

Decarbonisation of transport: options and challenges



EASAC policy report 37

March 2019

ISBN: 978-3-8047-3977-2

This report can be found at
www.easac.eu

EASAC

EASAC – the European Academies' Science Advisory Council – is formed by the national science academies of the EU Member States to enable them to collaborate with each other in giving advice to European policy-makers. It thus provides a means for the collective voice of European science to be heard. EASAC was founded in 2001 at the Royal Swedish Academy of Sciences.

Its mission reflects the view of academies that science is central to many aspects of modern life and that an appreciation of the scientific dimension is a pre-requisite to wise policy-making. This view already underpins the work of many academies at national level. With the growing importance of the European Union as an arena for policy, academies recognise that the scope of their advisory functions needs to extend beyond the national to cover also the European level. Here it is often the case that a trans-European grouping can be more effective than a body from a single country. The academies of Europe have therefore formed EASAC so that they can speak with a common voice with the goal of building science into policy at EU level.

Through EASAC, the academies work together to provide independent, expert, evidence-based advice about the scientific aspects of public policy to those who make or influence policy within the European institutions. Drawing on the memberships and networks of the academies, EASAC accesses the best of European science in carrying out its work. Its views are vigorously independent of commercial or political bias, and it is open and transparent in its processes. EASAC aims to deliver advice that is comprehensible, relevant and timely.

EASAC covers all scientific and technical disciplines, and its experts are drawn from all the countries of the European Union. It is funded by the member academies and by contracts with interested bodies. The expert members of EASAC's working groups give their time free of charge. EASAC has no commercial or business sponsors.

EASAC's activities include substantive studies of the scientific aspects of policy issues, reviews and advice about specific policy documents, workshops aimed at identifying current scientific thinking about major policy issues or at briefing policy-makers, and short, timely statements on topical subjects.

The EASAC Council has 29 individual members – highly experienced scientists nominated one each by the national science academies of EU Member States, by the Academia Europaea and by ALLEA. The national science academies of Norway and Switzerland are also represented. The Council is supported by a professional Secretariat based at the Leopoldina, the German National Academy of Sciences, in Halle (Saale) and by a Brussels Office at the Royal Academies for Science and the Arts of Belgium. The Council agrees the initiation of projects, appoints members of working groups, reviews drafts and approves reports for publication.

To find out more about EASAC, visit the website – www.easac.eu – or contact the EASAC Secretariat at secretariat@easac.eu

European Academies



Science Advisory Council

Decarbonisation of transport: options and challenges

ISBN 978-3-8047-3977-2

© German National Academy of Sciences Leopoldina 2019

Apart from any fair dealing for the purposes of research or private study, or criticism or review, no part of this publication may be reproduced, stored or transmitted in any form or by any means, without the prior permission in writing of the publisher, or in accordance with the terms of licenses issued by the appropriate reproduction rights organisation. Enquiries concerning reproduction outside the terms stated here should be sent to:

EASAC Secretariat
Deutsche Akademie der Naturforscher Leopoldina
German National Academy of Sciences
Jägerberg 1
D-06108 Halle (Saale)
Germany

Telephone: +49 345 4723 9833
Fax: +49 345 4723 9839
Email: secretariat@easac.eu
Web: www.easac.eu
Twitter: [@EASACnews](https://twitter.com/EASACnews)
Facebook: www.facebook.com/EASACnews/

Cover image: Schild mit CO₂ by Stockwerk-Fotodesign.

Copy-edited and typeset in Frutiger by The Clyvedon Press Ltd, Cardiff, United Kingdom

Printed by Schaefer Druck und Verlag GmbH, Teutschenthal, Germany. Printed on FSC-certified paper.

Contents

	<i>page</i>
Foreword	v
Summary	1
Target audience and aims of the report	4
Scope	4
Report structure	4
1 Introduction	5
1.1 The challenge of decarbonisation	5
1.2 The gap between GHG emission goals and expected market trends	5
1.3 How to close the gap: framework for transport decarbonisation	6
2 Transport demand	9
2.1 Links between transport demand, economic development and emissions	9
2.2 Containing transport demand and shifting to more efficient modes	9
2.2.1 Passenger transport	9
2.2.2 Freight transport	13
3 Transport supply options and technologies	17
3.1 Overview	17
3.2 Vehicle selection	18
3.3 Vehicle design	19
3.4 Powertrain technology and fuel substitution options	19
3.4.1 Overview of transitional options and long-term sustainable options	19
3.4.2 Internal combustion engine vehicles and hybrid electric vehicles	20
3.4.3 Battery electric vehicles and plug-in hybrid electric vehicles	23
3.4.4 Hydrogen and fuel cell electric vehicles	25
3.4.5 Electric road systems	26
3.4.6 Costs and efficiencies of transport electrification options	26
3.5 Coupling of transport, electricity, buildings and industry sectors	28
3.5.1 Overview of coupling interfaces	28
3.5.2 Future energy and power demands for transport electrification	29
3.5.3 Battery charging infrastructure	29
3.5.4 Markets for grid flexibility management services	30
3.5.5 Standards, rules and tariffs for charging electric vehicles	30
3.6 Timescales for decarbonisation using alternative technologies or fuels	31
3.6.1 Options for use in the transition phase	31
3.6.2 Sustainable solutions for the long term (2050)	32
3.7 Life cycle emissions of vehicles with different powertrains	32
4 Information and communications technologies (ICT) and autonomous vehicles	35
4.1 ICT	35
4.1.1 ICT for avoiding/reducing transport demand	35
4.1.2 ICT for road transport demand and traffic management	35
4.1.3 ICT with big data and artificial intelligence	36
4.1.4 ICT in vehicles	36
4.1.5 ICT for charging electric vehicles	36
4.2 Autonomous vehicles	36

5	Discussion and conclusions	38
5.1	Overview	38
5.2	Emission reductions from innovative transport demand management	38
5.3	Emission reductions from innovative vehicle technologies and fuels	38
5.4	Promoting emission reductions with taxes, incentives and public financing	41
5.5	Promoting EU industries, jobs, skills and further research	42
6	Advice for policy-makers	43
	References	47
	Abbreviations	54
Annex 1	2014 IPCC assessment report	55
Annex 2	Expected evolution of autonomous vehicles	56
Annex 3	Future availability of rare element resources	56
Annex 4	Working group composition and timetable	57
Annex 5	Acknowledgements	58

Foreword

The use of motorised transport has become a familiar feature of everyday life. Many of us regularly use a car, train or bus for travelling to school or college, to work or to meet with friends and family. Typically, most of us in Europe travel less than about 25 kilometres a day for much of the year, but we take longer trips at least once a year for holidays. This is made possible by the widespread availability of fossil fuels. Consequently, the use of fossil fuels for transport is now responsible for almost a quarter of all greenhouse gases (GHG) emitted in the European Union (EU), and thus is a significant contributor to global warming.

The latest analyses by the United Nations Intergovernmental Panel on Climate Change (UN IPCC) confirm the need for urgent actions to reduce GHG emissions if the world is to meet its Paris Agreement commitments to limit global warming to less than 2°C or further to 1.5°C. This, in turn, requires that we drastically cut the GHG emissions due to transport.

This line of thinking is also expressed in the UN framework. In 2015, all countries adopted the UN 2030 Agenda and its 17 Sustainable Development Goals (SDGs), among which the decarbonisation of transport is particularly relevant to SDG 7 'Ensure access to affordable, reliable, sustainable and modern energy' and SDG 13 'Take urgent action to combat climate change and its impacts'.

With these goals and commitments in mind, a group of experts, nominated by their national science academies (EASAC member academies), spent 18 months in 2017–18 reviewing the available options for reducing GHG emissions from the transport sector. This report summarises the group's analyses, conclusions and advice for policy-makers.

In agreement with many other groups of experts working in this field, EASAC confirms that there is no 'silver bullet' that can quickly reduce GHG emissions from transport to near zero. This report convincingly argues that a coordinated combination of policies and measures is urgently needed on many levels to deliver changes to the transport fleet and related infrastructure, to electrical power generation with which transport will be increasingly coupled in future and, last but not least, to human behaviour. It recommends immediate actions during a transition period, as well as sustainable actions for the long term; and it shows that both these types of action will affect many parts of society, and will require commitments, investments and changes from policy-makers at all levels, including international (EU), national (all countries), local (cities, regional and local communities) and individual (citizens and businesses).

Current policies and economic practices ('business as usual') fall far short of achieving the Paris Agreement goals. Drastic societal changes are required. These will need decisive political action by the EU, national authorities and local communities. They must include curbing the demand for transportation, shifting transport from high GHG emission vehicles to more efficient ones, and the development and use of carbon-free (mostly electric) vehicles, while decarbonising electricity production.

Reducing transport GHG emissions also improves health and the quality of life, particularly in cities, by walking and cycling instead of using motorised transport for short journeys. Such reduction is also achieved by using energy-efficient transport modes, such as buses, trains and trams instead of cars or planes whenever possible. Renewing the car and lorry fleet with energy-saving and low GHG emission vehicles is also an essential ingredient of a sensible political action.

Similar actions must be undertaken in the freight transport area. Vehicles must be used more efficiently and the use of energy-efficient transport modes, such as trains and ships, for deliveries must be increased. Here again decisive political action is required if significant results are to be achieved.

The electrification of transport is creating several challenges related to the generation, distribution and storage of electricity, both in vehicles and in the electricity supply system. To meet these challenges is a complex endeavour, which will require innovative policies and substantial investments in the coming years.

The decarbonisation of transport is a challenge; but it is also an opportunity for industries and businesses to develop and produce new products and services, which take advantage of new business models facilitated by digital technologies, and to create new high-quality jobs. It is our hope that this report and the analysis it contains will not only reinforce the EU's scientific basis for tackling GHG emissions from transport, but also help EU policy-makers and other stakeholders to prioritise their future policies, legislation and investments in this important sector.

Thierry Courvoisier
EASAC President

Summary

This report was triggered by discussions between members of the European Academies' Science Advisory Council's (EASAC's) energy steering panel on the challenges faced by the European Union (EU) in the light of the Paris Agreement; in particular, the challenge of reducing emissions from the transport sector, which relies almost totally on fossil fuels. It was also stimulated by the EU energy and climate package, which was released in November 2016, entitled 'Clean Energy for all Europeans', and the three packages of the EU initiative 'Europe on the Move'.

A group of 18 experts, who had each been nominated by their national science academies, came together in July 2017 to discuss the decarbonisation of transport at a workshop with officials from six Directorates-General of the European Commission (Mobility and Transport (MOVE); Energy (ENER); Climate Action (CLIMA); Environment (ENV); Regional and Urban Policy (REGIO); and Joint Research Centre (JRC)) as well as experts from the International Transport Forum within the Organisation for Economic Co-operation and Development (ITF-OECD), the European Automobile Manufacturers' Association (ACEA) and Local Governments for Sustainability (ICLEI). During the workshop, it was noted that greenhouse gas (GHG) emissions from the European transport sector currently represent approximately 24% of total GHG emissions from the EU and that, within this sector, the emissions were dominated by those from road transport (72%): those from passenger cars and light-duty vehicles (LDVs) amounted to about 53% and those from buses and heavy goods vehicles to about 19%.

After the workshop, it was concluded that EASAC should focus on the biggest challenge, namely road transport. This report therefore examines decarbonisation of road transport, with only brief comments on rail, maritime and aviation transport. It has separate chapters on demand and supply perspectives, and adopts a framework for tackling these challenges using sustainable solutions for the long term and transitional solutions for the short term.

Gap between GHG emission goals and expected market trends

The gap between the GHG emissions projected in the EU Reference Scenario 2016 and the level of emissions needed to limit global warming to less than 2°C or even further to 1.5°C (Paris Agreement) is huge. The EU has already adopted a strategy for low-emission mobility to promote the decarbonisation of transport and has strengthened the EU Emission Trading System (ETS) by increasing the pace of annual reductions in allowances and adding a market stability reserve. The ETS does not

directly address the transport sector, but doing so will become increasingly important as transport is electrified. The EU has also committed a growing fraction of its future budget to investments in infrastructure, and to research and innovation for a more sustainable economy.

Nevertheless, much more needs to be done to deliver the target set in the European Commission's White Paper on transport of 2011 to reduce emissions from the transport sector by 60% by 2050 (compared with 1990 levels) and to ensure that EU emissions are firmly on the way to zero by that date.

Future policy options

EASAC has developed advice for policy-makers by building on the initiatives that the EU has already taken to tackle transport emissions, and by prioritising policy options that could be adopted at EU, national and local levels both during the transition to low-carbon transport and in the long term.

Are current EU policies sufficient to deliver GHG emission reduction targets?

Current EU policies are unlikely to deliver emission reductions quickly enough to limit global warming to less than 2°C (Paris Agreement). Emission reductions should be accelerated urgently over the next 10–15 years because cumulative GHG emissions lead to global warming. It will take about 20 years to renew the current vehicle fleet, which could potentially reduce emissions more quickly than by promoting changes in the buildings and industry sectors. However, the current sales of low-carbon vehicles are less than 3% of new vehicles sold in the EU, so the challenge to increase this share is enormous. Decarbonisation of the transport, industry and buildings sectors depends to a large extent on electrification, so the electricity sector must be decarbonised as quickly as possible over the next 10–15 years. In addition, urgent policy support is needed for other short-term options that could quickly reduce emissions, such as containing transport demand and shifting passengers and freight to low-emission transport modes (e.g. buses, trains and ships), and improving vehicle design and the efficiency of powertrains through hybridisation.

Current EU policies do not adequately and visibly address the timely phase-out of fossil fuels. Stronger phase-out policies, regulations and incentives are needed across the competing sectors of transport, energy, buildings and industry. International collaboration and citizen engagement will become more important as falling consumption makes oil and gas prices more volatile.

What should be done to facilitate the transition to a decarbonised future?

There is no 'silver bullet', so a combination of long- and short-term policy options must be supported at EU, national, regional and local authority levels, including awareness campaigns with public sector investments and incentive schemes to help citizens to understand and agree to take action. Increased resources will be needed to inform and engage with local decision-makers, citizen groups and individual consumers throughout the next 10–15 years (transition period).

EASAC's policy recommendations are split into three groups:

- (1) *avoiding* demand for passenger and freight transport services;
- (2) *shifting* passengers and freight to transport modes with lower emissions;
- (3) *improving* performance through vehicle design, deploying more efficient powertrains, and substituting fossil fuels with low-carbon energy carriers.

The highlights of EASAC's advice for policy-makers are summarised below.

- 1. Avoid and contain the demand for conventional motorised transport, and reverse EU policy that 'curbing mobility is not an option'.**
 - (a) Policies by cities, local authorities and business to promote walking, cycling, car sharing, working from home, teleconferencing, etc. to discourage use of passenger cars in urban areas.
 - (b) Policies to contain growth of freight transport (sustainable urban logistics plans) and of aviation for both passengers and freight while supporting economic development, cohesion, consumer services and competitiveness.
- 2. Shift passengers from private cars to public transport services (trains, buses, trams, etc.).**
 - (a) Raise the occupancy levels of existing public transport, and use mobility-as-a-service business models. Use more information and communication technologies (ICT) to provide arrival, departure and overall journey times.
 - (b) Invest in more bus lanes, trams and park-and-ride schemes for rural commuters, and increase the frequency of services with more reliable transfers between buses, trams and trains.
- 3. Shift more freight off the road and onto railways or waterways.**
 - (a) Public and private sectors should jointly invest urgently in more and better access points for intermodal containers to transport freight by rail, inland waterways or maritime services.
 - (b) Substantially bigger investments should be made for the long term to expand routes and capacities for transporting freight by rail, inland waterways and maritime services.
- 4. Improve/introduce regulations during the transition period to decrease consumer demand for oversized vehicles and oversized engines.**
 - (a) Demand for oversized passenger cars and LDVs, and for oversized fossil-fuelled internal combustion engines, should be much more effectively limited and phased out by regulation as soon as possible
 - (b) Awareness campaigns and labelling are also needed to discourage the use of oversized vehicles.
- 5. Improve/reduce the average emissions of all passenger cars and light duty vehicles during the next 10 to 15 years – a crucial transition period.**
 - (a) Binding target dates for phasing out fossil fuels and subsidised scrapping schemes to accelerate renewal of the fleet should be implemented as soon as possible.
 - (b) Hybridisation and optimisation of internal combustion engine vehicle (ICEV) and powertrain design should continue to be promoted using legislation, standards and high-visibility vehicle labelling campaigns.
- 6. Improve/increase the rate of market penetration of battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) for passenger transport as soon as possible.**
 - (a) Incentivise purchase of BEVs and PHEVs (including buses), limit use of fossil fuels in urban areas, install public charging points, and provide recycling facilities for batteries.
 - (b) Certify and label BEVs and PHEVs for embedded emissions on a life cycle basis to limit carbon leakage through overseas battery manufacture. Support battery manufacture in the EU.
 - (c) Regulate the sizing of PHEV batteries and ICEs, so that PHEVs can be excluded from incentive schemes and credits unless they provide electric driving for at least 50–70 km.
- 7. Improve/increase the penetration rate of low-carbon electricity generation into the grid urgently.**
 - (a) Growth of low-carbon electricity generation must be higher than the total growth in electricity demand from transport, hydrogen/synthetic fuel production, industry and buildings sectors.

- 8. *Improve and adapt the design and regulation of electricity markets and tariffs that apply to electric vehicles, so that costs are minimized for all consumers.***
- (a) Promote synergies between grid flexibility management and BEV storage, sharing the costs and benefits between BEV users and others by using time-of-day and power-related tariffs.
 - (b) Permit aggregators and innovative ICT solutions to benefit grid operators and all electricity consumers including industry, buildings, BEV owners and hydrogen/synthetic fuel producers.
- 9. *Improve and simplify guidance on use of biofuels, biogas, natural gas and methane for transport.***
- (a) Sustainability criteria should continue, with a cap on conventional biofuels. Biofuels should not be zero-rated if produced from forest biomass with long carbon-payback times.
 - (b) Natural gas can reduce ICEV emissions but should only be used for transport if all upstream 'fugitive' leakages of methane are monitored, certified and limited to less than about 1%.
- 10. *Improve/increase resources for the development of technologies for producing synthetic fuels.***
- (a) Facilitate deployment for the long-term needs of long-haul transport (marine, aviation, heavy-duty vehicles (HDVs)) and the short/medium-term demand for 'drop-in' substitute fuels for conventional ICEs.
- 11. *Improve/increase the levels of investments in information and communication technologies and autonomous vehicles.***
- (a) Promote ICT for car sharing, traffic management, road pricing, electric vehicle charging, public transport information, automatic driving and interconnected vehicles, to reduce GHG emissions.
 - (b) Monitor progress with ICT and autonomous vehicle incentives, regulations, codes and standards to check and if necessary correct for possible rebound effects.
- 12. *Improve/strengthen preparations for long-term emission reductions by making long-term policy commitments to invest in innovation, jobs, skills and interdisciplinary research.***
- (a) Support the transition of the EU automotive industry to a decarbonised future by investing in low-carbon footprint battery manufacturing within the EU.
 - (b) Support collaborative research and innovation activities to build skills in ICT, life cycle analysis, electrical system management, and low-carbon vehicle manufacture, maintenance and repair.
 - (c) Promote market uptake of public transport, BEVs, fuel cell electric vehicles (FCEVs), electric road systems (ERS) and synthetic fuels through collaborative actions on behaviour change, socio-economics, business models and standards.
 - (d) Strengthen international cooperation on producing, certifying, labelling and using synthetic fuels in aviation and shipping, and on synthetic fuels for seasonal storage of electricity.

Target audience and aims of the report

The target audience for this EASAC report includes EU policy-makers, investors and related stakeholders (including vehicle manufacturers, fleet operators, city and regional authorities, and transport users) who are engaged in the policy debate on the future of transport in the EU. It is particularly relevant to those who are interested in the future development and implementation of the EU's 'Clean Mobility' and 'Energy Union' packages, as well as its 'Clean Planet for All' strategy.

The aims of the report are as follows:

- (1) to summarise the latest independent, objective, scientific evidence related to the decarbonisation of transport;
- (2) to explain the potential impacts on GHG emissions of recent and expected developments in transport

demand management, clean vehicles and energy carriers, infrastructure and emerging digital technologies;

- (3) to highlight what could be done through transport, energy and climate policy as well as investment support to maximise the contribution of the transport sector to the EU's decarbonisation commitments at affordable costs.

EASAC's mandate for energy and climate is to provide independent scientific advice to EU policy-makers. The report therefore has a focus on the complex issues being faced by EU policy-makers, at a time when the costs and performance of some transport options are evolving fast, and EU transport and decarbonisation policies are being reviewed and updated.

Scope

The focus of this report is on EU policies for the decarbonisation of passenger and freight transport, on urban and inter-urban roads in the period from 2020 to 2050, when major changes are expected to result from replacing gasoline and diesel engine vehicles with low-emission vehicles, and from the continuing growth in the use of ICT. Key issues include the need to contain growth of transport demand, the need for more low-carbon electricity generation to support the electrification of vehicle powertrains in parallel with growing demands for electricity from industry and the buildings sector, new business models for

road vehicle ownership and use, and the introduction of autonomous vehicles. The report reviews and analyses the available scientific evidence relating to the management of road transport demand, mobility and traffic, as well as driver behaviour and decision-making, clean vehicle powertrains and energy carriers (fuels), the implications of coupling with the electricity sector, and the overall design and operation of road transport systems. Policies relating to other forms of transport, including rail, inland waterways, maritime and aviation, are also briefly addressed.

