runs but is not illustrated by the aggregated figure.

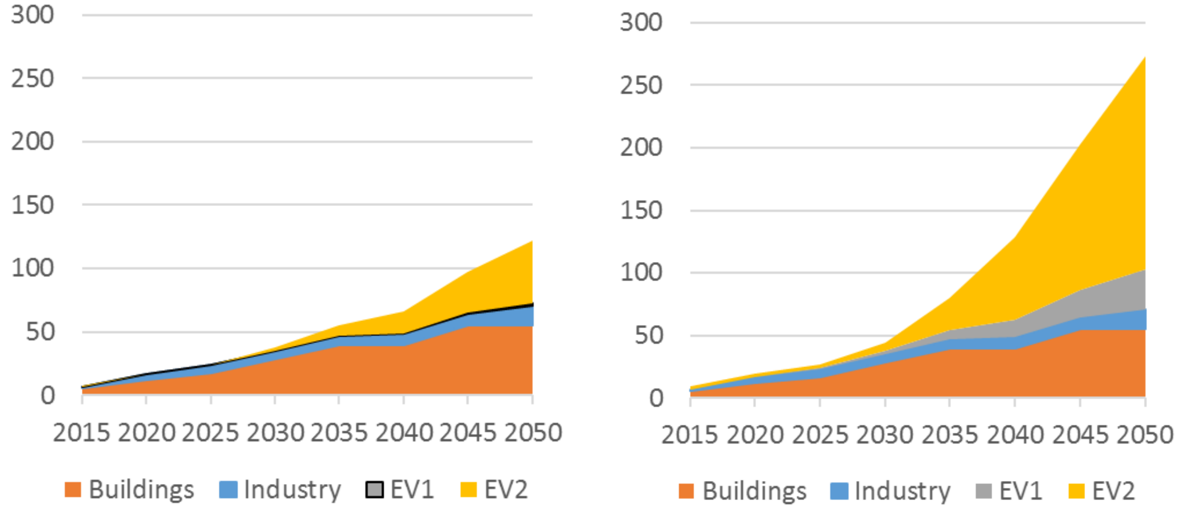


Figure 23: Installed flexible loads in GW by sector and transport group (EV1/EV2) with the reference case on the left and the policy case on the right

The countries with highest EV DR are shown in Figure 24. France, Germany, UK and Italy are the countries with highest DR installed capacity with 36, 32, 31 and 22 GW in EV1 and EV2. They are also countries with high shares of renewables, in particular PV.

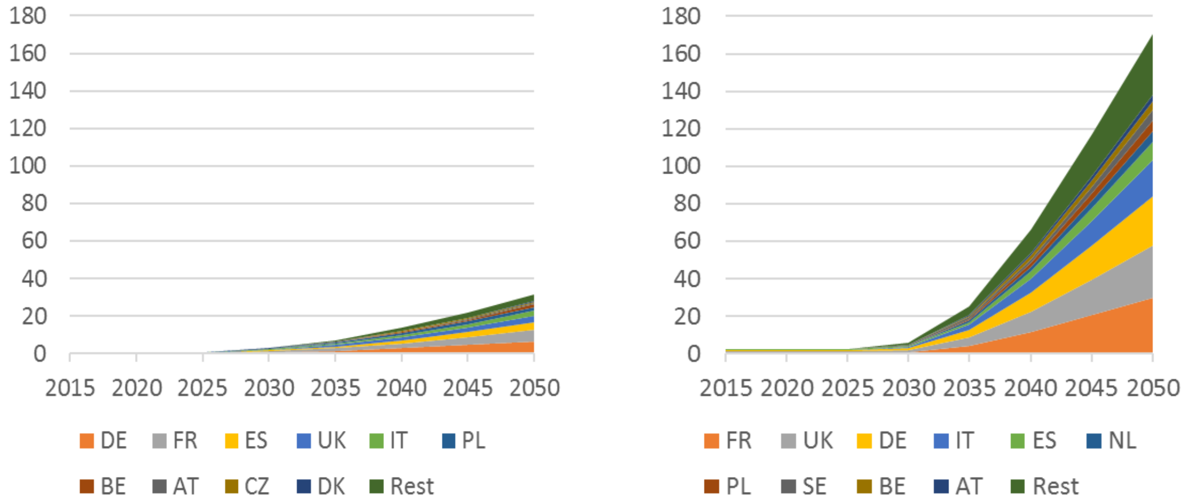


Figure 24: EV charging DR capacity in GW by country in the policy scenario for EV1 (left) and EV2 (right)

To compare different geographic locations across Europe, Figure 22 and Figure 25 show the flexible loads mix and generation mix of France, Germany, Spain and Norway in 2050. Countries with high solar radiation such as France and Spain take advantage of shifting demand to times of high electricity generation from PV by means of these flexible loads. Flexible loads are also used for shifting demand to times of high electricity generation from wind (Germany) or hydropower (Norway).

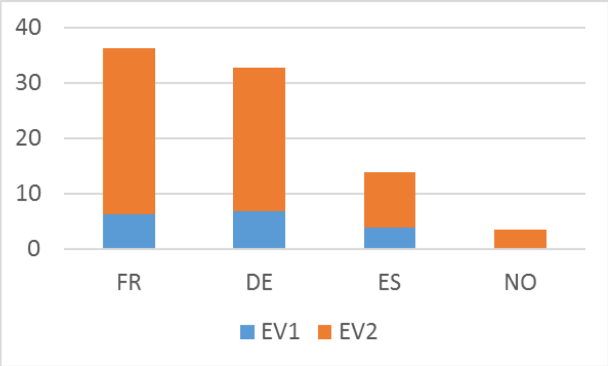


Figure 25: Installed flexible loads in GW in selected countries in the policy scenario

Figure 26 shows how shifting charging is cost effective during solar peak production. Most of the flexibility is provided by EV charging.

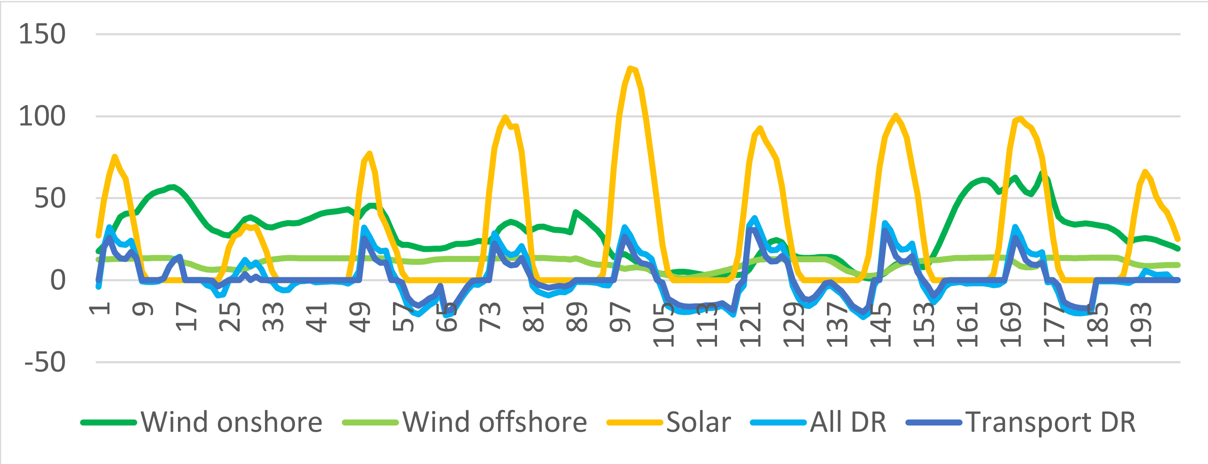


Figure 26: Sample of hourly operation in GW in Germany in 2050 during winter and spring

7.5 Summary of impacts on the electricity system

The following main conclusions can be drawn from the simulated scenarios in ASTRA and the optimization runs performed by the two electricity system models:

- Electricity demand for transport is expected to increase strongly by 2050 in the assumed policy settings due to the diffusion of BEV, PHEV, FCEV and trolley trucks. Therein, cars will be the transport mode with the highest electricity consumption in 2050.
- BEV, PHEV and FCEV can provide flexibility to the electricity system. If load shifting is accepted and charging infrastructure is deployed in public areas and at company sites, a certain flexibility potential can be provided by BEV and PHEV during day and night and peak loads in the early evening hours can be reduced. Hydrogen for FCEV can be produced in times of surplus electricity and be used as electricity storage with the option of reconversion.
- The results from the electricity system model Enertile® indicate that flexibility options in the transport sector can significantly reduce the need for back-up capacity in the electricity system.
- The results from the electricity system model EMPIRE suggest that a strong uptake of flexible EV charging could be cost effective. In general, there is a large potential for EV charging to contribute to balancing the variable supply of renewable electricity generation sources.