Report structure

The report begins with an introduction in [Chapter 1](#) to the current policy discussions on the decarbonisation of transport, and an overview of what has been happening recently in EU transport markets. This is followed in [Chapter 2](#) by a discussion of the options for reducing transport emissions by managing the demand for transport. Options for managing transport supply, namely improving vehicle efficiency, electrification or reducing emissions by using alternative fuels (including advanced biofuels, hydrogen and synthetic fuels),

together with the corresponding implications for the overall energy system are discussed in [Chapter 3](#). The impacts on transport emissions of ICT and autonomous vehicles, which are both evolving rapidly and being increasingly introduced into transport markets, are discussed in [Chapter 4](#). Some conclusions from the evidence presented in the report are drawn and discussed in [Chapter 5](#). Finally, the scientific evidence presented in the report is brought together in the form of advice for EU policy-makers in [Chapter 6](#).

1 Introduction

1.1 The challenge of decarbonisation

The reduction of GHG emissions to the atmosphere is one of the pressing issues facing humankind because of their contribution to global warming. The word decarbonisation is widely used to describe the substantial reduction, if not the complete elimination, of carbon emissions resulting, directly or indirectly, from the combustion of fossil fuels. The need for decarbonisation has been recognised at the highest levels by leading international organisations including the United Nations (IPCC 2018), European Commission (EC 2017b, EC 2018i; ELTIS 2017; SETIS 2017), OECD (ITF 2018) and International Energy Agency (IEA 2018). In the road transport sector, fossil fuels (gasoline and diesel) currently dominate (95%) the energy market; so far, little progress has been achieved in reducing the overall carbon and other GHG emissions because the increased number of vehicles on the road has counterbalanced the reductions that have been achieved per vehicle.

In 2016, overall GHG emissions in the 28 Member States of the EU (EU-28) were 22% lower than 1990 levels, putting the EU on track to deliver more than its 20% GHG emission reduction target by 2020. In contrast, the transport share of GHG emissions actually rose by almost 20% from 857 million tonnes of carbon dioxide equivalents (Mt CO₂-eq.) in 1990 to 1079 Mt CO₂-eq. in 2016 (Eurostat 2017).

In the transport sector worldwide, as in the EU, fossil fuels are the dominant energy source today (95%) and are a major contributor to global warming. Globally, transport produces 14% of total anthropogenic GHG emissions (IPCC 2014a). GHG emissions from the European transport sector currently represent about 24% of total GHG emissions from the EU (of which road transport produces about 17%), while the other 76% are produced by non-transport fuels, agriculture,

industry and waste management (Figure 1.1a) (Eurostat 2018a). Within the EU transport sector in 2016, the emissions were dominated by those from road transport (Figure 1.1b) (EEA 2018a).

At the 2015 United Nations Climate Change Conference (COP21) in Paris in 2015 (EC 2016b), the nations of the world agreed to strengthen the global response to the threat of climate change by committing to deliver GHG emission reductions ('nationally determined contributions'), which together would be sufficient to keep the global temperature rise in this century well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C. More recently, the EU has published its vision for a 'Clean Planet for All', which contains a long-term strategy for a prosperous, modern, competitive and climate-neutral economy by 2050, and confirms Europe's commitment to swiftly and fully implement the Paris Agreement (EC 2018a, EC 2018h).

1.2 The gap between GHG emission goals and expected market trends

To limit the global temperature rise to 2°C with a probability of 66% implies an approximate global CO₂ budget of between 590 and 1,240 gigatonnes of emissions until 2100 (Rogelj *et al.* 2016), which is broadly consistent with the estimate by IEA/IRENA (2017) of approximately 800 Gt CO₂. If the current levels of global emissions from fossil fuels (about 37 Gt CO₂ per year) were to be reduced linearly within this global CO₂ budget, then the budget would be used up within about 40 years (i.e. by 2060), which means that the use of fossil fuels, including in the transport sector, should be reduced to close to zero within that timeframe. The ambition to limit the global average temperature rise to 1.5°C would lead to a substantially smaller (550–750 Gt CO₂) CO₂ budget (IPCC 2018), and therefore to the need for even larger emission

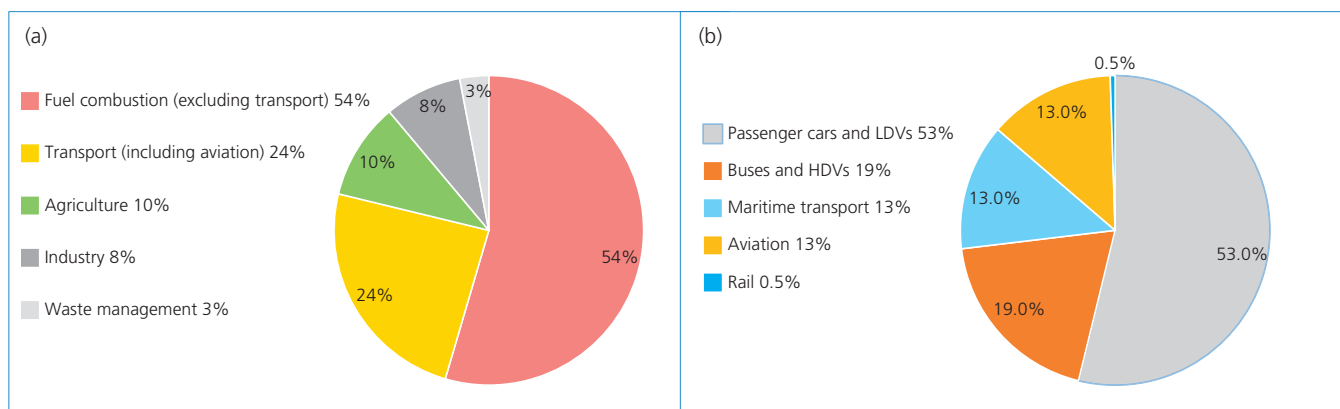


Figure 1.1 (a) Total GHG emissions from the EU. (b) GHG emissions from the EU transport sector.

Box 1.1 EU carbon emission targets

In their nationally determined contributions to the Paris Agreement, the EU and Member States committed themselves to a reduction of at least 40% in GHG emissions by 2030 compared with 1990, which is in line with the EU leaders' commitment to reducing overall EU GHG emissions by 80–95% by 2050, with milestones of 40% in 2030 and 60% by 2040 (EC 2011b). Moreover, there is a separate, but largely compatible, EU commitment to achieve a 60% GHG emissions reduction (compared with 1990 levels) in transport by 2050 to ensure that emissions are 'firmly on the way to zero by that date' (EC 2011a), which implies that other sectors must be decarbonised much faster than the transport sector to meet the overall 80–95% target.

In support of these commitments, the EU has put in place a set of recast directives and targets resulting from their November 2016 clean energy package (EC 2016c), and in November 2018 it published a new strategy for long-term EU GHG emissions reduction (EC 2018h).

EU legislation sets mandatory CO₂ emission reduction standards for new cars, LDVs (EURO 6) and HDVs (EURO VI) sold in EU markets. Since EU monitoring started in 2010, emissions from cars have decreased by 22 g CO₂/km (16%). The EU target for average emissions of new cars in 2015 was 130 g CO₂/km and, by 2021, the fleet average targets for new vehicles sold in the EU will be 95 g CO₂/km for cars (EC 2018f) and 147 g CO₂/km for vans (LDVs) used to carry goods weighing less than 3.5 t (EC 2018m).

In 2017, the European Commission presented a new legislative proposal setting CO₂ emission standards for cars and LDVs after 2020, with yearly targets for average emissions. This proposal includes a technology-neutral mechanism to incentivise uptake of zero- and low-emission vehicles (EC 2018k). In May 2018, the Commission presented a new legislative proposal setting the first-ever CO₂ emission standards for HDVs (EC 2018l).

EU emissions targets for 2020/2021 for cars and LDVs are based on the (old) New European Driving Cycle test procedure but, starting from 2021, they will be based on the (new) Worldwide Harmonised Light Vehicle Test Procedure that was introduced in September 2017, together with more reliable emissions tests in real driving conditions ('real driving emissions'), and will be phased in over the coming years. The new fleet-wide targets for 2025 and 2030 are not defined as absolute values (g CO₂/km), but as percentage reductions compared with the average of specific emission targets for 2021. Not all manufacturers will have to meet the same target. Instead, the EU-wide fleet target will be distributed among the manufacturers on the basis of the average mass of all new cars or LDVs in each manufacturer's fleet (EC 2018k; EC 2017b).

reductions within the same timeframe. Nonlinear emission reduction profiles could extend this timeframe, but would need to include faster reductions during the next few years to stay within the overall CO₂ budget.

For the EU transport sector, the EU Reference Scenario (EC 2016a) projects an increase of demand for passenger-kilometres of about 40% and for tonne-kilometres of about 60% between 2015 and 2050 (Figure 1.2). For EU aviation (intra- and extra-EU activities), it projects growth at 2% per year (2016–2050) while growth for the whole transport sector is projected to grow at 1%. Ploetner *et al.* (2018) project higher growth rates for aviation, around 4% per annum, which corresponds to doubling by 2040. At the same time, the ITF projects an increase in global road and rail freight volumes of 232–423% by 2050 and an increase in trade-related international freight (including shipping) by a factor of 4.3 by 2050 (ITF 2015a pages 55 and 62).

In contrast, the EU Reference Scenario 2016 (EC 2016a) projects reductions in the EU's overall GHG emissions over the period to 2050, but these are not sufficient to meet current EU targets. Nevertheless, in the EU scenario, CO₂ emissions from the passenger car sector are projected to decrease by about 10%, while those from the truck and bus sector are projected to increase by about 15%. In summary, the EU Reference Scenario projects CO₂ emissions from the EU transport sector (including aviation but not maritime freight) that will remain roughly stable or marginally reduced (at a level of around 1,000 Mt CO₂ per year) until 2050.

There is therefore a substantial gap between the EU's CO₂ emissions reduction goals (nationally determined contributions to the Paris Agreement) and the projected trends in the market.

Some experts have suggested that this gap could be bridged by removing CO₂ from the atmosphere using negative emission technologies. However, EASAC has shown that it is unlikely that any such technologies will be ready for deployment at a sufficiently large scale within the required timeframe (EASAC 2018a). Therefore it will be necessary to reduce GHG emissions by other means as quickly as possible.

1.3 How to close the gap: framework for transport decarbonisation

A mix of technology and policy options will be needed to close the gap between the EU's climate goals and the actual CO₂ emissions. This mix must be expected to evolve as new and improved technologies enter the market and as the demands for passenger and freight transport evolve.

The EU has taken many steps, since the adoption of its 2016 strategy for low-emission mobility (EC 2016d), to help the transport sector and public authorities to prepare for the mobility of tomorrow, including three substantial packages of 'Europe on the move' initiatives (EC 2017a, EC 2017e, EC 2018b). These packages address multiple objectives, including climate change, poor air quality and traffic accidents. They also aim to

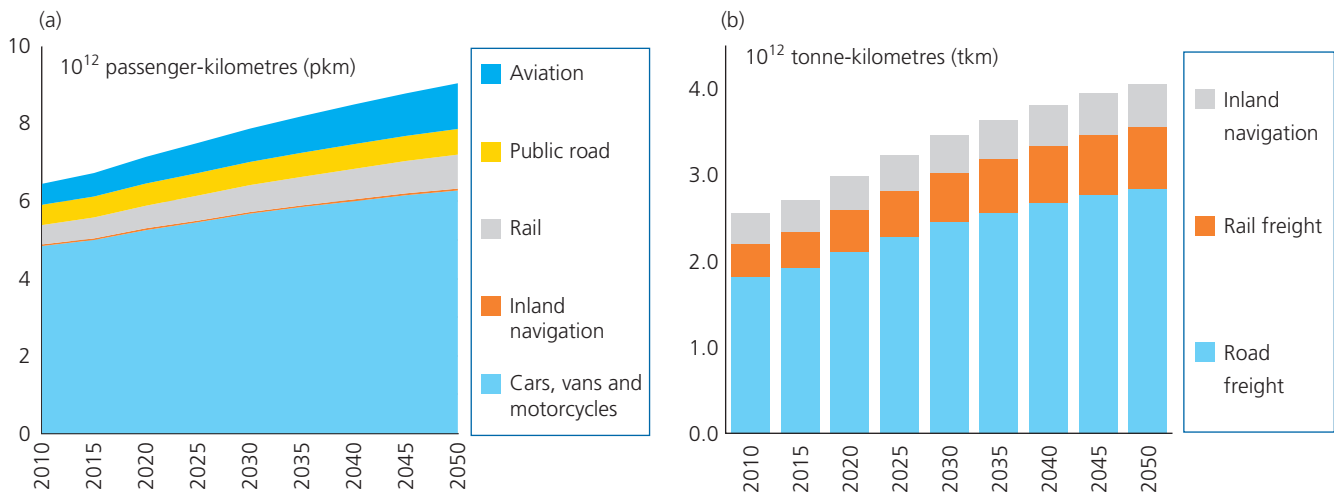


Figure 1.2 Transport activity projections in the EU Reference Scenario 2016. (a) Passenger and (b) freight transport activity by mode. Note: (a) reports the aviation activity related to the domestic and international intra-EU flights to maintain comparability with usual reported statistics; (b) reports freight transport activity excluding international shipping. (Redrawn from EC 2016a.)

empower EU citizens through new mobility solutions that match their changing needs, and to defend the competitiveness of European industry. However, more needs to be done to deliver the EU's CO₂ emission reduction goals.

In this study, the EASAC expert group has therefore developed a framework for studying, implementing and reviewing the main components of transition pathways to a decarbonised future for the transport sector. This framework can be used to study not only solutions that would be 'sustainable' in the long term, but also 'transitional' solutions that may not be sustainable in the long term but can be implemented quickly during the next few years at affordable costs. Transitional solutions over the next 10–15 years could lead to significant emission reductions during the transition period and could therefore help to deliver Paris commitments to limit global warming within the necessary time frame. Acting fast to reap the low-hanging fruits (without neglecting the longer-term options) is essential because it is the cumulative CO₂ emissions over time that define the carbon budget for the 2°C or 1.5°C scenarios. This approach also allows for policies and options, which are currently too expensive, to be delayed if necessary for a few years, until much lower overall emission levels need to be achieved.

EASAC's policy framework, within which priorities will evolve over time, is summarised below.

(1) Transport demand (see Chapter 2):

- (a) *avoid* demand for passenger transport services by encouraging people to change their behaviour (e.g. by facilitating walking, cycling, teleworking, teleconferencing, web-streaming of events, more healthy lifestyles, etc.);

- (b) *shift* to transport modes with reduced demand for vehicle-kilometres (vkm) (e.g. by shifting passengers and freight onto vehicles with higher specific load carrying capacities or by increasing load factors of existing vehicles through sharing or pooling).

(2) Transport supply (see Chapter 3):

- (a) *improve* vehicle design (e.g. improve aerodynamics, light-weighting to reduce vehicle energy demand, reduce fossil carbon footprint of newly manufactured vehicles, etc.);
- (b) *improve/deploy* – as transitional solutions – more efficient conventional powertrains and maximise the potential of hybrid vehicles (hybridisation);
- (c) *improve/substitute* – as transitional solutions – vehicles using oil-based fossil fuels in ICEs with vehicles using lower carbon fuels (e.g. advanced biofuels and natural gas), electric vehicles using the current mix of electricity generation, and vehicles using hydrogen and fuel cells;
- (d) *Improve/deploy* – as long-term sustainable solutions – vehicles with alternative energy carriers (e.g. low-carbon electricity, hydrogen, and synthetic fuels) fuelled by the available primary energy sources.

The portfolio of drivers and intervention options for the transition to a decarbonised future transport system is illustrated in Figure 1.3.

This approach is similar to the IEA's conclusion that policies to 'avoid, shift, improve' are needed to deliver the planned transition to a low-carbon transport sector (IEA 2018).

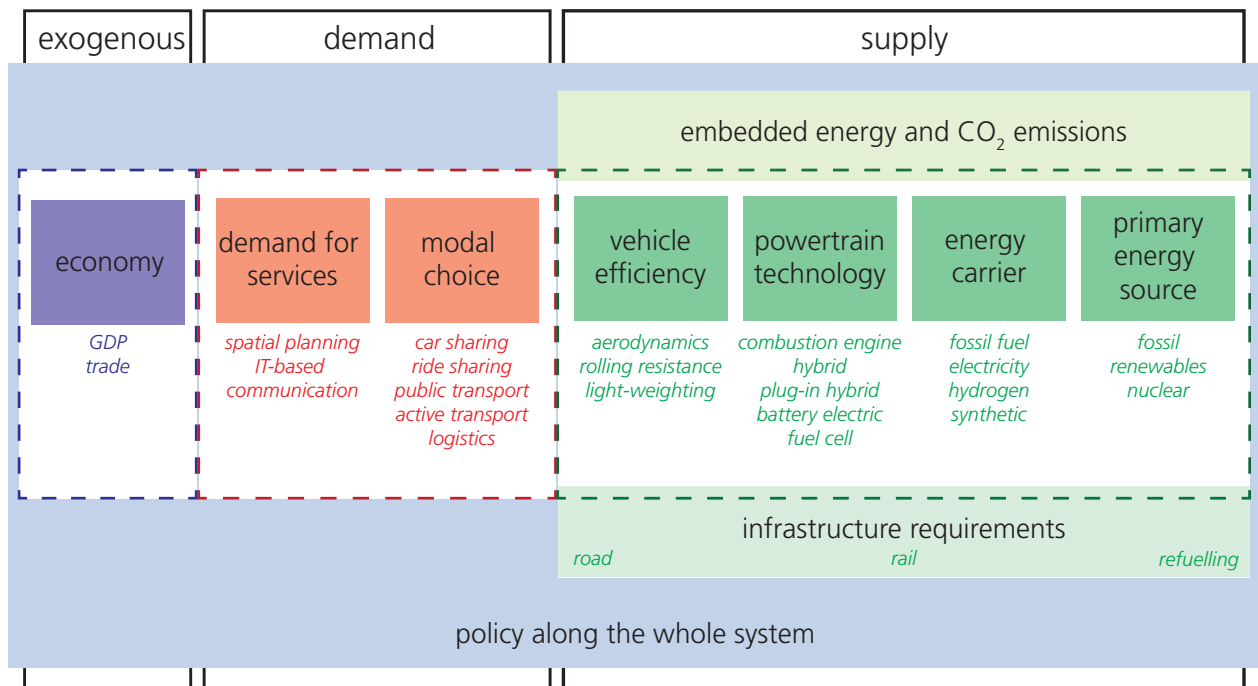


Figure 1.3 Policy framework for the decarbonisation of transport.

When considering any specific option or comparing different options within this policy framework, the analysis should address not only the emissions from road vehicles as they travel (72% of EU transport emissions), but also all other GHG emissions involved in their life cycle, such as those from the production and disposal of engines or batteries and electricity generation in the case of electric vehicles. Entire 'life cycle emissions' should be used as far as possible: see section 3.7 (Bauer *et al.* 2015; Cox *et al.* 2018).

Also relevant to the policy framework outlined above are some potential innovations for the transport sector that have begun to emerge on a global scale in recent years, notably ICT and autonomous vehicles, which may affect GHG emissions (positively or negatively). Most of these developments act at the interface of demand and supply, and are therefore discussed separately in [Chapter 4](#).

2 Transport demand

2.1 Links between transport demand, economic development and emissions

Transport plays a very important role in many aspects of modern society, by moving people and goods within and between regions. Trade, which requires the transport of freight, clearly helps emerging economies into the global system, and the transport of passengers is related to two main activities, working (including commuting and business travel) and tourism, each of which involve about half of a typical European's annual travelling distance.

For more than 60 years, people have spent between 1 and 1.5 hours per day travelling (Schafer 2000). However, increasing incomes and the growing availability of passenger transport with higher speeds and affordable costs (for most people) has encouraged the development of societies in which people travel further as speeds increase. In addition, the globalisation of business has led to growth in business-related travelling over long distances.

In the EU, transport currently contributes 6.3% to gross domestic product (GDP), employs almost 13 million people and is a major source of export earnings in several EU Member States (EC 2018c). The demand for passenger car transport in passenger-kilometres is continuing to grow in non-OECD countries and in the poorer countries of Central and Eastern Europe, but it has levelled off in recent years in the urban areas of the wealthier European countries. At the same time, the demand for freight transport in tonne-kilometres continues to rise in the EU as it does all over the world (ITF 2015a, pages 55 and 62).

Recent data for the EU from the European Environment Agency (EEA 2017a, EEA 2017b) show that passenger and freight transport demands have been growing since 2000 and are continuing to broadly follow the growth in GDP, despite some short periods without growth in passenger demand between 2011 and 2013 and in freight demand around 2009. A positive correlation between transport demand and economic growth was also found by Ecola and Wachs (2012). It is therefore likely that the simultaneous pursuit of economic growth *and* a reduction of passenger- and tonne-kilometres might encounter feasibility barriers as well as political resistance.

The continuing growth in transport demand leads to increases in GHG emissions from transport, and in costs for the infrastructure of highway and transport systems. Some of the emissions are related directly to the distances travelled; however, in urban areas where speeds are limited by traffic congestion, the emissions

have been increasingly linked to the time spent by slow-moving vehicles more than to the distances covered, although this is being addressed by the growing availability and use of 'start/stop' technology to minimise fuel consumption when vehicles are stationary. Other vehicle tail-pipe emissions such as nitrogen oxides (NO_x) and particulate matter (airborne pollution as emissions of particulates) are being addressed by new technologies such as filters, catalytic converters and additives. Policies aiming to reduce traffic congestion can also deliver important environmental benefits, including improvements in urban air quality.

In addition to addressing vehicle performance and fuel choice, which are discussed in Chapter 3, future policies for reducing the emissions from transport must address potential conflicts of interest. They must also replace the long-standing EU policy that 'curbing mobility is not an option', which was emphasised in the European Commission's White Paper on transport (EC 2011a), by innovative EU policies for containing demand. It is important to contain demand for both passenger and freight transport, but without jeopardising economic development, regional cohesion, consumer services, the competitiveness of EU industries or the well-being of citizens. The required policies are likely to include both containing the absolute demand for transport ('avoid') and facilitating the choice of low-emission transport modes ('shift').

The choice of transport mode is important for human health, and this is increasingly being recognised. A broad study on the relationships between climate change mitigation (including the decarbonisation of transport) and human health is currently being conducted (EASAC 2018b). This study highlights, for example, important links between global warming and the obesity epidemic (An *et al.* 2017), which can be weakened by adopting active mobility (walking and cycling) in place of motorised transport. In November 2018, the European Parliament launched an 'All policies for a healthy Europe' initiative (EP 2018), through which more than 25 cities belonging to the C40 cities network have pledged to transition to Fossil-Fuel-Free-Streets (C40 cities 2018), and other city networks have made commitments to develop more healthy communities (Global Covenant of Mayors 2018; ICLEI 2018).

2.2 Containing transport demand and shifting to more efficient modes

2.2.1 Passenger transport

Many different approaches for containing the demand for motorised passenger transport have been tested and studied in recent years. The results suggest that policies for containing transport demand must address

behaviour change and should be linked to policies for promoting a shift to more efficient transport modes and to other policies related to the way people live, especially in urban environments. For example, studies show that energy consumption per capita by private passenger vehicles and total expenditures (public and private) on passenger transport decrease as urban density increases (see, for example, Bruun 2014; Newman and Kenworthy 2015).

Driving for leisure and driving to work are the main components of passenger travel, depending on the city and country. For example, they represent 44% and 24% respectively of the daily distances travelled in Switzerland, with the remainder shared between shopping (13%), business travel (7%), education (5%) and other (7%) (FSO 2017).

Important reductions in carbon emissions can be achieved if people are motivated to live near their place of work, and if businesses prioritise reductions in the carbon emissions of their employees, including those caused by commuting to work. However, such policies must recognise the constraints under which people on low incomes, including the sick, handicapped and elderly, have to manage their lives. Such people may live outside the urban areas in which they work because they cannot afford the high costs of housing in city centres.

People who live in rural areas face particular challenges because the typical low density of their communities makes it difficult to operate public transport on a sustainable basis. Most rural dwellers will therefore have to rely in future on the use of low-carbon fuels and powertrains in passenger cars and LDVs to reduce their GHG emissions.

Many future transport options are already being studied and implemented in cities and other urban areas, including through 'smart cities' initiatives (EC 2017c) and Sustainable Urban Mobility Plans (SUMPs) (EC 2018d). These typically address the provision and promote the use of reliable, affordable, comfortable and interconnected public transport services (taxis, buses, metros, trams, trains, ships and planes) that offer travel at attractive speeds and with a pleasant experience for passengers.

Passenger transport decarbonisation options for urban areas typically include the following.

- *Safe cycle lanes, pedestrian zones, and walkways* to facilitate short-distance travelling without vehicles. A growing number of urban areas have introduced or increased the size of existing car-free zones, and added bicycle renting/hiring schemes in recent

years to promote more active mobility but, apart from in The Netherlands and Denmark (notably in Copenhagen: see Box 2.1), the distances travelled per year per capita by walking and cycling remain well below 10% of the total (Bassett *et al.* 2008; Statistics Netherlands 2016; Watts *et al.* 2018).

- *Banning cars from city centres and/or regulating vehicle speeds and out-of-town park-and-ride schemes* to discourage the use of passenger cars in the city.
- *Excluding vehicles unless they have more than one passenger from specific lanes* on busy roads has been tried in some cities. This approach has the potential to reduce the emissions per passenger-kilometre, but has not been widely adopted.
- *Incentivised access to relatively low-price public transport* (trains, buses, trams and metros) or in cases such as Luxembourg 'free' public transport (Boffey 2018), which produce lower emissions per passenger-kilometre than passenger cars or motorcycles (Table 2.1).¹ However, to shift a significant fraction (say 10%) of car travellers over to trains and buses would imply a massive increase (perhaps doubling) of EU public transport provision and associated investment needs because only about 16% of land transport passenger-kilometres is currently travelled by public transport compared with more than 80% by cars, and only a few percent by active mobility (walking and cycling).
- *Coordinated intermodal transfers* with easy-to-use information systems (ICT platforms) and multi-operator ticketing systems to encourage the use of public transport (e.g. inter-city trains linked to local trams or buses for the 'last mile').
- *Charges for parking and for vehicle access to city centres (congestion charge)*. As the ways in which people use passenger cars in urban areas evolve, for example greater use of private hire vehicles that circulate all day within congestion zones, the introduction of more *dynamic road pricing schemes*, such as those in Stockholm and Singapore, can be expected (NYC Streetsblog 2017).
- *Low-emission zones* together with transport management schemes aiming to limit transport emissions in highly congested or polluted areas. (Note: these are currently motivated largely by the need to reduce congestion and to improve air quality by reducing NO_x, carbon monoxide, hydrocarbons and particulate matter, rather than to reduce GHG emissions.)

¹ Note: emissions of the current passenger car fleet are higher, and those of public transport with high occupancy levels are lower, than the values shown in Table 2.1.

Box 2.1 The City of Copenhagen's bicycle strategy



(Image from Metropolis <https://policytransfer.metropolis.org/case-studies/cycling-in-copenhagen>.)

Copenhagen has set itself the goal of becoming 'the world's best bicycle city by 2025'. Achieving this goal is also viewed as integral to the city's health plan, to the environmental goal of making the city CO₂ neutral by 2025 and to enhancing the liveability of the city (City of Copenhagen 2011).

Copenhagen's plan for achieving a greater modal share for bicycles includes increasing the capacity of the cycle tracks to the city centre to accommodate an additional 60,000 cyclists by 2025.

The city's bicycle strategy with planning, infrastructure and financing mechanisms has been central to Copenhagen attaining the status of a world-leader in cycling and sustainable transport modalities.

Key results and impacts of the City of Copenhagen's Bicycle Strategy 2011–2015 include the following.

- 150,000 people cycle to work or educational institutions every day, with a modal share of 36% of all trips within the city.
- An increase in the number of kilometres cycled in Copenhagen by 30%, while cycling in Denmark overall has decreased by 30% since 1998.
- A key success factor was the organisation of urban and transport planning in an integrated and coherent way under a single Technical and Environmental Administration in the city government.
- The bicycle is now the most popular means of transport for commuting in Copenhagen.

Table 2.1 Modal split of passenger transport in the EU-28 and typical emissions per mode

Transport mode		pkm (%)	Emissions (g CO ₂ /pkm)	Comments
Car		71.5	75	Based on average emissions of 118.5 g CO ₂ /km of new cars sold in 2017 (EC 2018f) and an average occupancy of 1.6 (EEA 2016b). Emissions are therefore lower than for the current passenger car fleet.
Air	Short	9.8	260	Europe short distance flight ≤463 km (LIPASTO 2009a).
	Long		150	Europe long distance flight >463 km (LIPASTO 2009a).
Bus		8.2	50	Average city bus, 18 passengers (LIPASTO 2018).
Rail*	Electric	6.7	15	Electric inter-city train, based on 0.054 kWh/pkm (LIPASTO 2017a) and EU average direct electricity generation emissions of 276 g CO ₂ /kWh (EEA 2017c).
	Diesel		75	Diesel-driven railcar (LIPASTO 2017b), 35% occupancy (EU average for passenger trains) (EEA 2016b).

*About 80% of EU rail traffic is powered by electricity (EC 2017e).

Percentage of passenger-kilometres (pkm) in the EU is based on data for 2015 (EC 2017f). Emissions data for public transport modes are rounded values for Finland from LIPASTO Transport Emission Database.

- *Innovative urban/spatial planning* to bring together work, leisure and living areas, and to make it more attractive for workers and their families to live near to their schools and places of work. This option may be particularly valuable in areas that are being redeveloped or in new urban developments, but typically it has very long realisation times. Consequently, the impacts may be too late to contribute significantly within the timeframe required to limit global warming (Paris Agreement).
- *Business initiatives*, encouraging businesses to adopt policies on car sharing and working from home (teleworking), which reduce the daily commuting of their workforce, as well as teleconferencing and web streaming of meetings and conferences to reduce business travel. The use of ICT to perform remote monitoring (e.g. smart meters), servicing and maintenance of plant and equipment can also reduce the demand for transport. Other digitalisation solutions also offer a growing potential for reducing transport demand, such as the downloading of music, films, games, books and news in place of shopping for physical products, online services such as banking which avoid travelling to the bank, and three-dimensional printing which could allow small-scale manufacturing on site or the production of spare parts at home.

While each of the individual measures highlighted above may have only a modest impact on overall GHG emissions, analyses performed by the JRC of the potential emission reductions by cities working to implement their sustainable urban mobility plans suggest that overall emission reductions of up to about 9% could be achieved when several measures are implemented simultaneously, although the results can differ substantially between cities and countries (Cruetzig *et al.* 2012; COWI *et al.* 2013; EC 2013; European Platform on SUMP 2016).

Urban transport innovations: some important innovations are emerging in relation to the ways that people, notably young people, travel in urban areas. Some examples are the following.

- *Innovative business models for passenger vehicle ownership and use* are already operating in many urban areas, with an increasing number of people (especially young people) choosing to use ride sharing services, or to join 'car sharing' schemes which allow them to hire a car at short notice and to collect it from a nearby parking location, or car subscription schemes in which all driving-related costs are covered by a fixed monthly payment. A more flexible option, known as 'Mobility as a Service', gives the subscriber access to several modes of public transport and the use of a

passenger car for a monthly fee (Transport Systems Catapult 2016). The long-term impacts of these new business models are not yet clear. They may reduce the total number of vehicles on the road and in car parks. On the other hand, they may produce 'rebound effects', for example attracting people to drive passenger cars who do not have their own vehicles or in some cases undermining the competitiveness of public transport.

- *Innovative technologies for low speed travel* have entered the market in recent years, including electric bicycles and electric scooters which make it easy for people to travel on longer journeys than they would contemplate on a normal bicycle, as well as lightweight scooters and skateboards without power. Their impact on EU transport emissions is currently negligible, but might have the potential to save up to about 10% of CO₂ emissions from short-distance passenger car journeys in the future (Boulouchos *et al.* 2017). Mason *et al.* (2015) calculate that, through a range of policies and investments, the global share of bikes and e-bikes in urban passenger transport could increase from 6% in 2015 to 11% in 2030. They conclude that such shares may also be possible across the EU. Some e-bikes are now so fast and powerful that their use may soon have to be regulated like motor cycles or mopeds.
- *Autonomous passenger vehicles* are expected both to increase and decrease future demands for passenger transport (see Chapter 4).

Sharing of experience with the measures highlighted above can be encouraged by policies and programmes at EU and national levels, and by standardisation that helps to reduce costs and other market barriers; however, their implementation must largely be managed at local and regional levels. Such initiatives may seem expensive, but their costs can be justified not only in terms of more sustainable mobility but also as other benefits including improved quality of the air and public spaces, which not only improve the quality of life for those living and working in the area, but also improve their health (reduced costs of health care).

Inter-city (long distance) transport policies to reduce GHG emissions focus largely on the following.

- *Speed restrictions, lane restrictions and road pricing* to discourage the use of passenger cars, although such policies are often unpopular.
- *Ride sharing in cars*, which can reduce emissions, compared with those when each passenger drives their own vehicle (European Platform on SUMP 2016). (Note: ride sharing works well for some people and cultures, but for others the loss of

freedom to choose their own travel times makes it unattractive.)

- *Investments in trains, rail networks, buses, bus lanes, trams and ICT* to improve the attractiveness of public transport, which typically produces lower GHG emissions per passenger-kilometre than passenger cars (Table 2.1) or ride sharing, but requires good connections from the terminals at each end (first/last mile problem). The frequency, reliability, speed and occupancy of public transport services are also important. However, it is widely reported that investments in public transport across the EU are currently insufficient (EIB 2017).

The degree to which a shift to public passenger transport is possible is contested. Kemp (2016) indicates that a further increase of inter-urban rail travel is possible, but that a 10% increase of the shift to rail is open to doubt. For the case of Germany, Nordenholz *et al.* (2017) report that the share of trains in long-distance transport can increase from 15% in a baseline scenario to 20% in an ambitious policy scenario.

For the longer term, further shifting is possible. Nelldal and Andersson (2012) report that it is likely that the European rail system in 2050 can be positioned to handle 25–30% of total passenger transport, but that this would require increasing the investment in rail from 0.36% of GDP in 2008 to 0.5% of GDP over the period 2015–2050. Replogle and Fulton (2014) have performed a global analysis and find that, for the global transport system, the use of LDVs can be reduced by 45% for a reference development, mainly because of a shift to buses and trains.

Air transport: the growing demand for air transport, which has been stimulated by low-cost airlines and subsidies given to regional airports within the EU as well as by the globalisation of business and the availability of low-cost holidays in faraway destinations across the globe, is producing higher emissions per passenger-kilometre than rail or bus services (Table 2.1), and the demand for international passenger aviation is predicted to quadruple by 2050 (ITF 2017). To some extent, businesses and other organisations can reduce their need for air transport by holding more meetings via videoconferencing, and they can reduce their travelling to conferences by participating through web streaming and webinars. However, it is politically difficult to curb air travel by holiday-makers within the EU, other than by investing in faster rail connections to tourist destinations, because some EU Member States, notably the Southern Member States, are dependent on income from tourism.

Air travel to outside the EU is even more difficult to curb. Airport charges are applied by most EU airports in compliance with EU Directive 2009/12/EC (EU 2009),

but the charges are typically very low compared with flight ticket prices and there is no tax on aviation fuels. EU aviation flying within the European Economic Area has been included in the Emission Trading System (ETS) (EC 2018e) since 2012, but the resulting impacts of the ETS are weak and a new market-based mechanism will not be applied to extra-EU aviation until 2021 (EU 2017a). The impact of the ETS on ticket prices is small, so its impact on reducing the demand for air transport has been similarly so. It is therefore very important that the fourth phase of the ETS will succeed in raising carbon prices (EC 2018e), and additional policies to reduce emissions from air travel are also needed (see section 5.4).

Quantifying the potential savings in GHG emissions per passenger-kilometre, which could be achieved by shifting to public transport, is challenging because the performance of public transport modes, such as buses and trains, depends on their size (e.g. minibus or double decker), loading (e.g. half or fully loaded), driving conditions, operating mode (e.g. non-stop inter-city train, or short-distance local train which stops at all stations) and powertrain (e.g. diesel or electric). Emissions data for some typical examples of public passenger transport are shown in Table 2.1; these show that air transport has the highest emission levels per passenger-kilometre, and that electric trains and buses produce significantly fewer GHG emissions than passenger cars. However, it is important to point out that, in addition to the points highlighted above, the emissions performance of all transport modes depends on the detailed design of the vehicles used, and is improved when operating at full capacity.

2.2.2 Freight transport

The overall demand for freight transport in the EU continues to grow and is expected to increase by one-third by 2050 according to the EU Reference Scenario 2016 (Figure 1.2). This growth is driven partly by globalisation and the interconnections between regional economies, partly by the economies of scale that can be achieved when the manufacturing of products, product components or processes is centralised in very large plants, and partly by other evolving aspects of consumer demand.

Recent analyses suggest that it will not be possible to achieve the required emission reductions from freight transport simply by reducing the carbon intensity of freight movement (McKinnon 2018). Therefore containing the growth of total freight transport must be included in future EU transport policies.

Approximately 70% of EU tonne-kilometres of inland freight (51% if maritime freight is included) is currently transported by road (Eurostat 2018b), with most of this being carried by HDVs. However, the fleet of LDVs in the

Box 2.2 Potential for shifting freight from road to rail in the EU

Tavasszy and Van Meijeren (ACEA 2011) have analysed the feasibility of moving 30% of the total weight of commodities transported by road over distances of more than 300 km in the EU (which represents 75% of the total weight of commodities transported by road) away from roads to rail and inland waterways, as proposed in the European Commission's White Paper on transport (EC 2011a). They concluded that this would be very ambitious and costly, because a reduction of 30% in long-haul road transport over distances of more than 300 km would decrease the share of such road transport from 75% to 52% while almost doubling the share of commodities transported by rail from 21% to 39% and doubling the share of inland navigation from 4% to 8% (if the shift of commodities transported by road is equally distributed over rail and inland navigation).

In contrast with the recent trends, which show decreasing use of rail for freight transport in the EU (Eurostat 2018b), Kemp finds that increasing the modal share of rail by 10% in the UK is possible, but would require the construction of dedicated freight lines (Kemp 2016).

When considering potential investments in railroads for freight transport in the EU, it can be useful to review the success of freight railroads in the USA, which are widely acknowledged to be the best in the world. In the 1950s, the USA and Europe moved roughly the same percentage of freight by rail; however, by 2000, the share of rail freight in the USA was 38% while in Europe it was only 8% (Vassallo and Fagan 2005). The authors of this study concluded that almost 80% of the gap between the levels of rail freight carried in the USA and the EU in 2000 was probably due to natural or inherent differences, principally geography, shipment distance and commodity mix. However, a little more than 20% of the gap could not be explained by these inherent differences. The authors suggested that it was instead due to EU policies including priority to passenger services, lack of interoperability at borders, and incentives given to rail operators. Lastly, they concluded that, if the policy gap were closed, then the share of freight transported by rail in Europe would almost double, i.e. increase to about 15%.

EU, which carries both goods and equipment, has been growing in recent years, notably in the UK (DoT 2016).

The use of LDVs for carrying freight over short distances in urban areas is beginning to be replaced by cargo bicycles and cargo e-vehicles, which have lower operating costs and greater flexibility. However, for transporting freight over long distances, fossil-fuelled trucks and rail transport are still the most common solutions. Trucks bring the advantage over rail transport that they can complete the journey door to door, and can usually meet the 'just in time' needs of modern manufacturing plants.

In addition to changing fuels and powertrains, which are discussed in Chapter 3, the following measures have the potential to reduce the GHG emissions from road freight vehicles, as well as to bring other benefits to the businesses involved.

- *Improve vehicle utilisation (load factors):* select more efficient and more widespread (online) freight procurement, use vehicles with higher carrying capacities, improve collaboration between logistics hubs to increase loading efficiencies and return journey loading, and introduce new IT-based supply chain management and asset tracking tools (use the Internet of things²).
- *Improve vehicle routing:* reduce the distance travelled by freight consignments (restructure supply chains), use computerised vehicle routing and scheduling software, and use big data and predictive analytics to increase efficiency of delivery

and customer service. (Note: software packages are commercially available that help businesses to schedule delivery journeys so that distances travelled are minimised and vehicles operate outside the periods when vehicle access charges apply.) Electric vehicles can be used to deliver some freight in urban areas at night because of their low noise emissions (provided unloading can be performed quietly), and this can help to reduce daytime traffic congestion.

- *Improve driver performance* by training to use eco-driving and platooning, each of which have the potential to deliver 5–10% reductions in fuel consumption and correspondingly in GHG emissions (ACEA 2017b).
- *Shift to lower emission transport modes* by transferring loads from road to rail, inland waterways and short sea shipping. Policies, initiatives and incentives to shift freight off the road and onto rail, inland waterways and short sea shipping have been promoted by the European Commission for more than a decade (e.g. the Marco Polo programme) because of their ability to carry heavy loads over long distances with lower emissions (EC 2014a). This, however, will require substantial increases in investment in rail capacity and infrastructure see Box 2.2.

Some of the policies and schemes, which have been introduced by local or regional authorities as part of their 'smart cities' or SUMP initiatives, and which were discussed above in relation to passenger transport, can also lead to reduced congestion, improved air quality

² The Internet of things uses energy for computing, displays, etc., which must be managed for maximum sustainability.

and GHG emission reductions from freight transport. These include the following.

- *Limiting or charging for vehicle access to city centres (congestion charge and/or dynamic road pricing schemes)* to discourage the use of freight transport in busy areas during peak periods. Such schemes typically include exemptions for low-emission vehicles, such as electric or hydrogen-powered vehicles.
- *Low-emission zones* together with transport management schemes aiming to limit transport emissions in highly congested areas.

In addition, some cities and communities have started to develop sustainable urban logistics plans (SULPs) to address the most efficient and convenient ways to manage the distribution of freight within their urban areas. These can be particularly helpful in historic towns and cities, which are constrained by ancient infrastructure and narrow streets (ELTIS 2018).

Other innovations are beginning to impact on the ways that freight is transported, for example the following.

- *The recent growth in Internet shopping* is reducing the numbers of consumer trips to supermarkets and shopping centres, but increasing the use of LDVs in retail supply chains. This innovation has led to the establishment of major new product sales and delivery businesses, with very profitable business models which have created many new jobs including high-quality jobs for the development and deployment of new ICT systems for stock control

and logistics as well as jobs of lower quality for drivers and warehouse operatives. However, the impact of these innovations on GHG emissions is not yet clear.