8 Summary, interpretation and lessons learned for the decarbonisation pathways

The major strategies for decarbonising the transport sector are (1.) shifting to more efficient transport modes, (2.) diffusion of low/zero-emission technologies, and (3.) bio & synthetic fuels. In this case study, ambitious policy scenarios were analysed to achieve a CO_2 emission reduction in the transport sector of 60% to 65% by 2050 compared to 1990. The case study differentiated two ambitious policy scenarios due to two promising technologies for road freight transport: (1.) Direct electrification achieved by hybrid-trolley trucks on motorways, and (2.) Power-to-Hydrogen based fuel cell electric vehicles. These transition scenarios include several strong policy measures. As methodology, a modelling approach was applied which linked the transport sector model ASTRA with the model ALTER-MOTIVE for the simulation of technological progress of electric vehicles and with the electricity system models Enertile® and EMPIRE.

The results show that all three strategies for decarbonisation have to be combined. The shift to more efficient road modes is partly restricted by limited capacities of public transport and railways, and depends a lot on behaviour change that is hard to achieve and is influenced by various factors. The new powertrain technologies offer huge potentials for decarbonisation, however, due to high production costs at market entry level, a lack of infrastructure in many countries and low acceptance, the diffusion of these technologies has to be pushed with diverse measures including stronger R&D, subsidies, deployment of the filling and charging infrastructure and increased CO_2 emission standards. Even phase-out decisions of pure internal combustion engine vehicles should be considered. After having achieved a certain diffusion level, decreasing prices and range increases due to technological learning as well as higher acceptance due to familiarity with the alternative options are expected to accelerate the diffusion. As sustainable biomass is limited and the efficiency of synthetic fuels is low, both options should mainly be considered as supplement for aviation and ships for which low-emission alternatives will not be available in the upcoming decades. Moreover, technological options have to be assessed on their flexibility potential that they provide for the electricity system and on the overall efficiency because sector coupling is key to achieve the overall energy system transformation in a cost-efficient way. The results from the electricity system models indicate that flexibility options provided by the transport sector can significantly reduce the need for back-up capacity in the electricity system. While battery charging and hydrogen production constitute promising flexibility potential in Europe, it seems more cost-efficient to produce other synthetic fuels that are based on electrolysis in non-European countries at locations where renewable electricity can be generated at lower cost due to better conditions.

The analysed ambitious scenarios reflect a radical change to be achieved within three decades only. Policies need to be in place soon to drive this transition. It has to be noted that the European reduction target by 2030 will leave a huge gap to meet the very challenging target in 2050 in only 20 years. The argument for an increasing effort over time is that a wider set of cost-effective technologies will become available (European Commission (2011a)). However, considering the lifetime of vehicles and the accumulation of carbon dioxide in Earth's atmosphere, policies might rather aim at overachieving the 2030 target. Furthermore, the reduction target for the transport sector of minus 60% in 2050 compared to 1990 was defined in 2011 in the European Low Carbon Roadmap that aims at reducing overall European GHG emissions by 80% across all sectors. The 2015 Paris Agreement calls for countries to pursue efforts to limit global-mean temperature rise to significantly below 2°C, ideally to 1.5°C. Therefore, it is under discussion that the EU should even aspire to reduce overall GHG emissions by up to 95% by 2050 in order to achieve this goal. This could mean even more efforts for the transport sector. To decarbonize transport even further, the bio-fuel share could be increased or PtX-fuels could be used if not enough sustainable biomass is available. In addition, more efforts could be made to achieve behaviour change in order to shift to more efficient or active modes. This could also include fully automated vehicles that bridge the 'last-mile' to improve access to public transport.