- Autonomous vehicles and drones are being developed for freight transport applications, and could offer potential GHG emission reductions; however, autonomous vehicles could also produce emission increases (see Chapter 4). These innovations are still in the demonstration phase and would require substantial regulatory changes, particularly from a safety perspective, before they could be implemented at commercial scale.

Freight is transported across the EU by air, sea, inland waterways, rail and road. The challenge to quantify the potential GHG emissions savings per tonne-kilometre, which could be achieved by modal shift, is similar to that discussed above for passenger transport because the performance of the different transport modes depends on their size (e.g. HDV or LDV, large or small ship), loading (e.g. half or fully loaded), driving conditions, operating mode (e.g. urban or highway) and powertrain (e.g. diesel or electric). Emissions data for some typical examples of freight transport are shown in Table 2.2, which shows that air transport has the highest emission levels per tonne-kilometre, and that trains and large container ships produce significantly fewer GHG emissions than trucks on the road. However, it is important to note that, in addition to the points highlighted above, the emissions performance of all transport modes depends on the detailed design of the vehicles used, and is improved when operating at full capacity on both outward and return journeys.

Table 2.2 Modal split of freight transport in the EU-28 and typical emissions per mode

Transport mode		tkm (%)	Emissions (g CO ₂ /tkm)	Comments
Road		50.9	60†	Tractor-semitrailer, about 30t load capacity, average driving (urban, rural, highway), (CE Delft 2017)
Maritime (deep sea shipping)		33.3	15	Container ship 8,000 + TEU (IMO 2009)
Rail*	Electric	11.6	10	Heavy container (70 TEU), electric train, based on 0.03 kWh/tkm, (0.11 MJ/tkm, CE Delft 2017) and EU average direct electricity generation emissions of 276 g CO ₂ /kWh (EEA 2017c)
	Diesel		20†	Heavy container (70 TEU), diesel train (CE Delft 2017)
Inland waterways		4.2	20	General cargo ship (0–4999t load capacity) (IMO 2009)
Air	Short	0.1	1,400	Short-haul international flights (LIPASTO 2009b)
	Long		600	Long-haul international flights (LIPASTO 2009b)

*About 80% of EU rail traffic is powered by electricity (EC 2017e).

†Values given in g CO₂-eq./tkm.

Percentage of tonne-kilometres (tkm) for the EU is based on data for 2016 (Eurostat 2018b). Emissions per mode are from CE Delft (2017), IMO (2009) or for Finland from the LIPASTO Transport Emission Database.

TEU, 20-foot equivalent unit.

Little is known about the impact of measures to reduce freight movement. Enquiries among 100 Dutch freight companies showed that fuel use could be reduced by 12–18%, through a combination of more efficient loading, technical measures and modal shift (Scholtes *et al.* 1998). However, it is not clear whether these results are still applicable and to what extent they can be extrapolated.

Future innovations in EU markets can be expected in most cases to reduce the demand for freight transport for the following reasons.

- There are growing pressures to design products with *reduced materials content* (miniaturisation, light-weighting), and to *localise production* to

create local jobs and to minimise energy and transport costs.

- Continuing development of the '*circular economy*' can be expected to contribute to decarbonisation, notably by improving energy and resource efficiency (EASAC 2016a). For example, the creation of 'closed-loop supply chains' should minimise waste, and extract values and energy from recycled products, although it is not yet clear how these developments will affect freight transport demand.
- *Supply chain initiatives*, such as the promotion of locally sourced foods, can bring reductions in freight transport demand as well as a broad range of economic, social and health benefits.

3 Transport supply options and technologies

3.1 Overview

In addition to the options for reducing GHG emissions by addressing transport demand, which were discussed in [Chapter 2](#), the GHG emissions from vehicles can be reduced by using the right size of vehicle for each application, by improving the designs and performance of vehicles and powertrains, and by using low-carbon energy carriers (alternative fuels) including electricity.

The speed of decarbonisation of road transport is limited to some extent by the maximum rates of renewal of vehicle fleets. Nevertheless, the fact that the average age of the EU fleet of 256 million passenger cars is about 11 years and of the 38 million commercial vehicles about 12 years ([ACEA 2018](#)) offers much potential for improvement, because most of the fleet will be renewed within about 20 years. Although an annual renewal rate of road vehicles of typically about 5% may seem low, it is much higher than the 0.5–2.5% per year that is being achieved by the EU building sector ([EP 2016](#)), and significant changes to the transport fleet can be expected in the next few years.

A range of policies, including lower tax bands for diesel vehicles and lower prices for diesel fuel, have been put in place by governments in many EU countries since 1995 to tackle global warming because the CO₂ emissions from diesel engines were recognised to be substantially lower than those of gasoline engines ([EC 1995](#)). However, the difference between the CO₂ emissions of diesel and gasoline ICEs has been decreasing in recent years, and the emission target of 130 g CO₂/km, which was set for 2015, was met 2 years early by both engine types. In 2017, the average CO₂ emissions of petrol cars in the EU-28 was 121.6 g CO₂/km, which was similar to that in 2016, while those of diesel cars worsened slightly from 116.8 g CO₂/km in 2016 to 117.9 g CO₂/km in 2017 ([EEA 2018b](#)). (Note: to some extent, these differences result from the fact that vehicles with diesel- and gasoline-fuelled powertrains have different market shares in different segments of the EU vehicle fleet.)

Initially, the growth in the use of diesel cars, which was stimulated by government policies, led to increases in emissions of NO_x and particulate matter from transport, but these are now decreasing through the use of selective catalytic reduction and other pollutant emission controlling technologies. Nevertheless, these emissions, which have serious negative impacts on human health, are still produced by old vehicles and can be found at levels that are above the EU's air quality standards, mainly at roadside locations, in many urban areas ([EEA 2016c](#)). The decarbonisation of transport must therefore continue to be addressed together with measures to

accelerate the reduction of other harmful emissions (notably NO_x and particulate matter), to avoid poor air quality in urban areas.

In recent years, the EU has introduced increasingly demanding vehicle emission regulations, standards and procedures for type testing new vehicles (see [Box 1.1](#)). In response, the newest gasoline ICEVs are now equipped with particulate traps while new diesel ICEVs already demonstrate ultra-low NO_x emissions. However, emissions from the existing vehicle fleet are typically much higher and much of the existing fleet will still be on EU roads for another 10 years or more. Typically the oldest vehicles are owned by people or small businesses with low incomes and therefore limited funding for vehicle maintenance. To address this challenge, the emissions from old vehicles are monitored – but only to a limited extent – through periodic roadworthiness tests in accordance with EU Directive 2014/45/EU ([EU 2014b](#)). More needs to be done to accelerate the replacement of the highest GHG and pollutant emitting vehicles.

In EU markets, the sales of diesel cars are falling in many EU countries, and this fall is being compensated by increased sales of gasoline cars, hybrid and plug-in electric vehicles (PEVs). Plug-in vehicles still represent less than 0.5% of the current EU fleet of about 250 million passenger cars, but the number of new BEVs and PHEVs sold in Europe during the first three quarters of 2018 was 291,000, which was about 35% higher than in the same period in 2017. Sales of over 400,000 new PEVs in the EU were predicted for the whole of 2018, which would represent a market share for new electric vehicle sales in the EU of about 2.3% ([Irlle 2018](#)). In contrast, on average only about 120 fuel cell electric vehicles (FCEVs) per year were sold in Europe in the period from 2013 to 2017, and this market is expected to grow more slowly owing to higher costs and the need for more hydrogen distribution infrastructure ([Kane 2018](#)).

In the EU, the market for battery electric buses has grown rapidly since 2010, leading to around 1,600 such buses on EU roads in 2018, and an estimated 9% market share of new EU bus registrations in 2017. Orders for 1,140 new electric buses in the EU in 2017 were dominated by battery electric buses (946), followed by trolley buses with battery (91), plug-in hybrid buses (91) and fuel-cell buses (11), most of which can typically take up to about a year to be delivered ([Transport and Environment 2018](#)).

Vehicle manufacturers are continuing to improve the energy efficiency of conventional road vehicles, and it seems likely that the life cycle carbon emissions from vehicles using conventional ICEs can be further

reduced by up to about 25% through improved powertrain design (mainly hybridisation) in addition to a reduction of up to about 20% from improved vehicle design (Onder *et al.* 2011). Such improvements, which are discussed below, can be seen as potentially valuable transition options for delivering GHG emission reductions in the short to medium term, while work continues on the development and implementation of fully sustainable long-term transport supply options involving new powertrains and alternative fuels.

The emissions of vehicles include embedded emissions created during vehicle manufacture and recycling/disposal, and operating emissions from driving (see section 3.7). In the case of electric vehicles, the operating emissions correspond to those produced by the mix of electricity generators that supply them. These emissions can be quite low if the electricity is produced by hydropower, nuclear, solar or wind generation (see Annex 1), but higher than those from an ICE if the electricity is produced by thermal power stations burning coal (Cox 2018). Because the mix of generation varies geographically across the EU and with time over the day and year, the emissions from power generation differ substantially between countries, which implies similar differences between the emissions that will result from the use of electric vehicles in different countries. From the perspective of overall GHG emissions, all those from electricity generation in the EU are capped by the ETS regardless of its final use; however, from the perspective of transport sector emissions, it makes more sense to substitute the use of fossil fuels with electricity if that electricity comes from additional low-carbon generation, rather than from fossil-fuelled electricity generators.

Road vehicles also produce particulate matter emissions from their tyres and brakes. As regulations for tailpipe emissions from conventional vehicles become increasingly strict, non-exhaust emissions account for over 90% of PM₁₀ (particulate matter of sub-10 µm size) and 85% of PM_{2.5} (sub-2.5 µm) emissions (Grigoratos and Martini 2014; Timmers and Achten 2016). PM₁₀ emissions from tyres and brakes are strongly dependent on vehicle weight, so weight reduction can help to reduce pollutant emissions. Regenerative braking, which is typically used in electric and hybrid vehicles, and more demanding particulate matter emission standards for vehicle tyre and brake materials can also contribute to particulate matter emission reductions.

Some transport supply options require new infrastructure, such as charging points for electric vehicles or distribution networks for hydrogen, which may need to be financed, at least partly, by public funding. Others can be implemented with relatively little additional infrastructure. The funding by national governments of transport infrastructure can be expected

to become more challenging in the future, as fossil fuels are replaced by alternatives and the revenues from taxes on fossil fuels decrease. New mobility pricing and taxing schemes may need to be introduced to fill this gap.

3.2 Vehicle selection

In the short to medium term, GHG emissions from road vehicles could be reduced by *encouraging users to choose the right size* of vehicle and engine for their needs (e.g. by taxation based on vehicle emissions, and/or by taxation on fossil fuels). Currently, passenger cars are equipped with much higher engine powers than necessary for dynamic performance under normal conditions. For example, a maximum of 8% savings in fuel consumption and corresponding emissions can be achieved by increasing the time needed for passenger cars to accelerate from 0 to 100 km/h by 2.5s, which corresponds to lower engine power (Boulouchos *et al.* 2017). The choice of engine size lies, of course, with the consumer, so it is important that easily understandable information is provided with all vehicles, and that consumer trust in that information is secured to maximise the potential for GHG emission reductions.

Similarly, the widths and heights of passenger cars have significantly increased during the past 20 years, which may provide better visibility and protection for drivers and their passengers, but also increases fuel consumption and GHG emissions, as well as creating the need for investments in wider roads and bigger car parking spaces. However, selecting the right size of vehicles seems to be a very difficult issue on which to produce politically acceptable policies and legislation, especially for passenger cars.

One of the obstacles to right sizing is that some owners use their cars and LDVs (used to carry goods weighing less than 3.5 t) as status symbols, and therefore choose large but often inefficient vehicles to boost their personal image. Price and taxation may not deter such people if they are proud to be able to show off a big vehicle. Although taxation of vehicles based on emissions and/or fuel economy is being introduced in some EU Member States with the aim of reducing vehicle emissions, this tends to impact first on drivers with low incomes but to have only a limited effect on many drivers, as can be seen by the increasing numbers of large passenger cars on European roads today. Potentially valuable experience on such issues is being gathered in Norway, where exemptions from road tolls and public parking charges, free access to bus lanes, reduced ferry charges and an innovative initial vehicle purchase tax have been introduced to promote the use of low-carbon vehicles (Fridstrøm *et al.* 2018). The purchase tax, which is technology neutral (with the exception of giving special treatment to zero-emission vehicles and PHEVs), is designed to influence vehicle choice.

3.3 Vehicle design

Light-weighting can typically reduce the energy consumed by existing vehicles, either LDVs (used to carry goods weighing less than 3.5 t) or passenger cars, by about 10% (Boulouchos *et al.* 2017), because lighter vehicles need less energy to accelerate and less energy to drive up hills. However, the reduction potential is not the same for all powertrains. The energy consumption of ICEVs can be reduced more by weight reduction than that of hybrid electric vehicles, BEVs and PHEVs, because electrified powertrains are able to recover and use part of the weight-related energy spent on acceleration that is otherwise wasted during conventional braking to charge their batteries (Lewis *et al.* 2014). Vehicle weight has been shown to correlate with particulate emissions (PM₁₀ and PM_{2.5}) from tyres and brakes, so there is also an important potential benefit from light-weighting in terms of improved air quality (Timmers and Achten 2016). Incorporating lighter materials into vehicle bodies is increasingly being made possible by the introduction of new and more robust plastics and composite materials, including natural fibres and materials made from biomass, which should make recycling easier as well as reduce vehicle fuel consumption. However, attention must also be given to possible increases in the 'embedded' carbon emissions resulting from vehicle manufacture because it is the overall life cycle emissions of vehicles that must be reduced to limit global warming.

Improved aerodynamics can typically reduce the energy used by LDVs and passenger cars, and the increasingly demanding tailpipe emissions standards set in EU legislation are intended to encourage vehicle manufacturers to improve the energy performance of their vehicle fleets. However, performance improvements through aerodynamic design have been weakened in recent years by the growing demand for sport utility vehicles, which have high seating positions and therefore relatively high wind resistance.

Improved rolling resistance, which is normally achieved by using energy-efficient tyres, can typically reduce the energy used by current designs of LDVs and passenger cars.

Recent research at the ETH Zurich has concluded that the impacts on emissions of combining the three vehicle design options highlighted above depend on the size and use of the vehicle as well as on the powertrain because of the different conversion and recuperation efficiencies involved under different operating conditions, but could typically lead to emission reductions of up to 20% (Boulouchos *et al.* 2017).

For HDVs (trucks), the potential for reducing emissions by improving vehicle design (light-weighting, aerodynamics and rolling resistance) is likely to be lower

than for passenger cars because such optimisation has already been driven by fuel costs, which constitute a larger share of ownership costs for HDVs than for passenger cars (typically about 30% for HDVs and only 10–15% for passenger cars).

For aviation, the industry has a long history of developing improved aerodynamic designs and lightweight materials to increase performance and reduce operating costs. However, there are no taxes on aviation fuels, which make them relatively cheap (compared with road transport fuels) and, despite the inclusion in the ETS of aviation fuels used in the EU, emissions from the EU aviation sector continue to increase.

For deep-sea maritime transport, the dominant factor for reducing fuel consumption per tonne-kilometre is the choice of vessel size, although hydrodynamic resistance also contributes to fuel consumption and can typically be further optimised (IMO 2009). In addition, 'slow steaming' can be adopted when fuel costs are high, leading to lower specific fuel consumption (per tonne-kilometre), although this may not be compatible with the short delivery times needed for perishable goods. Similarly, there is a trade-off between ship size and the required frequency of deliveries, and there are limits to the size of the largest ships, mostly owing to the size of existing ports and the costs of upgrading them as well as other adverse environmental impacts.

3.4 Powertrain technology and fuel substitution options

3.4.1 Overview of transitional options and long-term sustainable options

Although fossil fuels will need to be completely phased out to fully decarbonise and deliver sustainable road transport services in the long term, a series of transitional options must be deployed in the short to medium term to deliver the EU's interim goals in 2030 and 2040. Such transitional options will naturally include the use of vehicles with more efficient conventional powertrains and hybrids of all kinds, in parallel with a growing market share of electric vehicles.

The electrification of road transport services can be justified during the transition period and in the long term because the overall emissions from the power generation sector are capped by the ETS, and electrification will make an increasing contribution to decarbonisation of the transport sector as the EU's electricity generation mix is increasingly decarbonised and its costs decrease. The use of electricity for road transport is already growing, with BEVs entering markets across the world. However, the demand for low-carbon electricity for transport can be expected to increase in the future not only because of growing markets for BEVs but also because it can be used to

produce hydrogen for fuel cells in cars, buses and long-haul freight vehicles (HDVs). In addition, there will also be a growing future demand for low-carbon electricity to produce green hydrogen for existing and emerging hydrogen markets in industry, and to produce synthetic hydrocarbon fuels for use in combustion engines.

As a transitional option, more of the existing ICEs (with minor modifications where necessary) should be adapted immediately to use alternative 'drop in' fuels, such as natural gas, conventional biofuels (to a limited extent to avoid indirect land-use change (ILUC) effects and competition with the production of food and feed crops) and advanced biofuels to meet the demand for transport with reduced GHG emissions and thereby deliver progress towards decarbonisation.

Also as a transitional option, ICEs can be used together with batteries in hybrid electric vehicles or PHEVs, which offer significant improvements in energy efficiency and the long-distance capabilities of ICEs as well as the low GHG, NO_x and particulate matter emissions of electric vehicles in urban areas. Hybrid electric vehicles and PHEVs are expected to gain higher market shares in the road transport sector in the near future because they offer an affordable and attractive combination of reduced emissions and flexibility of use for both LDVs and passenger cars.

Looking to the future, there are growing expectations that it may become possible to produce advanced biofuels, hydrogen, synthetic hydrocarbon fuels (and perhaps also ammonia) with more competitive costs and that these may offer sustainable long-term solutions for decarbonising some of the more difficult subsectors of transport including aviation, deep-sea maritime freight and HDVs, which require energy carriers with high energy densities.

3.4.2 Internal combustion engine vehicles and hybrid electric vehicles

Currently more than 97% of conventional road transport vehicles in the EU use internal combustion engines, with either spark ignition engines fuelled by petrol (about 56%) or compression ignition engines fuelled by diesel (about 41%) (ACEA 2017a). A small number of road transport vehicles (5%) use natural gas or liquefied petroleum gas (LPG). Future policies to deliver GHG emissions savings from the road transport sector may need to address one or more of the following issues.

3.4.2.1 Air quality and other environmental impacts of vehicle emissions

While the recent EU regulations and standards are succeeding in reducing GHG and pollutant emissions from new vehicles, additional policies and support

schemes are still needed to accelerate the scrapping and replacement of old vehicles that have poor NO_x and particulate matter management technologies, with modern vehicles that meet the highest vehicle emission standards. However, all vehicle scrapping and replacement policies should be accompanied by measures to avoid the export of old vehicles with high emissions to countries outside the EU, and to minimise the waste of embedded energy during the scrapping process.

While the focus of this report is mainly on road transport, it is noteworthy that ships cause pollution in oceans and inland waterways, and that aviation is an important source of air pollution especially in high regions of the atmosphere where contrails also contribute to the greenhouse effect. Because the decarbonisation of the aviation and maritime transport sectors is likely to involve the introduction of alternative fuels and powertrains, future policies for those sectors should address all potential emissions and environmental impacts that might result from those alternative fuels and powertrains.

Noise pollution, especially near to major highways and air traffic, has a negative impact on human health and the quality of life, as do some forms of transport infrastructure which damage visual amenities and natural habitats. Policies aimed at the decarbonisation of air transport should address in particular improved aircraft routing to reduce emissions associated with take-off and landing, hybridisation of aircraft powertrains to facilitate extra power for take-off together with highly fuel-efficient engines for cruising, and electrification of small aircraft for short trips. (Note: detailed analyses of decarbonisation options for aviation are outside the scope of this report.)

3.4.2.2 Improve internal combustion energy efficiency

Efficiency increases are still being achieved by most engine manufacturers, partly as a result of improved combustion, but also by introducing more ICT to manage engine performance. Recent analyses suggest that CO₂ emission reductions of up to about 25% and 20% can be achieved in passenger cars and LDVs with gasoline and diesel ICEs, respectively, by improving ICE efficiency (Cox 2018; Elgowainy *et al.* 2018), for example through variable compression ratios, improved valve timing, better combustion control and advanced fuel injection systems. For HDVs, most of the efficiency improvements are expected to come from waste heat utilisation and electrification of auxiliaries.

3.4.2.3 Hybridisation of powertrains

Vehicles with ICEs that are complemented by electric motors (hybrid vehicles) can deliver significantly reduced GHG emissions by using energy that would otherwise be wasted to charge the battery, for example through

braking, and then using the stored energy later to drive the vehicle. Analyses from ETH Zurich (Onder *et al.* 2011; Ott *et al.* 2013) give evidence of a reduction potential of 20–30% through full hybridisation of conventional gasoline ICEs in passenger cars. The lower potentials refer to ICEs that are optimally designed to suit everyday transport services, while the higher potential reductions apply for oversized powertrains (unfortunately a current trend in the market), where hybridisation can help to avoid inefficient engine operation at low loads, for example under typical urban driving conditions.

3.4.2.4 Alternative fuels in internal combustion engines

Natural gas and LPG are already used to a limited extent (about 5%) in ICEs for transport. Compressed natural gas and LPG can be stored in a tank in passenger cars and in both LDVs and HDVs, while liquefied natural gas, which must be maintained at low temperature (–161°C), is less attractive for use in small vehicles than compressed natural gas. Both natural gas and LPG are fossil fuels. LPG is separated from natural gas during production and from crude oil during refining. LPG creates safety issues in closed garages/parking spaces owing to its high volatility, but it benefits from a well-established distribution infrastructure.

In spark ignition ICEs, methane is an appropriate substitute for gasoline and its chemical composition (with 4:1 hydrogen to carbon ratio compared with less than 2:1 for gasoline) leads to a theoretical CO₂ emission reduction per energy unit of 25% (van Basshuysen 2015). Owing to methane's low auto-ignition propensity, which allows for higher thermodynamic efficiency due to an increased compression ratio, spark ignition engines exclusively designed for CH₄ could offer efficiency gains of up to 28% compared with the same engine optimised for gasoline (van Basshuysen 2015).

In compression ignition ICEs, dual fuel operation with up to about 80% methane combined with diesel fuel has been demonstrated to deliver a CO₂ reduction potential of about 20% compared with diesel-only vehicles (van Basshuysen 2015).

The use of natural gas in vehicles carries an additional risk in relation to global warming because leakages

(fugitive emissions) of methane (the main component of natural gas) into the atmosphere from upstream processes can substantially reduce or even outweigh its climate benefits (see Box 3.1). However, if the known cost-effective steps are taken to avoid up to half of the fugitive leakages, then substituting gasoline and diesel transport fuels with natural gas would be a potentially valuable transitional option for delivering GHG emission reductions in the short to medium term.

Biogas is already collected from landfill sites and from municipal (including sewage sludge) and agricultural waste digesters. It is used for distributed power generation, heating and, on a limited scale, as a transport fuel. Looking to the future, it is expected that a growing share of biogas will be cleaned and upgraded to biomethane (>90% methane) and that more of this will be distributed through the existing natural gas networks. Because of its renewable nature, biogas is a sustainable transport fuel that potentially offers substantial reductions in GHG emissions compared with conventional transport fuels; however, its costs, which depend strongly on its feedstocks and on the energy used to upgrade it, are still too high (IRENA 2018a). The benefits of using biogas are particularly high where the alternative would be for its potential feedstocks to decay and emit methane, because of the high global warming potential of methane (see Box 3.1).

Conventional biofuels used for transport include biodiesel and bioethanol. Biodiesel is currently produced in the EU mainly from waste cooking oils, rapeseed or palm oils. Blended with fossil diesel oil, it can be used in compression ignition engines and is the most widely used conventional biofuel in the EU transport sector. When its feedstocks are processed with hydrogen to produce hydrotreated vegetable oil (HVO), this can be blended to higher percentages than conventional biodiesel and produces significantly lower harmful tailpipe emissions (Aatola *et al.* 2008). Bioethanol is produced by fermentation of carbohydrate-rich biomass, such as maize or sugar beet. It can be used in spark ignition engines when blended with gasoline and is the second most widely used conventional biofuel in the European transport sector.

Biodiesel and bioethanol dominated the renewable energy contribution of 7% to transport fuels in 2016 (Eurostat 2018c) and, despite the new 7% limit on the

Box 3.1 Climate impacts of methane

Methane has a strong global warming potential, which is between 28 and 36 times higher than that of CO₂ over a 100-year period (and even higher over a 20-year period). The extent of the leakages during the collection, processing, transmission, storage and distribution of natural gas depends on the source and the technologies used. The IEA estimates that upstream leakages/fugitive emissions of methane from the global energy sector are about 1.7%, but that 40–50% of these could be avoided in future at no net cost (IEA 2017). Concerns remain, however, about the consistency and transparency of emissions data across the natural gas supply chain. There is therefore a need for stronger regulations on emission control, and improved reporting requirements (Le Fevre 2017).

Box 3.2 Renewable Energy Directive II (EU 2018a)

The 2018 Renewable Energy Directive (recast) contains a complex set of targets, flexibility schemes and deadlines among which the headline requirements for the transport sector include the following.

- (1) An EU target of 14% for renewable transport fuels by 2030.
- (2) Biofuels and biogas for transportation in future to deliver increasingly demanding GHG emission savings (with biogenic emissions excluded), reaching 65% for biofuels and biogas produced in installations starting operation after 1 January 2021.
- (3) Biofuels and biogas for transportation to comply with an extensive list of updated sustainability criteria to avoid indirect land use change (ILUC) and other negative environmental impacts.
- (4) A 7% limit on the use of conventional biofuels produced from food and feed crops.
- (5) Phasing out of high ILUC-risk feedstocks, such as palm oil, by 2030.
- (6) A 3.5% sub-target for advanced biofuels and biogas in the transport sector by 2030.
- (7) Delegated acts covering certification and guidance on demonstrating compliance with requirements for low ILUC-risk biofuels and biomass fuels by February 2019 and January 2021, with review by September 2023.

Box 3.3 EASAC comment on the use of forest biomass

In view of the time-dependent commitments to decrease GHG emissions which were adopted in the Paris Agreement, and the urgent need within the next 10–15 years to reduce GHG emissions to limit global warming to less than 2°C or even 1.5°C, EASAC recommends that the delegated acts and updates to the 2018 Renewable Energy Directive, which are scheduled up to 2023, should include further clarifications about the use of forest biomass. Trees remove carbon from the atmosphere as they grow, and serve as carbon sinks throughout their lives, which can extend to hundreds of years. However, when trees are harvested and burned, it can take many decades – or, for some trees, centuries – before all of the carbon that is released during their combustion is taken back from the atmosphere and stored in new trees. This time delay is known as the carbon payback period. To safeguard against systematic over-harvesting causing losses of forest carbon stocks and sink capacity, the delegated acts and updates should make it clearer that forest biomass can only be used for bioenergy if it comes from sustainably managed forests and that forest biomass with long carbon payback periods must not be used to produce biofuels (or for power generation), because of the short- and medium-term impacts on forest carbon sinks (EASAC 2017b, EASAC 2018c, EASAC 2018d).

use of conventional biofuels in the 2018 Directive, they are expected to continue to offer a transitional option for the decarbonisation of transport and specifically to play a significant role in meeting the new 14% EU target for renewable transport fuels by 2030 (EU 2018a). However, in line with the recommendations made by many stakeholders and experts including EASAC (EASAC 2012) since the first renewable energy directive was adopted in 2009, they will have to meet a far more comprehensive and demanding set of sustainability criteria to comply with the 2018 directive.

Advanced biofuels are defined in the 2018 renewable energy directive as those that can be produced from a list of feedstocks (annexed to the directive), which includes a range of wastes and lignocellulosic materials (including forest biomass) that do not come from food or feed crops. These are prioritised in the directive and given a specific target (with biogas) of 3.5% by 2030 because they offer a more sustainable long-term decarbonisation option. The listed feedstocks can be treated using several different processes to produce ethanol or synthetic fuels. There are many different estimates for the future availability of biomass for energy purposes, but most credible studies agree that bio-energy can provide a limited but nevertheless significant contribution to future energy demand in the transport sector (Creutzig *et al.* 2015). This being the case, it will undoubtedly make sense for the limited resources of advanced biofuels to be made available and eventually limited to those transport subsectors

for which other low-carbon fuel options, such as electrification, are difficult or in some cases impossible, such as aviation, deep-sea shipping and possibly some long-haul HDVs.

Synthetic fuels can be counted towards targets in the 2018 Renewable Energy Directive as renewable fuels of non-biological origin. Also known as synthetic hydrocarbon fuels, they can be produced using 'green' hydrogen (see section 3.4.4) in combination with a suitable source of carbon (e.g. atmospheric CO₂) to produce syngas as a basis for making liquid (oxygenated) hydrocarbons including alcohols and single-molecule fuels such as methanol, dimethyl ether, oxymethylene ether, dimethyl carbonate and methyl formate. Such hydrocarbons are being studied as potential synthetic fuels for use in ICEs, although research is still at relatively low technology readiness levels. Synthetic fuels could in the longer term also be used as a means of seasonal electricity storage. It is too early to predict future markets and prices for synthetic fuels, but they could perhaps be imported in future from countries with the potential to develop large and cheap supplies of low-carbon electricity. Ammonia is also being studied as a potential future synthetic fuel because it contains high amounts of hydrogen and, despite being highly corrosive, is relatively easy to transport and store, being a liquid at room temperature under modest pressures. Research is ongoing to develop ways of using ammonia to transport and store hydrogen for use in conventional ICEs, and to minimise

its NO_x emissions (David *et al.* 2014). However, because of the multiple steps in their production, which are discussed in section 3.4.6, synthetic fuels have low overall conversion efficiencies (Nationale Akademie der Wissenschaften Leopoldina *et al.* 2017). Consequently, their use will only become justifiable in the long term for applications where other, more efficient options cannot be used, such as in aviation or long-haul HDVs or maritime transport, or for energy storage.

3.4.3 Battery electric vehicles and plug in hybrid electric vehicles

The two main types of electric vehicle on EU roads today are BEVs and PHEVs.

1. BEV. These are powered by electricity that has been stored in an on-board battery. Driving range and charging the batteries of BEVs are two of the biggest challenges faced by those who are working to promote the use of electric vehicles.

The driving range of BEV passenger cars and LDVs on the road today is limited, typically to between 200 and 300 km, although this is increasing and some already deliver significantly more. The average driving distance of a car in Europe is around 25–30 km per day (FSO 2017; Odyssee-Mure 2018), which is well within the capacity of all BEVs in EU markets today. However, most car owners wish to make much longer journeys from time to time, and many BEVs still have a driving range of less than 300 km, although this is expected to grow towards 500 km in the next few years. The costs of batteries are falling fast (see Box 3.4) but, until batteries with higher capacities at acceptable weights become available at affordable costs, there will be a market for PHEVs (see below), because these can be driven on their ICEs when their batteries become discharged. The use of batteries for long-distance road transport (HDVs) is expected to be limited, even in the long term, because of their weight; similarly, weight will continue to limit the feasibility of battery use in aviation.

BEV batteries can be charged in different ways. The battery capacities of current models of BEV passenger cars are, with a few exceptions, less than 50 kWh so they can be fully recharged slowly overnight using the existing electricity supply from a normal house (e.g. at about 3.5 kW) or more quickly with a fast charger rated between 7 and 22 kW. Currently, fast chargers such as those installed at motorway service stations can recharge typical BEVs within 20–30 minutes using special power supplies rated at 50 or 120 kW. The next generation of fast chargers may be rated at 350 kW or higher (NPE 2018a, NPE 2018 b) and, together with advances in battery technology, these can be expected to bring charging times down to 15 or perhaps 10 minutes within the next 7–10 years. However, the speed of charging must be selected to suit the battery technology (internal modules, cells and processes within the battery). Fast charging stimulates degradation processes and causes overheating, and frequent use of fast charging strongly reduces battery life. Charging speeds may also be limited by the available power source (electricity grid constraints), and thermal management of batteries may be needed during charging to avoid overheating and consequent lifetime reduction (EEA 2016a; Toll 2018). More research is needed on (1) battery design and thermal management to minimise degradation and lifetime reduction caused by supercharging (Liu *et al.* 2016) and (2) electricity distribution grid management when using clusters of battery chargers that are rated at more than about 150 kW.

Recent experience in Norway can provide valuable lessons on electric vehicles for policy-makers because Norway has put in place a wide range of incentives to support their use and consequently now has the most electrified passenger car fleet in the world. Here a survey of more than 8,000 vehicle owners has shown that, in Norway, PHEVs drive using electricity for 55% of the time while BEVs are driven further and more often in traffic. BEV owners are younger, have more children, have a longer

Box 3.4 Batteries for electric vehicles

The most widely used battery in electric vehicles today is lithium ion, for which the costs have fallen very quickly in recent years (EASAC 2017a) and are expected to approach US\$100/kWh in 2025 (Bloomberg NEF 2018).

Batteries remain a research area of high strategic significance. Battery technology can be expected to continue to evolve, but with lithium-ion batteries dominating for at least the next 10 years. Their energy densities at cell level currently lie between 200 and 240 Wh/kg and may rise further; however, to exceed 300–350 Wh/kg with lithium-ion batteries will be very difficult, perhaps impossible.

It is not yet clear which battery technology will replace lithium ion. One possibility is the all-solid-state battery, which could offer greater safety and higher energy densities than lithium ion. However, significant problems must be solved before a commercial product could compete with lithium ion on cost, and major investments in new manufacturing processes would also be necessary. Other possibilities include lithium–sulfur and lithium–air technologies, which also offer higher energy densities than lithium ion, but both would also require new manufacturing processes and it is not yet clear whether their benefits would justify the additional costs.

distance to work and own more vehicles than other vehicle owners. Electric vehicles are mainly charged at home, partly at work and rarely elsewhere. Fast charging is used for irregular trips where users plan to use fast chargers to accomplish the trip or to solve a problem on the way (Figenbaum and Kolbenstvedt 2016).

The lifetime of BEVs is important for owners, although it is actually the lifetime of batteries that is more important because, for current technologies, the battery lifetime will normally be shorter than that of the rest of the vehicle. Battery life is not simple to predict because it must be assessed in terms of cycling life and calendar life, both of which depend on how the battery (and therefore the vehicle) is used. This is a potentially important issue for electric vehicle owners and buyers, because the value of the battery depends on how much of its life has been consumed. To meet this emerging need, more advanced battery test methods must be developed and reliable service providers established with the ability to value old batteries. Some manufacturers are already offering an 8-year or 160,000-km warranty on their vehicle batteries, together with a warranty for loss of battery capacity (e.g. reduction to 70% of nominal capacity) and the hope is that such warranties will be extended as battery technologies develop over the coming years. Recycling of batteries will become increasingly important as the numbers of electric vehicles and electric vehicle batteries grow, both to supplement the limited supplies of battery material resources (notably cobalt and lithium (see Annex 3)) and to ensure proper implementation of the circular economy. Schemes need to be put in place very soon for the recycling of electric vehicle batteries in all EU Member States.

The energy efficiency of BEVs on a tank-to-wheel basis is high compared with that of conventional vehicles: for example, BEV efficiencies are around 65–70% (including non-propulsive energy demand) compared with 25–30% for ICEVs, around 30% for passenger car hybrid electric vehicles and 40–45% for long-haul HDVs³. However, the extent to which electric vehicle efficiencies are reflected in lower CO₂ emissions from the transport sector depends on the CO₂ footprint (g CO₂/kWh) of the electricity used to charge their batteries. Furthermore, when comparing the overall decarbonisation potential of electric vehicles with that of other transport options, it is important also to consider the embedded CO₂ emissions caused by battery and vehicle production, recycling and disposal processes (see section 3.7).

From an air quality perspective, which is an increasingly urgent priority in many EU towns and cities, the use of electric vehicles is attractive because they do not produce tailpipe emissions of NO_x and particulate matter when being driven (Cox 2018). Such emissions are produced, however, during vehicle and battery manufacture (see section 3.7). Electric vehicles are typically heavy and therefore produce significant particulate matter emissions from their tyres, but fewer particulate matter emissions than ICEVs from their brakes because electric vehicles largely use regenerative braking.

Buses have provided a rich resource for studies of innovation processes and how to introduce new environmental technologies into the market (Berggren *et al.* 2015). Electric buses are being increasingly selected as the preferred option for reducing harmful emissions and improving overall air quality in EU cities and urban areas (see section 3.1), and there are already well over 300,000 electric buses on the road globally, with the vast majority of them in China (Bloomberg NEF 2018).

Battery safety in BEVs is an issue that may require specific legislation. It is particularly important to minimise the risks of thermal runaway in lithium ion batteries, and to provide trained staff and facilities to deal with fires involving battery materials in confined spaces, such as tunnels and battery storage rooms in ships (e.g. passenger ferries), where it is difficult to evacuate people.

Battery research is being given a very high priority by national governments across the world as well as by industry, and significant progress has already been achieved in reducing battery costs and improving their performance (notably energy density) over the past 5–10 years (see Box 3.4). In the near future, it seems unlikely that the use of batteries and BEV technology can be competitive in aviation, maritime shipping or long-haul HDVs, with the possible exception of combinations with ERS for HDVs on highways (see section 3.4.5), but continuing research could of course lead to unexpected breakthroughs. The launch in 2017 by the European Commission of the European Battery Alliance (EC 2017g) is therefore a welcome initiative.

2. PHEV. This is a vehicle that runs on a battery that can be charged by the mains electricity grid, but which is also powered by a conventional ICE that charges the battery while it is running. PHEVs

³ Efficiencies given here are indicative: actual values depend on the size and use of vehicles, and the degree of hybridisation.

therefore have the potential to offer flexibility when used on long journeys and thereby to minimise the need for public fast-charging facilities. With appropriately sized batteries, PHEVs have an indicative electric driving range of 20–85 km (EEA 2016a), so they can meet the needs of many users by operating for most of the time as electric vehicles because 93% of all passenger car journeys within the EU involve less than 25 km (JRC 2013). The current generation of PHEVs also have the potential advantage of low life-cycle CO₂ emissions because the embedded CO₂ emissions in their batteries are lower than those in BEVs. This is because their batteries are smaller (Cox 2018).

Because it is much cheaper to drive using electricity than fossil fuels, there is a customer incentive for PHEV drivers to maximise the use of their battery; so, in the absence of other incentives for BEVs, there should be much less resistance to switching from fossil fuel vehicles to PHEVs than to BEVs because there is also no compromise in the driving range even with today's technology.

With today's relatively high battery prices, many passenger PHEVs are currently sold with over-powered ICEs and under-sized batteries (typically around 10 kWh, although PHEVs with larger batteries are coming onto the market). This helps to minimise their total cost of ownership, but causes their emission reduction performance to be relatively poor. Better emission reduction performance and lower running costs could be achieved in many cases if PHEVs were driven mainly using electricity (especially in urban areas) but the battery size would need to be selected to suit individual (or possibly national or regional) customer requirements, and larger batteries would typically result in higher total costs of ownership. Incentive schemes aiming to promote the use of passenger PHEVs should take into account the costs and benefits of introducing PHEVs with larger battery options into mainstream markets (see the experience from Norway above). Plug-in electric trucks are also emerging onto EU markets, and offering the possibility to operate in compliance with new regulations in low-emission zones.

3.4.4 Hydrogen and fuel cell electric vehicles

Most of the hydrogen used today is produced by steam methane reforming from natural gas, but this process produces large quantities of GHG (about 10 kg of CO₂-eq. per kilogram of hydrogen produced (Spath and Mann 2001)), which must be capped and in future reduced under the ETS. Instead, 'green' hydrogen could be produced without GHG emissions by using low-carbon electricity (e.g. from hydro, nuclear, solar or wind) with well-established electrolysis technologies to

split water into hydrogen and oxygen (power to gas), although so far the costs and efficiency of sufficiently large-scale electrolysis have proved to be barriers to mass implementation. Alternatively, hydrogen could be produced using emerging pyrolysis techniques to split methane into hydrogen and solid carbon (Holladay *et al.* 2009; Abanades 2016, Abanades 2018), or without net CO₂ emissions by an integrated process of steam methane reforming from natural gas together with carbon capture and storage, but not until sufficient carbon capture and storage plants have been built and put into commercial operation, which does not seem likely in the EU very soon.

Looking to the future, it is important to recognise that the use of hydrogen for transport will have to compete with its growing use by other industries, which also need to reduce their carbon emissions, notably the global steel industry which is developing technologies and steel making plants that will use hydrogen for large-scale oxygen reduction. The future production methods, costs and availability of hydrogen will surely be strongly influenced by such developments, and future EU policies addressing the use of hydrogen for transport will need to take this into account.

The use of hydrogen in ICEs has been demonstrated since the early years of the 19th century, and some vehicle manufacturers have continued working on it into the 21st century. However, in recent years the focus has shifted to the much more efficient option of using hydrogen in FCEVs. Hydrogen has a higher gravimetric energy density than batteries, so FCEVs typically have a longer driving range than BEVs and offer faster refuelling capabilities. They are therefore seen as a potentially more attractive alternative to fossil fuels in ICEs for HDVs and long-haul buses as well as for non-electrified trains and some maritime applications, such as ferries and mid-range shipping. A recent detailed study for the Swiss HDV sector shows that large-scale electrification of the HDV market would require either an enhanced battery energy density (by a factor of 5–6 compared with the current state-of-the-art) or multiple swaps (4–6) per day to replace batteries (Çabukoglu *et al.* 2018). In comparison, hydrogen-fuelled FCEVs could achieve a high electrification potential with a small number of hydrogen recharging stations (Çabukoglu *et al.* 2019). An advantage of FCEVs powered by hydrogen is that they emit only water vapour through their tailpipes, but their overall emissions can nevertheless be very high because these depend on how the hydrogen is produced (see section 3.7).

The sizes of future transport markets for hydrogen will depend on the costs of the new supply and distribution infrastructure involved as well as on the efficiency with which the available low-carbon electricity can be used compared with that of using the electricity in BEVs

(Miotti *et al.* 2016; Agora Verkehrswende *et al.* 2018; Dena 2018). The costs of fuel cells and of on-vehicle hydrogen storage are also challenges that still have to be addressed. However, hydrogen offers seasonal storage capabilities, thus providing synergies with the evolution of the electricity sector (see section 3.5.)