Thus, intensive discussions are required on the best policy mix on European and national level as well as on further required framework conditions. Relevant discussion points include the current strategy of technological openness versus a focus on the most cost-efficient technology pathway, the role and appropriate production sites of synthetic fuels and most effective and cost-efficient policy measures. More research seems needed to evaluate alternative strategies for the deployment of new infrastructure, in particular for hydrogen production, distribution and an adequate filling station set-up as well as for the production of synthetic fuels. Moreover, measures for the transition should ensure affordability and inclusiveness of mobility.

The ambitious policy scenarios investigated in this case study assume a strong cooperation between all European countries with joint decisions on strong policy measures and on technology choice for freight road transport leading to a comprehensive electrification of road transport. Under different conditions, synthetic and bio fuels might have a stronger role for decarbonising the transport sector. Within the SET-Nav project, four holistic transformation pathways will be simulated with the whole SET-Nav consortium to achieve EU GHG reduction targets across all sectors. Each pathway represents specific framework conditions and trends that might evolve in the upcoming decades varying the two key uncertainties degree of cooperation and degree of decentralisation. The insights gained in this case study will be the basis for defining the pathways for the transport sector. Results will be available for download on the project website www.set-nav.eu.

9 References

Capros P. et al. (2016): EU Reference Scenario 2016: Energy, transport and GHG emissions Trends to 2050, Download at: https://ec.europa.eu/energy/en/data-analysis/energy-modelling.

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

European Commission (2011b): The Transport White Paper - Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. White Paper, COM(2011)144 final, Brussels.

European Commission (2017): EU Transport in Figures - Statistical Pocketbook 2017.

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

Gnann T. et al. (2017): Brennstoffzellen-Lkw: kritische Entwicklungshemmnisse, Forschungsbedarf und Marktpotential. Final report of the study on behalf of the German Federal Ministry of Transport and Digital Infrastructure. Karlsruhe, Germany.

Krail M. (2009): System-Based Analysis of Income Distribution Impacts on Mobility Behaviour. Dissertation at the University of Karlsruhe (TH), Nomos-Verlag, Baden-Baden, Germany.

Krail M. et al. (2018, upcoming): Energie- und Treibhausgaswirkungen des automatisierten und vernetzten Fahrens im Straßenverkehr. Final report of the study on behalf of the German Federal Ministry of Transport and Digital Infrastructure. Karlsruhe, Germany.

Mock P. (2018): The role of standards in reducing CO2 emissions of passenger cars in the EU. Policy paper from ICCT. Brussels, Belgium.

OPSD (2017): Open Power System Data. Data Package Time series. Version 2017. Download at: https://data.open-power-system-data.org/time_series/2017-03-06.

Robinius M. et al. (2018): Comparative Analysis of Infrastructures: Hydrogen Fueling and Electric Charging of Vehicles. Energy & Environment. Volume 408. Jülich, Germany.

Schade W. (2005): Strategic Sustainability Analysis: Concept and application for the assessment of European Transport Policy. Nomos Verlag, Baden-Baden, Germany.

Schipper L., Marie-Lilliu C. (1999): Transportation and CO2 Emissions. Flexing the Link - A Path for the World Bank. Paper published by the World Bank.

SETIS (2017): EMHIRES datasets. Strategic Energy Technologies Information System. Download at: https://setis.ec.europa.eu/EMHIRES-datasets.

Skar, C. et. al. (2016): A multi-horizon stochastic programming model for the European power system. CenSES working paper 2/2016. ISBN: 978-82-93198-13-0.

Timmerberg, S. et al (2018, upcoming): Importoptionen für strombasierte Kraftstoffe aus Erneuerbaren Energien für den Lkw-, Binnenschiff-, Hochseeschiff- und Luftverkehr; Report of the study on behalf of the German Federal Ministry of Transport and Digital Infrastructure; TU Hamburg-Harburg IUE, Fraunhofer ISI; Hamburg, Karlsruhe.

Wietschel M. et al. (2017): Machbarkeitstudie zur Ermittlung der Potentiale des Hybrid-Oberleitungs-Lkw. Final report of the study on behalf of the German Federal Ministry of Transport and Digital Infrastructure. Karlsruhe, Germany.