The EU has funded demonstrations of around 100 fuel-cell buses and their infrastructure in EU cities for more than 15 years (Eltis 2003), but their total cost of ownership is still higher than that of battery electric buses (Transport and Environment 2018). Many of the well-known automotive vehicle manufacturers across the world are working on the development of FCEVs today, including long-distance (inter-city) buses and long-range HDV applications. Similarly, train manufacturers are developing hydrogen- and fuel-cell-powered trains. Industry-funded projects are regularly announced in the press and progress is being made⁴.

Further research is needed to reduce costs, address safety issues and increase the lifetimes of key fuel-cell components (e.g. fuel cell stacks) before recycling (Schiebbahn *et al.* 2015). Further research is also needed on catalysts, both to improve the efficiency of hydrogen production and to reduce the costs of fuel cells. The production of hydrogen using electrolysis currently involves the use of metal catalysts with potentially limited resource availability, in particular platinum-group metals, which could limit the commercial viability of hydrogen-powered vehicles in the relatively near future (Ellingsen *et al.* 2016; see also Annex 3). For the longer term, if the production of hydrogen could be increased in line with the supply of variable renewable electricity generation (wind and solar), then it could be useful for balancing electricity networks. However, there remain questions about the commercial viability of hydrogen storage for balancing the grid because of the high pressures and low temperatures needed for its liquefaction. A public-private partnership between the European Commission, industry and research organisations was set up in 2008 with the title 'Fuel cells and hydrogen joint undertaking' (FCH JU 2018) to fund research and promote the uptake of hydrogen and fuel cell technologies.

3.4.5 Electric road systems

BEVs are already proving to be a reliable and potentially cost-effective option for short journeys such as those of many urban commuters, but the electrification of buses and HDVs may be easier to achieve by connecting them to continuous supplies of electricity along the road. This can be done using overhead lines and pantographs, or connectors that pick-up electricity from conductor rails in the road or, at some future date, inductive solutions that supply electricity from above, below or beside the

vehicles. Such electric road systems (ERS) could use electricity more efficiently than BEVs, but their efficiency could be influenced by the choice of connection between the vehicle and the electricity supply as well as by the use (if any) of on-board batteries (Taljegård 2017). ERS could reduce the need for potentially more expensive options such as FCEVs and synthetic fuels in ICEVs (Connolly 2016). In addition to connecting vehicles to the grid, ERS infrastructure could operate as a reinforcement for electricity distribution networks, which would bring a potential source of revenue but also a potential loss of efficiency to its operators. Further research and field experience is needed to evaluate these potentials.

Pilot ERS systems are already being demonstrated, so combinations with on-board batteries for driving short distances on non-electrified roads and for manoeuvring around off-road sites at each end of the journey can be evaluated. ERS can also be combined with hybrid ICE powertrains to provide operational flexibility. There is already an ERS test track operating on a public road in mid-Sweden between Gävle and Sandviken, and a test site using conductive rails in the road at Arlanda airport near Stockholm (eRoad Arlanda 2018). In addition, three ERS test tracks are under planning in Germany (Taljegård *et al.* 2019), and a few are already in operation in USA (Connolly 2016).

There is a need to find international agreement on standards before ERS systems can be implemented across the EU, and large investments will be required to build ERS infrastructure and to produce new heavy-duty electric vehicles, all of which can be expected to take several years to implement. ERS systems are therefore not expected to make significant contributions to the electrification of transport at EU level before 2030.

3.4.6 Costs and efficiencies of transport electrification options

Although some detailed studies of possible future cost scenarios have been published recently (Agora Verkehrswende *et al.* 2018), it is difficult to predict with confidence the future costs of deploying new technologies on the scale that will be required to meet the EU's long-term global decarbonisation goals. Nevertheless, some clear trends can be drawn from the evidence that is already available.

Firstly, the direct use of electricity, for example by connecting vehicle motors to the grid through ERS, is likely to be the most energy-efficient option; however, in addition to a major expansion of low-carbon electricity generation, it would require major investments in new infrastructure before even one vehicle could operate. Once they are in mass production, the costs

⁴ Note: it is neither feasible nor appropriate for EASAC to attempt to present an independent analysis of commercial projects and activities here.

of the electric motors and control systems in the new vehicles would probably be lower than those of ICEs, so the infrastructure costs per vehicle-kilometre would dominate the overall operating costs of direct electrification in the early years of the transition phase. However, the infrastructure costs per vehicle-kilometre would decrease as more electric road vehicles were deployed, so ERS could become the lowest cost option in the long term.

In contrast, for the short term, although PHEVs would also require an expansion of low-carbon power generation, the introduction of more hybrid electric vehicles and PHEVs would require relatively minor investments in infrastructure and could make valuable but limited short-term contributions to CO₂ emission reductions at modest costs. However, hybrid electric vehicles and PHEVs will not be able to deliver the emission reductions that will be required for the long term unless their ICEs were to be fuelled with low-carbon fuels, such as advanced biofuels or synthetic fuels.

BEVs and FCEVs could deliver high levels of decarbonisation in the long term, but both will require a major expansion of low-carbon electricity generation, BEVs will require reinforcements of electricity grids and new charging points, while FCEVs will require hydrogen distribution networks. The logistics and distribution infrastructure for synthetic hydrocarbon fuels is essentially in place, and any fuel station modifications would be marginal (unless oxygenated fuels are used), but the technological innovations and cost reductions needed to mass produce synthetic fuels on a sufficiently large scale remain major challenges.

To produce hydrogen, which is also needed for synthetic fuels, the costs of electrolyzers are still high, but these are expected to fall as the market for green hydrogen grows for industrial as well as for transport applications. In addition, a carbon source is needed to produce synthetic fuels; if this is CO₂ from the atmosphere, then systems and infrastructure for its capture and use are also needed (Haszeldine *et al.* 2018; Keith *et al.* 2018; SAPEA 2018).

BEVs, FCEVs and ICEVs using synthetic fuels all require low-carbon electricity if they are to contribute to the decarbonisation of transport. However, the overall efficiencies with which that electricity is used in these three options differ substantially, with the efficiency of making and using synthetic fuels being very much lower than that of hydrogen and fuel cells, which itself is significantly lower than that of BEVs, as was clearly summarised in a recent report by Agora Verkehrswende *et al.* (2018), based on work by Nationale Akademie der Wissenschaften Leopoldina *et al.* (2017) (see Figure 3.1).

In summary, Figure 3.1 shows that it will require approximately 2.5 times as much electricity to run the same vehicle with fuel cells as it would with batteries, and about 5 times as much electricity to run the same vehicle with synthetic fuels. However, it is important to note that these multipliers are only 'indicative', because they are based on simplified analyses using average values, and no account is taken of the energy required to supply carbon for making synthetic fuels. Multipliers for specific cases will depend on the sizes of the considered vehicles (LDV or HDV) as well as on the degree of hybridisation, and should be determined using full life-cycle assessment (see section 3.7).

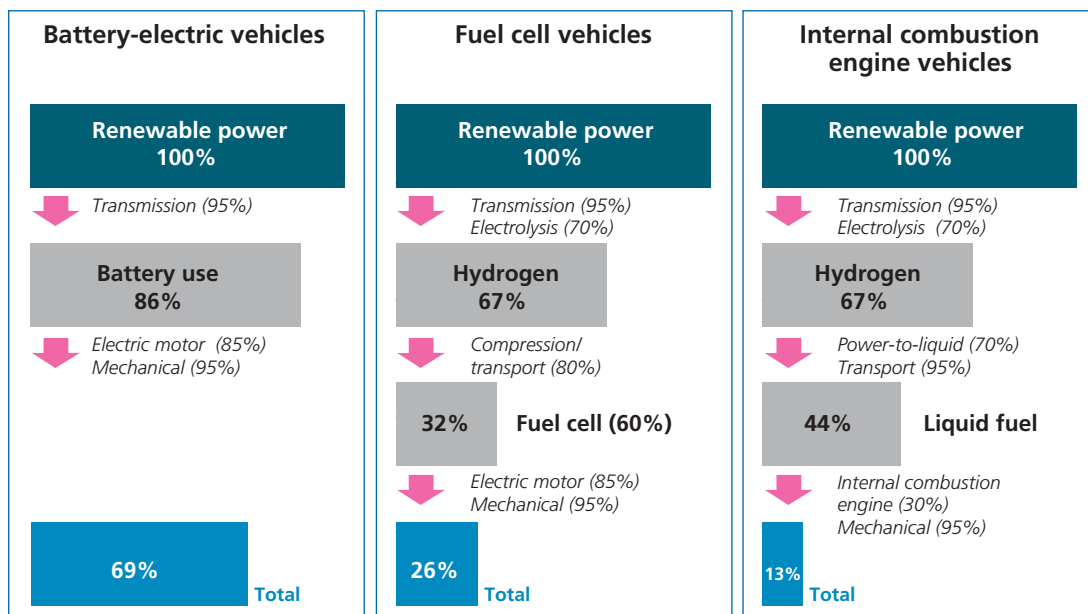


Figure 3.1 Conversion efficiency comparison for electricity used in BEVs, FCEVs and synthetic fuel ICEs. (Redrawn from figure 5 in Nationale Akademie der Wissenschaften Leopoldina *et al.* 2017.)

In terms of the overall life cycle costs of these three transport options, the cost of the underlying low-carbon electricity is of course only a part, and other important constraints on each option will contribute to future decisions on where and when they should be deployed.

There are potential opportunities for synthetic fuels to be produced in geographical areas with high renewable energy potentials, for example in sunny parts of Africa, Latin America or the Middle East, and then to be shipped to Europe for use where renewable electricity is more expensive to produce. Such options could eventually provide valuable storage of renewable electricity, which could be used in Europe, for example when the wind is not blowing and the sun is not shining.

In summary, it is difficult to predict how such a complex global market for low-carbon transport will develop over the coming decades, but there will certainly be an important role for electrification, both of the vehicles themselves and of the fuel supply chains on which future vehicles will depend.

3.5 Coupling of transport, electricity, buildings and industry sectors

3.5.1 Overview of coupling interfaces

Apart from the use of low-carbon advanced biofuels, each of the long-term sustainable options for substituting oil-based transport fuels, namely electric vehicles, hydrogen and eventually synthetic fuels (made from hydrogen and captured-fossil CO₂), will clearly increase the coupling between the transport and electricity sectors. However, decarbonisation of transport by any of these means will only occur if the electricity sector is decarbonised by building additional low-carbon generators to meet the additional demand for electrification, by closing down fossil-fuelled electricity generators, especially coal-fired generators and/or by building new infrastructures for CCS.

At the same time as the transport sector is being decarbonised, buildings and industry (especially the energy-intensive industries, including aluminium, cement, steel, petrochemicals and many others) must also be decarbonised; much of that is also expected to involve electrification, with the largest electrification potential being in the buildings sector and the lowest in transport. Consequently, there will be growing competition for low-carbon electricity, and a substantial overall increase in demand for electricity as all three sectors (transport, buildings and industry) adapt their systems to use it.

The Treaty on the Functioning of the European Union confirms each EU Member State's right to determine the conditions for exploiting its energy resources, its choice between different energy sources and the general

structure of its energy supply (EU 2008). In other words, the Treaty confirms that the choice of electricity generators lies with individual EU Member State governments. How to optimise this choice is a complex issue, which lies outside the scope of this report. Some of the future low-carbon electricity may come from nuclear power generators, but these take many years to build and are not accepted in all EU Member States, so a large part of the additional low-carbon electricity in the EU is currently expected to come from wind and solar photovoltaic generators. Consequently, there will be a growing need for flexibility management systems, which can maximise the benefits resulting from potential synergies between varying supplies of electricity and the varying demands of the transport, industry and buildings sectors.

An overview of the coupling between the transport and electricity sectors is shown in Figure 3.2, where it can be seen that electricity produced from low-carbon energy sources can power ERS and BEVs directly. Alternatively, when electricity demand is low, hydrogen can be produced and fed into either a new hydrogen grid or the existing natural gas grid, stored and used to power FCEVs, or converted into synthetic fuels (see section 3.4.2) for use in aviation, shipping or long-haul HDVs, where ICEs are likely to remain important. Figure 3.2 also shows that low-carbon electricity can be supplied to consumers in the industry, buildings or transport sectors; so, in a competitive market, it is likely to be supplied first to consumers who are willing to pay the highest price. It follows that, to promote decarbonisation, appropriate incentives should be put in place to ensure that the available low-carbon electricity will be supplied first to those consumers from the industry, buildings or transport sectors who can deliver the biggest GHG emission savings for a given cost.

From a policy perspective, to promote decarbonisation is quite difficult in the EU because of the need to work with three different tools that are used to drive down carbon emissions: (1) taxation on transport fuels with (2) the ETS for electricity supplies (including supplies to electric vehicles and electrolyzers for hydrogen production) and industrial energy demands (including heat for steam methane reforming to produce hydrogen for transport) and (3) the Effort Sharing Regulation for buildings and transport. Transport was not included in the original ETS, which resulted in the energy-intensive industries, including power generation, being able to compete for certificates among themselves without the challenge of having to compete with transport users and operators who are typically willing to pay more than big industries for energy. However, the electrification of transport effectively brings it into the ETS and may therefore produce some unexpected outcomes for the ETS in the future, for example crowding some industries out of ETS markets because of their lower willingness to pay.

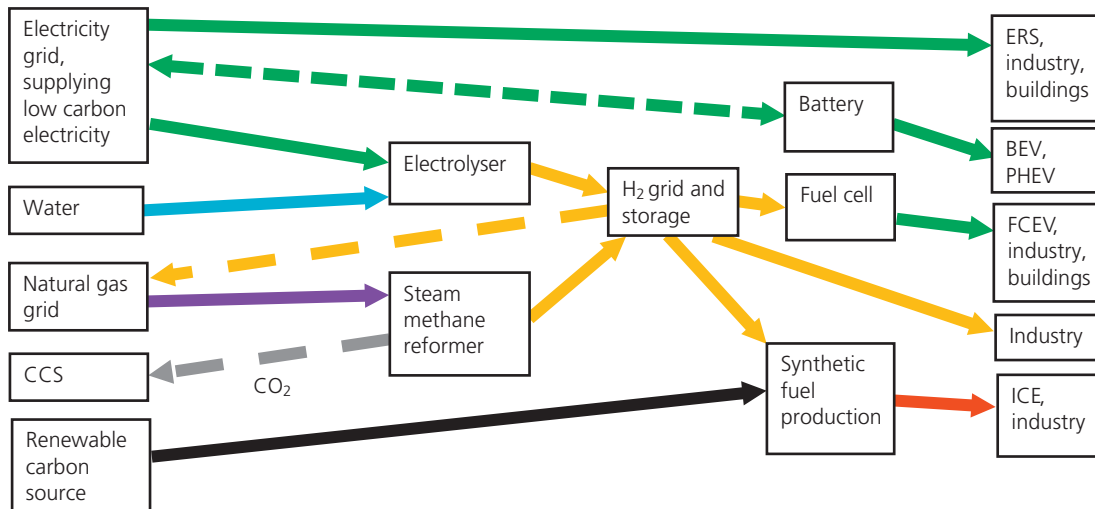


Figure 3.2 Overview of coupling between transport, electricity, buildings and industry sectors.

Box 3.5 Estimates for energy and power demands of BEVs

The electrical energy demand of a BEV can be crudely estimated by assuming that it runs approximately 15,000 km per year at about 200 Wh/km, and therefore creates an electrical energy demand of about 3 MWh per year. Under a scenario of high electricity demand in which all 250 million cars that are currently running in the EU are replaced by BEVs, the additional annual electrical energy demand for cars would be approximately 750 TWh. If, under the same scenario, all EU road freight transport (currently consuming about half the energy consumed by cars) were converted to run on fuel cells and hydrogen produced using low-carbon electricity (with about half the overall efficiency of BEVs (see Figure 3.1)), then the total electrical energy required for cars and freight together would be about double that for cars, i.e. about 1,500 TWh/year. This would equal approximately 46% of the EU's annual electricity generation (about 3,255 TWh per year in 2016), or about 1.5 times the renewable electricity that was generated in the EU in 2016 (about 980 TWh).

The electrical power demand of a BEV is directly related to the required charging rate (the acceptable time taken to recharge a battery). Most BEVs are charged overnight using a 'slow' charger rated at about 3.5 kW, but faster 'superchargers' with ratings up to about 120 kW or more per vehicle are also used, for example at motorway service stations where drivers want to recharge their batteries quickly. Under a scenario of high electricity demand in which all 250 million cars that are currently running in the EU are replaced by BEVs, the additional power demand for slow charging all those BEVs simultaneously at the rate of 3.5 kW would be approximately 0.9 TW, which is about equal to the total generating capacity in the EU (about 1 TW) and nearly twice the current peak demand in the EU (about 550 GW). This clearly shows the need for 'smart charging' to spread the demand over the day and night. Similarly, it is relatively easy to show that the use of fast chargers, which are largely used during daytime peak hours, must be limited and managed using IT (smart charging) systems to smooth out potential peak loads on the EU's electricity networks, in order to minimise the investments needed to reinforce the grid infrastructure.

3.5.2 Future energy and power demands for transport electrification

Although the mix of vehicle types and powertrain technologies is difficult to predict for future EU fleets of passenger and freight vehicles, from a long-term policy perspective it is important to ensure that the expected growth in the use of BEVs, FCEVs, ERS and synthetic fuels can be supplied by additional low-carbon electricity generation and with the existing or reinforced grid networks. This implies that sufficient new low-carbon electricity generators must be installed or additional output produced by existing low-carbon generators, and that the networks must be reinforced where necessary to ensure that they are able to supply both (1) the energy (in terawatt-hours, TWh) required by the vehicles and fuel-producing facilities over the year and (2) the power (in terawatts, TW) needed to charge clusters of vehicles and fuel-producing plants at any given time (see Box 3.5).

IT systems for managing the speed at which batteries are charged are important from both grid and battery perspectives, because fast charging is less efficient than slow charging (i.e. it consumes more electricity to achieve a given level of charge in the battery) and reduces battery life.

3.5.3 Battery charging infrastructure

An important potential market barrier to the use of BEVs and PHEVs is limited access to recharging infrastructure. Fast-charging facilities are needed on major highways, for example at motorway service areas, to meet the needs of BEV owners when they are travelling long distances, and slow-charging facilities are needed where vehicles are parked overnight and near to places of work.

Policies to achieve a fair allocation of costs for installing new public charging points and any related grid

infrastructure costs will become increasingly important as the numbers of BEVs grow. During the past few years, vehicle charging points for public use have been installed with funding from a mix of vehicle owners, vehicle suppliers, utilities and retailing companies (e.g. fast-food chains and department stores) as well as national and local authorities. The EU is also making funding available for vehicle charging infrastructure as part of its Connecting Europe Facility initiatives (EC 2018g) and through the European Investment Bank (EIB 2017).

Requirements to install vehicle charging points and/or infrastructures for charging points have been introduced for new and refurbished, residential and non-residential buildings with multiple parking spaces in the recast of the EU Energy Performance of Buildings Directive (EU 2018b). Electricity connections for slow (overnight) charging can usually be installed at affordable costs by BEV and PHEV owners who have their own garage or their own car parking spaces close to their house. In contrast, however, it is much more difficult for drivers who live without their own parking spaces in terraced housing or in apartments. Schemes to address the needs of such drivers are still in their infancy, but some cities and service providers are already putting in place stand-alone charging points alongside residential roads in urban areas or charging points attached to lamp posts that can be accessed using smart cables that recognise the vehicle being charged and automatically invoice the owner for the electricity used. However, such schemes can trigger new social challenges in areas with limited parking spaces: for example, in some areas, BEV and PHEV drivers may have to compete every day for access to a limited number of parking spaces that are fitted with charging points. Looking ahead, it has been suggested that the problems of BEV owners without their own off-street parking may eventually be solved by autonomous vehicle technologies (section 4.2) that can guide vehicles to nearby charging points, but such options are not generally available today.

3.5.4 Markets for grid flexibility management services

The increase in variable renewable electricity generation is already being complemented by emerging markets for flexibility management services and generating capacity on European grids. The market for flexibility services includes moving electricity in time (shifting services), converting electricity to a fuel or other energy carrier such as heat (absorbing services) and injecting electricity into the grid when generation is insufficient to meet demand (complementing services) (Göransson and Johnsson 2018).

Flexibility management services, including flexible generation, interconnections, demand response, storage and the curtailment of variable renewable electricity generators (EASAC 2017a), can be supplied to different extents by operators from the power

generation, industry, buildings and transport sectors. Their contributions will need to be increasingly well coordinated in future to maximise the benefits of potential synergies.

During periods of high output from variable renewable electricity generation, when electricity prices typically fall, it will increasingly make sense to charge the batteries of electric vehicles or to produce hydrogen or synthetic fuels for use in the transportation sector and/or in industry. Such operations are likely to be managed for clusters of actors in the future by independent organisations known as ‘aggregators’ who are able to deliver economically valuable synergies between energy generators, energy users and energy (electricity and heat) storage providers, for example by using clusters of batteries for short-term services, stored hydrogen for medium-term services and stored synthetic fuels for long-term (possibly inter-seasonal) services.

The markets for flexibility management services in a particular region are influenced by costs, the nature of the local load curve and the import/export capacity to neighbouring regions (as well as by the characteristics of the electricity system in the neighbouring regions) (Göransson *et al.* 2010). Appropriate market and policy frameworks should be put in place to encourage the further development of such services, and these should be developed on the basis of field experience, such as that being gathered through projects being funded by the EU Framework Programme for Research and Innovation - Horizon 2020 programme (EC 2017h).

3.5.5 Standards, rules and tariffs for charging electric vehicles

For vehicle-charging solutions to offer the grid flexibility management services discussed above, more advanced system management tools will be required for the grid, together with time-dependent tariffs, and possibly special tariffs for transport users.

Technologies and rules for accessing the grid and making payments at charging points will need to be harmonised across the EU, and rules introduced to avoid visitors, who wish to charge their vehicles when outside their usual operating areas, having to pay excessive ‘roaming’ charges like those that have recently been removed from mobile telephones.

Future policies and rules related to the charging of electric vehicle batteries should also address the need to avoid ‘lock in’ solutions, which might be promoted by vehicle and technology suppliers with vested interests to protect their market shares in what is already becoming a rapidly growing market opportunity.

Providing storage and possibly also flexibility services to the grid could provide a source of revenue for car

owners. Appropriate ICT and management systems are currently being developed to manage batteries in electric vehicles, taking into account business models for the storage of electricity and the provision of flexibility services, as well as the revenue and comfort requirements of the car users/owners. However, it must be recognised that the provision of services to the grid requires a battery to undergo additional operational cycles, which will reduce its operational lifetime. Further experience with providing grid flexibility management services is needed before the impacts on battery lifetimes can be quantified with confidence, but the results will be very important to future business models for the provision of grid services by electric vehicles, and to the providers of BEV battery warranties.

3.6 Timescales for decarbonisation using alternative technologies or fuels

The alternative technologies and fuels that can be used to reduce CO₂ emissions from the transport sector have been discussed earlier in this chapter. These include some that will be sustainable for the long term and others that are not sustainable but could contribute useful GHG emission reductions during the transition phase.

The time needed to decarbonise the transport sector will depend on the levels of investment made in supply infrastructures for low-carbon energy carriers and in the manufacture of low-carbon vehicles. It will also depend on the ability of the transport sector to compete with the buildings and industry sectors for the use of those low-carbon energy carriers, because all three sectors must be decarbonised in parallel. Electrification is perceived as a potentially attractive option for the decarbonisation of all three sectors (transport, buildings and industry), but the timescale for this option will depend directly on the rate of construction of new low-carbon electricity generation.

Policies and incentives aiming to accelerate decarbonisation will therefore need to be coordinated across four sectors (electricity, transport, buildings and industry) to ensure not only that those consumers and applications that offer GHG emission savings at the lowest costs today will be decarbonised first, but also that adequate support is given to accelerate the development and commercialisation of those options that are not yet competitive but have the potential to offer substantial emission savings at competitive costs in the future. In addition, future decarbonisation policies and incentives must take into account potential impacts on consumers, industry and trade. For example, the deployment of BEVs would reduce GHG emissions and help to improve urban air quality but might involve bigger investments with lower financial returns for consumers during the transition phase than electric heat pumps to heat their homes or electric

water-heating systems, all of which could provide future returns to consumers through electricity market payments for demand response and storage. Similarly, energy-intensive industries, whose decarbonisation is regulated by the ETS, may have to compete with new consumers of low-carbon electricity, who may have a higher willingness to pay.

3.6.1 Options for use in the transition phase

Assuming a transition phase with a timeframe of the next 10–15 years (2030), the light-weighting of vehicles, the use of small vehicles and improving the emissions performance of conventional vehicles should continue to be prioritised. In addition, some options, which are not sustainable but could be valuable during the transition phase and are already available in EU markets, could be accelerated relatively quickly: for example, the use of hybrid vehicles and the replacement of diesel and gasoline with natural gas or low-carbon biofuels.

PHEVs are a potentially attractive transitional option, especially in urban areas where 93% of journeys are less than 25 km (JRC 2013), because they reduce GHG emissions but do not compromise consumer requirements, are affordable and can help to reduce tailpipe emissions. However, while PHEVs have marginally reduced emissions resulting from energy recovery and powertrain optimisation, they can only contribute substantially to decarbonisation when they operate on batteries that are charged with low-carbon electricity (e.g. from hydro, nuclear, solar or wind generators). It is therefore important to prioritise the use of PHEVs with adequate battery capacities and the provision of adequate low-carbon electricity. In areas where it is politically or technically difficult to generate sufficient low-carbon electricity during the next few years, carbon capture and storage might be used to remove and store the carbon emissions from fossil-fuelled power generators to meet the needs for low-carbon electricity.

BEVs are not an immediately sustainable option with the current mix of electricity generation in the EU, but they have the potential to become a sustainable solution during the transition phase as the electricity generation sector is decarbonised. Moreover, BEVs cannot add to the overall GHG emissions from the EU because the emissions from the electricity generating sector are capped by the ETS. Against this background, it is already evident from the range of efficiencies with which electricity can be used within the transport sector (see Figure 3.1) that the most efficient transport electrification options are direct electrification using ERS (once infrastructures have been built) and BEVs. However, as discussed in section 3.4.6, the limited range and relatively slow charging constraints of BEVs, together with the weight of batteries, may leave room

in the market during the transition phase for FCEVs, especially for long-haul buses and HDVs.

Independently of the new technology used, it will be very difficult to accelerate the rate of renewal of the EU car fleet, which currently takes about 20 years. To renew all of the HDVs, ships, planes and infrastructures will take even longer.

In parallel with the decarbonisation of transport through electrification, important contributions to the reduction of GHG emissions are also expected to come during the transition phase from the use of advanced biofuels, which can be deployed in conventional ICEs and are therefore not subject to vehicle replacement rate constraints. However, most of the conventional biofuels that are currently available in EU markets are blended with gasoline and diesel, neither of which is sustainable. Their use will therefore be limited to 7% at least until 2030, in accordance with the 2018 Renewable Energy Directive, and their use will continue to be limited in the long term. In addition, a modest contribution (the 2018 Renewable Energy Directive has set a target of 3.5% by 2030) can be expected during the transition phase from advanced biofuels and biogas, provided they meet appropriate sustainability criteria.

3.6.2 Sustainable solutions for the long term (2050)

Light-weighting, efficient vehicle design and choosing smaller vehicles are options that are equally applicable for the short and long terms. Advanced biofuels that meet the required sustainability criteria also offer a potential long-term sustainable option. However, the extent to which advanced biofuels will contribute to the decarbonisation of transport will depend to a large extent on other demands for biomass and on decisions that have yet to be taken about the need to protect forest carbon sinks and to keep the carbon, which is bound in forest biomass, on the ground.

Direct electrification through ERS and BEVs, together with indirect electrification through hydrogen and fuel cells, will become environmentally sustainable for the long term, once the electricity generation sector has been decarbonised. However, the lower energy densities of batteries and hydrogen-based options may leave room in aviation, deep-sea maritime freight and possibly also in long-haul HDV markets for synthetic fuels. Markets for synthetic fuels may be triggered if they can one day be supplied at competitive prices by countries with large resources of low cost, low-carbon electricity. Alternatively, aviation and maritime freight may continue to be supplied with fossil fuels in the long term, with their emissions compensated by carbon capture from the air for underground storage (CCS). However, the technologies required for this are not yet ready for large-scale deployment.

Possible scenarios for the evolution of future EU passenger and freight transport markets between now and 2050 have been studied by several groups including IRENA (2018b), but it is difficult to find a consensus. A baseline scenario was published by the European Commission in its reference scenario in 2016 (see Figure 3.3), which projected a rather limited penetration of electric vehicles compared with more recent expectations. Figure 3.3 illustrates not only the difficulty of predicting how such complex markets will evolve in the future, but also the importance of introducing new policies and regulations to incentivise the use of low-carbon energy carriers in place of fossil fuels.

3.7 Life cycle emissions of vehicles with different powertrains

Life cycle analysis (LCA) is important when comparing the environmental performance of vehicles with different powertrains because GHG emissions are not only produced when vehicles are driving but also by the processes used to manufacture dispose of and

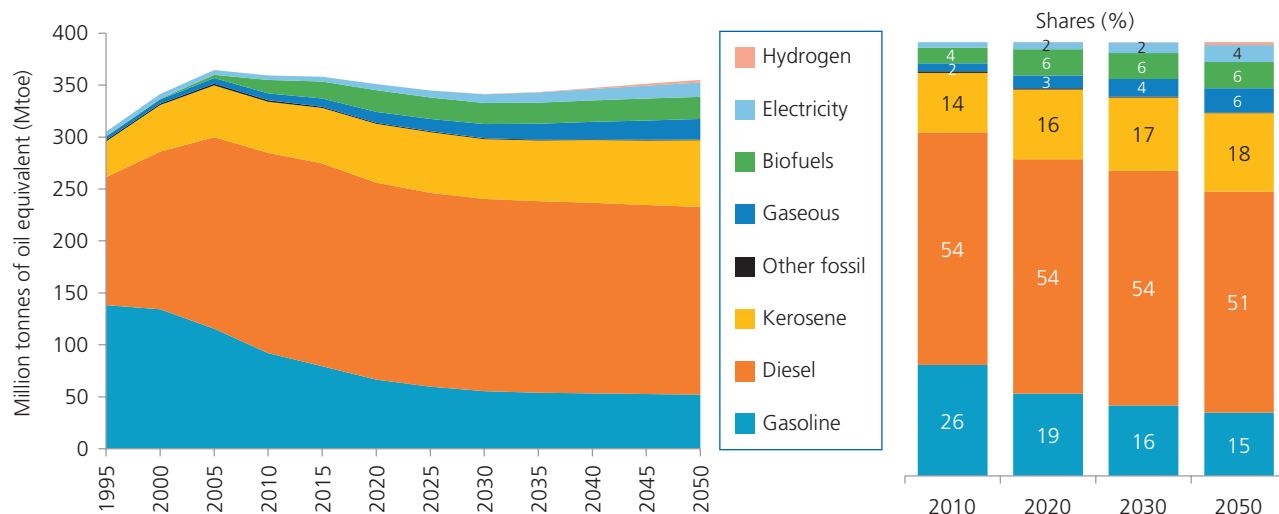


Figure 3.3 Final energy demand by fuel type projected in the EU Reference Scenario (EC 2016a).

recycle the vehicles, produce their fuels and provide the infrastructure to supply them with fuel. A growing number of LCA-based studies of transport options have been published in recent years, of which the following have been noted by EASAC during the preparation of this report: Bauer *et al.* (2015); EEA (2016a); Cox (2018); Elgowainy *et al.* (2018).

Such LCA-based studies define the GHG footprint of a vehicle as the sum of the emissions from its fuel (e.g. the electricity that it uses) during its working life on the road, the emissions produced during the manufacture of the vehicle itself (embedded emissions) and the emissions produced during the final disposal of the vehicle and/or the recycling of its component parts. The embedded emissions can be particularly important for BEVs if their batteries are large and produced in a country where the electricity, which is used by battery manufacturers, is generated mainly using coal or other fossil fuels. The importance to a vehicle's GHG footprint of its embedded emissions compared with those from its fuel consumption also depends on the total distance

that the vehicle is able to drive during its lifetime. Looking to the future, it is important to note that as battery manufacture becomes more efficient (and the costs of batteries are reduced), the emissions produced during battery manufacture will typically decrease.

Over the next few years, namely during the transition period, it is reasonable to expect that the GHG footprints of BEVs per vehicle-kilometre will be reduced in three important ways: (1) battery manufacture will become more energy efficient, leading to lower embedded emissions; (2) the lifetime of low-carbon vehicles/powertrains will increase, giving them the ability to drive longer distances and leading to lower embedded emissions per vehicle-kilometre; and (3) EU electricity supplies will come increasingly from low-carbon generators, leading to lower fuel emissions per vehicle-kilometre. In other words, the electrification of transport in the EU will lead to growing GHG emission reductions, and the biggest reductions will occur in those parts of Europe with high fractions of low-carbon electricity generation.

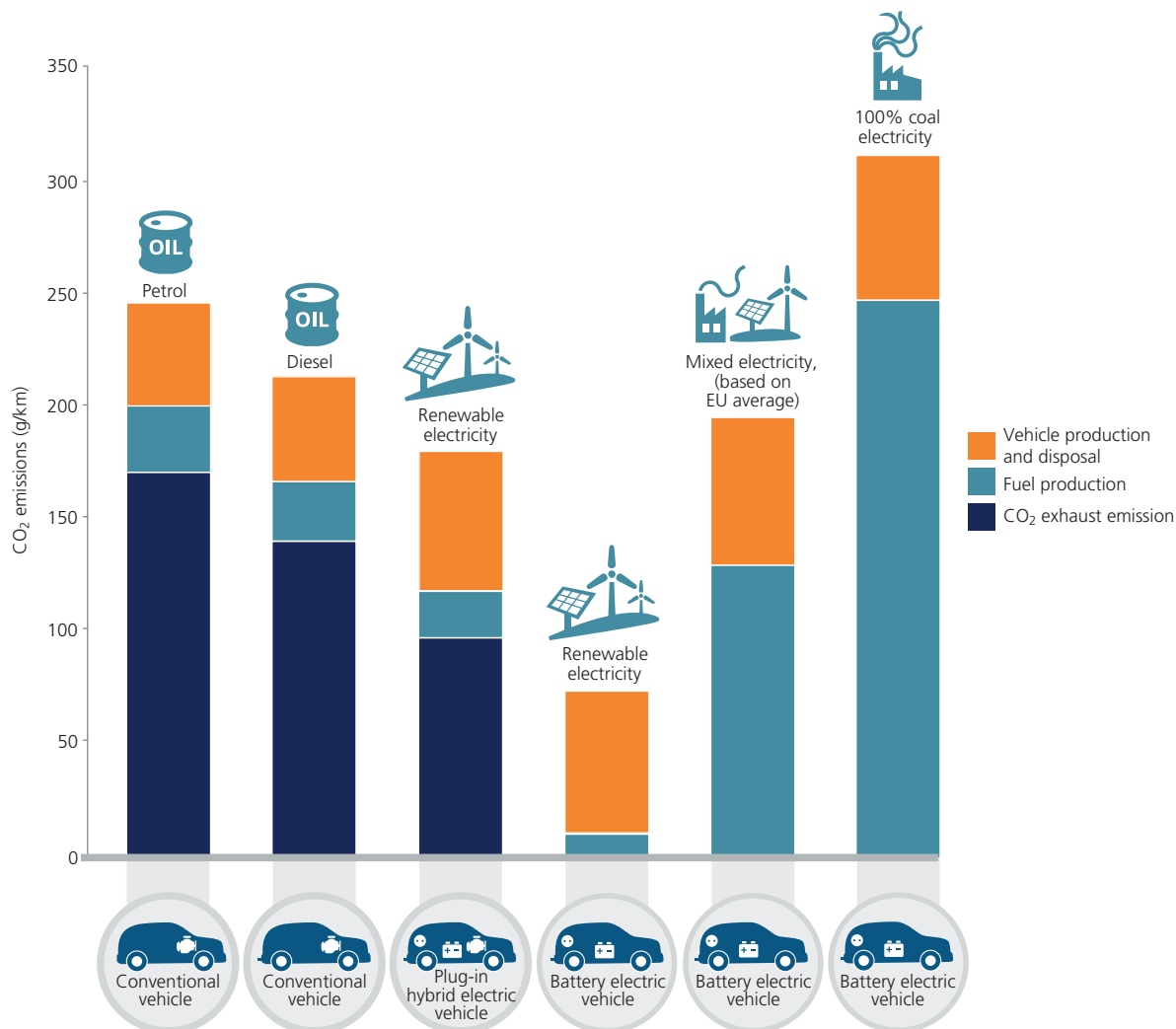


Figure 3.4 The range of life cycle CO₂ emissions for different vehicle and fuel types. Values are estimated for an average mid-class vehicle, based on 220,000 km. (Reproduced courtesy of the European Environment Agency (EEA 2016a).)

A simple comparison of the life cycle emissions of different vehicle and fuel types, based on a vehicle lifetime of 220,000 km, is given in [Figure 3.4](#), and the highlights from a recent detailed Swiss LCA study of future transport options are discussed in [Box 3.6](#).

There is growing recognition of the importance of using LCA to guide future policy and investment decisions in

the transport sector. LCA is not only important for road transport but also for prioritising policies and decisions relating to investments in public transport, such as trains and aviation, where embedded carbon emissions in steel and concrete infrastructures can be substantial. It was not possible to fully address the topic of LCA in this EASAC report, but more research on these issues would certainly be valuable.

Box 3.6 Example of results from a recent LCA study

A recent study by Cox (2018) using LCA shows that batteries have high embedded GHG emissions and that the current LCA GHG footprint of EU electricity, which is 430 g CO₂-eq./kWh (Wernet *et al.* 2016), is expected to decrease as coal-fired generators are phased out and the shares of nuclear and renewable generation evolve. Some of the results from Cox (2018) are summarised in [Figure 3.5](#), from which the following insights can be drawn:

- Power generation for BEVs has a breakeven GHG footprint of 700 g CO₂-eq./kWh compared with conventional gasoline ICEVs, but of only 370 g CO₂-eq./kWh compared with gasoline hybrid electric vehicles.
- BEVs supplied with electricity from combined-cycle gas power plants (which have a GHG footprint of about 600 g CO₂-eq./kWh) produce higher emissions than hybrid electric vehicles.
- FCEVs and ICEVs using synthetic fuels will have higher GHG footprints than BEVs, hybrid electric vehicles and fossil-fuelled ICEVs until almost all electricity comes from low-carbon sources.
- PHEVs have low GHG footprints compared with other technologies for all electricity mixes, owing to the small size of their batteries (even with a range of about 50 km, which is more than 50% of the average daily demand in EU).
- Embedded emissions resulting from BEV battery manufacture (largely outside Europe) currently dominate the overall footprint of BEVs. Battery production should therefore be established in the EU, where power generation is scheduled to be rapidly decarbonised. This would help to create jobs and competitiveness.

The LCA work of Cox (2018) on other environmental indicators (particulate matter formation, photochemical smog precursors, overall human toxicity index, etc.) has shown that the impacts of BEVs are similar to those of ICEs and hybrid electric vehicles, while PHEVs exhibit the lowest impacts. However, tailpipe pollutant emissions from conventional cars still pose health risks, particularly in urban areas.

Overall, these results (in agreement with other studies) confirm the need to accelerate the decarbonisation of the power generation and the industrial manufacturing sectors in parallel, and to continue efforts to electrify vehicle powertrains and to build up the necessary charging/energy carrier infrastructure.

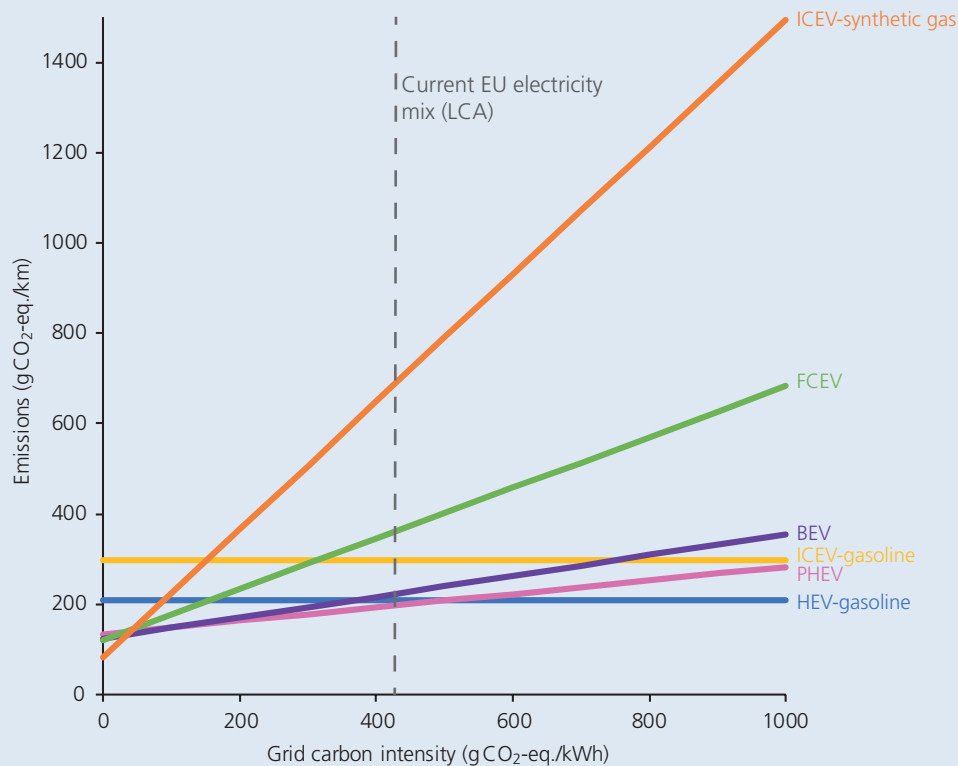


Figure 3.5 Sensitivity of emissions of different passenger car technologies to carbon intensity of electricity mix. (Adapted from Cox 2018.)

4 Information and communications technologies (ICT) and autonomous vehicles

4.1 ICT

Rapid digitalisation has a disruptive character in virtually all economic activities, and is certainly going to affect the ways that future transportation systems operate. Impacts can be expected on both the demand and supply of passenger and freight transport, with common threads being the emergence of new business models, market actors and possibly new patterns of behaviour by consumers as they change the ways that they use transport services.

Since 2010, the EU has introduced a series of policies to promote and regulate the use of ICT in the transport sector including a European strategy on Cooperative Intelligent Transport Systems (EC 2016e). These could be strengthened in the future in relation to the applications highlighted below, to reduce GHG emissions. Among these, the potential for Internet-connected vehicles is particularly important because of the many opportunities which this offers for reducing GHG emissions as well as improving safety and reducing traffic congestion. However, it is still too early to judge which will be the most reliable and cost-competitive means of connecting vehicles to the Internet: both Wi-Fi- and 5G-based solutions are currently under development (EC 2017d). ICT will have various roles and effects on transportation, as discussed below.

4.1.1 ICT for avoiding/reducing transport demand

Well-known forms of ICT, including the Internet, can be used for teleworking, teleconferencing, social media networking, etc., which can all contribute to reducing the demand for passenger transport services, and therefore to reducing GHG emissions. Similarly, e-mail reduces the demand for freight transport services (Kramers *et al.* 2014).

On the other hand, these forms of ICT can also be used to encourage interactions between people who live a long distance apart, which can lead to more people travelling to see each other (rebound effect). Similarly, electronic shopping can increase the demand for individual package transportation, which replaces conventional distribution to shops and subsequent customer shopping (Visser *et al.* 2014).

4.1.2 ICT for road transport demand and traffic management

ICT solutions are becoming increasingly common in our daily life and their future deployment will offer new ways for communities (e.g. Smart cities) to limit GHG emissions from passenger and freight transport

(Kramers *et al.* 2014). Data on current and future social events, weather conditions, disruptive events (incidents, calamities), traffic conditions, holidays, etc. are already being collected in various ways to provide information for citizens and for the management of local community systems, including traffic and transport demand. However, the impacts of such data from ICT on reducing GHG emissions are difficult to predict, as can be seen from the five potential ICT applications that are highlighted below:

- *Public transport information.* ICT can be used to provide real-time information (online and on-site arrivals and departure boards and location tracking for trains, trams, buses, taxis, planes and ships) as well as scheduling (in real time and in advance), which encourage passengers to use public instead of private transport, thereby reducing GHG emissions. ICT can also be used for integrated public transport scheduling and to help consumers to use connected multi-modal public transport services. Today, it remains a challenge for different transport service providers to cooperate but, as ICT systems for public transport become more user-friendly and cheaper, cooperation between providers will become easier and the attractiveness of public transport will increase, which could stimulate increased transport demand (rebound effect) (Kramers *et al.* 2014).
- *Passenger vehicle sharing and carpooling.* ICT can be used to facilitate the use of the emerging business models for bicycle and car hiring and carpooling schemes, which are discussed in section 2.2.1. ICT can, for example, facilitate real-time reservation of vehicles positioned in convenient (street) locations, or which are fitted with global positioning systems so that they can be left anywhere and found by the next user through a mobile phone application, which also unlocks the vehicle when reserved online. Like several of the innovations discussed in this chapter, the impact of ICT on vehicle sharing and carpooling is expected to be a reduction of GHG emissions (Martin and Shaheen 2011), but its magnitude is difficult to predict because it may create some rebound effects by making passenger transport easier, more attractive and potentially cheaper (Kramers *et al.* 2014).
- *Freight transport management.* Various ICT systems are available to allocate shipments between the trucks of a company fleet and, through optimised routing, to minimise costs, fuel consumption and therefore carbon emissions. Further reductions can

be made by anticipating the timing and location of upcoming transport tasks as well as optimising supply chain logistics (Kramers *et al.* 2014; Wang *et al.* 2015).

- *Road pricing.* Dynamic and localised pricing systems using ICT are already available to charge vehicles different prices for using specific road segments at different times (e.g. congestion or low-emission zone charges), which can reduce traffic and therefore GHG emissions in urban areas (see Chapter 2). However, their introduction is typically constrained by political and social barriers arising from concerns about the privacy and reliability of the data and information involved, because such systems have to detect and record the locations of vehicles at all times (Small and Gómez-Ibáñez 1998; NYC Streetsblog 2017).
- *Road traffic management.* ICT is already contributing to GHG emission reductions by improving traffic flows (managing traffic lights and warning signals), and helping drivers to choose the shortest or least congested routes (by giving access to traffic information and satellite navigation). ICT for coordination between vehicles (for more efficient driving or platooning) may further increase this contribution in the future (Tsugawa and Kato 2010).

4.1.3 ICT with big data and artificial intelligence

An important feature of each of the ICT applications discussed in this chapter is the production of vast amounts of data, which can be used together with artificial intelligence for a wide range of machine learning processes, that could enable further optimisation of transport systems.

For example, data on transport flows, traffic management and congestion are currently being collected by many private businesses for their own commercial purposes, but could be used to maximise the potential for reducing GHG emissions in the EU, if they were also made available to city and transport planners and researchers. Crucially important when collecting and storing such data is to avoid political and social barriers being erected by ensuring proper stewardship of data: that is, there should be strict security and privacy/confidentiality of all data that might contain information about the movements of individuals and their vehicles.

4.1.4 ICT in vehicles

Already for tens of years, ICT systems have been deployed to manage the operation of vehicle powertrains. Related objectives are to improve vehicle safety through automatic braking, which can also help to reduce fuel consumption and its related emissions (Tsugawa and Kato 2010).

The introduction of satellite navigation systems in vehicles and smart phones, together with traffic information updates in real time that allow drivers to choose the shortest routes and avoid traffic congestion or to take overall emissions into account, can help to cut emissions by improving the overall travelling efficiency (Tsugawa and Kato 2010; Boriboonsomsin *et al.* 2012). On the other hand, they can also make the use of private cars more attractive and therefore increase passenger-kilometres and passenger transport emissions (rebound effect).

4.1.5 ICT for charging electric vehicles

Slow charging of electric vehicles can be managed with ICT using centralised or local scheduling for multiple vehicles in a small area (street, building, etc.) and with time-varying tariffs (dynamic pricing) to minimise the use of high GHG emission power generators on the grid. ICT can also be used to minimise congestion on electricity distribution networks by coordinating electric vehicle charging, and thereby again reduce GHG emissions (Deilami *et al.* 2011; Gerding *et al.* 2011; Fan 2012).

Fast-charging of electric vehicles can use ICT to avoid overloading the electricity network by employing scheduling and pricing approaches (Bayram *et al.* 2013; Mwasilu *et al.* 2014).

Self-consumption. Slow charging of electric vehicles can, for a domestic owner/prosumer, be achieved with minimal GHG emissions by charging their electric vehicle using their own renewable electricity generation, either at home or at their work place. In addition, electric vehicle owners can use ICT not only to manage the storage of electricity in electric vehicles for home usage but also to manage the discharging of their electric vehicles to supply electricity to the grid or to neighbouring electric vehicles. When such systems are operated with information from the electricity grid operator or with dynamic price incentives, they can serve as mobile storage for the electricity grid and achieve further GHG emission reductions (Ortega-Vazquez 2014; Schuller *et al.* 2014; Gough *et al.* 2017).

Harmonised protocols for card payment systems with ICT can allow electric vehicles to access many different charging points and avoid 'roaming' charges when charging outside their usual area. Such schemes encourage the use of electric vehicles and help to deliver GHG emission reductions.

4.2 Autonomous vehicles

The introduction of autonomous passenger vehicles is not necessarily linked to making vehicles more energy efficient or to reducing their emissions. Passenger vehicle manufacturers are currently developing and

introducing autonomous capabilities as innovative features, which can increase road safety, provide greater freedom to travel for less mobile population groups (young, elderly and disabled consumers), and enhance smooth driving, which could reduce emissions on a per vehicle basis. Autonomous trucks are also under development and are likely to be used first in isolated areas, such as airports, rail terminals or ports, and in factories, construction sites and mining areas.

Autonomous vehicles have been defined under five different levels of autonomy, from very little to fully 'driverless' (see Annex 2). While fully autonomous vehicles (level 5) may not become available within less than a decade, autonomous vehicles at level 4 will emerge sooner and can be expected to influence the patterns of both passenger and freight transport use on the road as well as the total demand for both. The extent to which autonomous vehicles can be expected to produce fewer emissions per passenger-kilometre or per tonne-kilometre than well-driven conventional vehicles is not yet clear.

Studies of the potential impacts of autonomous passenger vehicles suggest that they could provide a new source of competition with existing public transport services and taxis; however, they could, in contrast, also be used to encourage greater use of public transport (e.g. high-speed trains) by providing individuals with very convenient tailored transport services between their home and their departure station, and then onwards from their arrival station to their final destination (ITF 2015b). Similarly, some studies suggest that autonomous vehicles will have shorter calendar lifetimes than conventional vehicles because they will be subjected to more intensive use, and that they could reduce the total number of vehicles on the road. This does not necessarily mean that fewer vehicles will need to be built or that the overall transport emissions will be

reduced, but it could reduce the number of car parking spaces needed in the future (see, for example, ITF 2015b).

Eco-driving could be implemented by autonomous vehicles with the use of ICT, which would drive the vehicle without harsh acceleration, harsh braking or high speeds, and therefore reduce fuel consumption by about 10% (Barkenbus 2010). It would similarly reduce GHG emissions.

Conversely, fully autonomous passenger vehicles could actually increase the overall emissions from passenger transport ('rebound effect') because the availability of autonomous vehicles will make it possible for new categories of passenger to travel more easily (e.g. young, elderly and disabled persons). In addition, autonomous vehicles may attract some passengers away from public transport, thereby encouraging them to use smaller vehicles with higher emissions per passenger-kilometre (Wadud *et al.* 2016).

Similarly, autonomous freight vehicles may not necessarily offer reductions in carbon emissions, if they follow the same delivery routes as conventional delivery vehicles. Nevertheless, driverless trucks could become cost-competitive in urban areas and, if electrified, could be allowed to operate even during the night, thereby increasing their market share. Autonomous long-haul freight vehicles may, however, offer more significant opportunities for emission reductions, because their wind resistance is reduced when they travel in 'platoons' (Tsugawa and Kato 2010). EU vehicle manufacturers claim that platooning could reduce emissions by up to 10% (ACEA 2017b). On the other hand, if driverless trucks become cost-competitive with rail freight and ships, then there is a risk that they could increase the overall emissions from freight transport.

5 Discussion and conclusions

5.1 Overview

GHG emissions from the EU transport sector currently amount to 24% of the total GHG emissions in the EU and are not projected to decrease in a 'business as usual' scenario. Consequently, their reduction forms an important component of the EU's commitment under the Paris Agreement to limit global warming to 2°C, or if possible to 1.5°C. To deliver on this commitment, the EU has agreed to reduce its GHG emissions by 80–95% compared with 1990 levels by 2050, and is putting in place increasingly demanding policies and regulations for the transport sector. It is also supporting the deployment of innovative schemes and technologies and funding large amounts of research, studies and analyses.

An overall governance framework is required to ensure that carbon emission reductions are met as efficiently and cost effectively as possible across all sectors of the EU economy. In particular, transport sector policies and regulations must be coherent with those for electricity markets, energy efficiency, energy performance of buildings, energy from renewable sources (including biofuels), as well as with those for climate action (including the ETS and the Effort Sharing Regulation) and air quality. Policies should be harmonised wherever possible to prevent CO₂ 'leakage' from one sector to another and to avoid creating transport barriers between Member States.

This EASAC report acknowledges the current and proposed EU policies and regulations, and builds on recent scientific analyses to clarify which policy options offer the best potential for reducing transport emissions. In view of the very large number of recent publications in this field, as well as trials and pilot initiatives, an effort has been made in this report to clarify which options could be implemented immediately to facilitate the transition to a low-carbon future and which options are likely to become more important in the future for delivering long-term sustainability.

5.2 Emission reductions from innovative transport demand management

An important short-term objective must be to contain, and where possible to reverse, the growth of demand for motorised transport.

There are many ways for people to avoid using passenger cars, which produce more than 50% of CO₂ emissions from EU transport: for example, by walking or cycling, or shifting to more energy-efficient transport modes, such as buses or trains. The responsibility for policies to deliver such solutions lies largely with cities

and local communities, but they can be helped by policies established at EU and national levels, as well as by private initiatives with new business models such as mobility-as-a-service. In addition, multi-modal transport service offerings, increasingly using innovative ICT developments and eventually also autonomous vehicle options, can reduce emissions by providing a seamless transition between public and individual transport solutions. This, however, requires significant investments in the public (mainly) rail transport infrastructure. Aviation poses particular challenges because it has a very high rate of demand growth, which is stimulated by low-cost airlines, zero tax on aircraft fuels, airport subsidies and cheap holiday packages, but limited technology options for reducing its GHG emissions, other than by investing in faster rail connections to tourist and other key destinations.

European policy has for a long time been constrained by the premise that 'curbing mobility is not an option', as was clearly stated in the European Commission's White Paper on transport (EC 2011a). However, containing growth in the demand for transport is an important first step towards achieving the required emission reductions, and one that should be more actively addressed using innovative policy measures on a sector-by-sector basis. Moreover, in the case of essential freight transport, there are several options for reducing the GHG emissions which could be more widely promoted, including improved vehicle utilisation (load factors), improved freight logistics (route planning), training drivers in the skills of eco-driving, and shifting loads to lower emission transport types, for example from road to rail, inland waterways or shipping.

5.3 Emission reductions from innovative vehicle technologies and fuels

The three main transport supply options for reducing GHG emissions are (1) to improve vehicle design, (2) to use more efficient vehicle powertrains, and (3) to substitute fossil fuels either directly with low-carbon biofuels or low-carbon electricity, or indirectly by using low-carbon electricity to produce hydrogen or synthetic hydrocarbon fuels. All three of these options are needed together with stronger policies and legislation to reduce emissions from vehicle manufacturing, including the production of batteries, because it is the overall life cycle GHG emissions of vehicles and their fuels (cradle to grave) that need to be reduced.

Modest short-term reductions in emissions of up to about 20% per vehicle could be achieved by manufacturers through improvements to the design of conventional passenger cars and LDVs, including light-weighting, reducing aerodynamic drag and

reducing rolling resistance (Boulouchos *et al.* 2017). Such reductions can be applied to existing vehicle designs, but are equally applicable to future vehicles with different powertrains. However, the potential emission savings from improved vehicle design are much smaller for HDVs because some optimisation has already been achieved by their manufacturers as a result of cost considerations, given that fuel costs typically account for about one-third of the total costs of ownership for HDVs.

Under the reasonable assumption that conventional combustion-based powertrains will maintain a significant share of new vehicle markets over the next 15–20 years, all new vehicles must be equipped urgently with state-of-the-art technologies, in particular full hybridisation which is already mature, cost efficient and can deliver at least 20% additional fuel savings in conventional ICE vehicles.

The largest reductions in GHG emissions from all road vehicles will result from replacing fossil fuels with alternative energy carriers, such as low-carbon or advanced biofuels, electricity, hydrogen and – for certain applications – synthetic fuels. The phasing out of gasoline and diesel vehicles by a specific date has already been announced by several national governments, including China, France, India, The Netherlands, Norway and UK. This has opened up new opportunities and created a long-term policy framework, which should give vehicle manufacturers confidence to invest in the production of new models of vehicle with alternative powertrains. It should also give other organisations and authorities the confidence to invest in building infrastructure for the supply of alternative fuels. However, these announcements need to be backed up by concrete measures for ensuring that alternatives will be put in place at the required pace.

With regard to replacing fossil fuels, the largest contribution to transport until now has come from the use of conventional biofuels, which delivered approximately 7% of transport energy and more than 90% of the renewable energy used in the EU for transport in 2016 (Eurostat 2018c). However, estimates of the climate-change mitigation benefits of biofuels are diverse and controversial (Plevin 2017). For the future, the 2018 Renewable Energy Directive sets a target of 14% for transport energy from renewable sources by 2030. This is largely expected to be met by biofuels, but with updated sustainability criteria, the phasing out of high indirect land use change risk (ILUC-risk) feedstocks and a requirement that the use of conventional biofuels be limited to no more than 7%. The use of conventional biofuels must be limited because of their carbon footprint, their impacts on ILUC and the need to maintain production of food and feed for the continuously growing world population. Advanced biofuels will be promoted in addition to conventional

biofuels in the future, although their contribution is not expected to exceed 3.5% before 2030.

The 2018 Renewable Energy Directive requires the European Commission to adopt a delegated act in 2019 setting out criteria for the certification of specific types of biofuel. As part of the implementation of that mandate, the EASAC working group recommends that the delegated act should limit the use of forest biomass, such that forest biomass with long carbon payback periods cannot be used to produce biofuels (or burned for power generation). This would minimise the negative impacts on forest carbon sinks in the short to medium term, and help to avoid putting the less than 1.5°C and 2°C global warming targets at risk (EASAC 2017b). In contrast, as recommended by EASAC in 2012, priority should be given to producing biofuels and biogas for transport applications from municipal, industrial, agricultural and forest wastes (EASAC 2012).

Electrification can only deliver its full potential in terms of CO₂ emission reductions if it is accompanied by the phasing out of coal-fired and other high-emission power generation plants or possibly fitting them with carbon capture and storage systems (after further development), and by the construction of adequate capacities of low-carbon power generation, such as hydro, nuclear, solar and wind generators. Strengthening of the ETS will therefore continue to be important to encourage the construction of new low-carbon power generation at a pace that is sufficient to meet the combined and rapidly growing electricity demands from the transport, industry and buildings sectors. So, provided the EU keeps to its commitments to decarbonise electricity generation, the electrification of road transport using BEVs, PHEVs and ERS is a ‘no regrets’ option, which should be implemented urgently for passenger cars, LDVs and buses wherever the required range can be delivered by the available batteries. This is important because it will take up to about 20 years to replace a substantial fraction of the existing fleet of conventional fossil-fuelled vehicles, but the emission reductions from each electric vehicle that replaces a conventional vehicle will increase as the electricity generation sector becomes more decarbonised. Moreover, electrification will stimulate investments in the mass production of vehicle batteries, which is expected to become more energy efficient through economies of scale and thereby to reduce the GHG footprint of BEVs and PHEVs.

Decarbonisation of transport can also be achieved by indirect electrification, using low-carbon electricity to produce hydrogen (mainly for use with fuel cells) and synthetic fuels which will be easier to deploy than batteries in aviation, ships and possibly long-haul HDVs. However, direct electrification using batteries (BEVs) should be deployed wherever possible because it requires about 2.5 times as much electricity to run the

same vehicle with fuel cells as it would with batteries, and approximately 5 times as much electricity to run the same vehicle with synthetic fuels depending on the vehicle type and powertrain⁵. Moreover, electrification through hydrogen and fuel cells or synthetic fuels only makes sense from a perspective of transport GHG emissions if very low-carbon electricity is used to produce them. It is important to note, however, that it may become possible to store large quantities of excess energy from variable renewable electricity generation in synthetic fuels (see below).

The direct electrification of long-haul freight transport using ERS could be more efficient than using batteries once the required infrastructure has been built. This could take the form of modest adaptations to technologies which have been well proven over many years for trains and trams and/or more innovative alternatives, such as inductive connections between the vehicles and electricity supplies in the road. There would seem to be a good long-term potential for the direct electrification of long-haul freight transport using ERS.

The electrification of all road transport in the EU (e.g. by 2050) would require an additional supply of electricity (see [Box 3.5](#)) of the order of 1500 TWh per year, or about a 50% increase compared with existing electricity supplies. The corresponding increase in electricity generating power that would be needed to charge the electric vehicles would depend on the mix of slow- and fast-charging systems installed and on the successful use of smart charging systems to spread the load over the day. However, the required increase could possibly be limited to no more than about one-third or one-half of the currently installed EU generating capacity of 1 TW. All increases in electricity supplies for the transport sector will need to be complemented by increases for buildings and industry within a similar timeframe. In addition, transport will require major investments in the reinforcement of electricity transmission and distribution grid infrastructures, as well as further integration of electricity storage systems into electricity markets. The management of grid flexibility will become more important as the penetration of variable renewable electricity generation (primarily from wind and solar generators) increases on the grid ([EASAC 2017a](#)).

The deployment of electricity for transport through hydrogen or synthetic fuels could provide new ways to store renewable electricity over extended periods, thus providing synergies with the overall storage needs of the electricity sector. However, the value of such options to EU generators and grid operators will depend on how much hydrogen and/or synthetic fuel is produced in the EU and how much is imported. Imports are likely

to come from emerging economies that have high levels of low-carbon energy resources and can produce low-carbon fuels at competitive prices for export to Europe. The main transport markets for hydrogen are expected to lie in fuel-cell-driven buses, taxis, trains (for use on remote, non-electrified lines) and long-haul HDVs, for which batteries are unable to deliver the required range and weight. The main markets for synthetic fuels are expected to emerge only in the long term (after 2040) and to lie mainly in aviation, maritime transport and long-haul freight transport by HDVs.

The electrification of road transport is an attractive option, which should be implemented urgently with as much support as possible. However, with the average age of the EU fleet of 256 million conventional passenger cars being about 11 years and that of the 38 million commercial vehicles and buses being about 12 years ([ACEA 2018](#)), it will inevitably take at least 20 years to replace most of the existing fossil-fuelled vehicles with electric vehicles or other alternatives and it will also take years to replace all of the high-GHG-emitting electricity generators with low-emission alternatives. Consequently, other decarbonisation options should be used to contribute emission reductions during the transition to a low-carbon future. These options should include natural gas, which can be burned in conventional ICEs and offers potential savings of 15–20% per vehicle. However, natural gas should only be used if all of its upstream ‘fugitive’ methane leakages have been limited to less than about 1%, because methane has approximately 28 times higher GHG impacts than CO₂.

PHEVs should be strongly promoted during the transition phase because they can contribute substantial emission reductions (20% or more) if used mainly as electric vehicles, even if they sometimes use conventional fossil fuels. Their relatively small batteries have the advantage of lower embedded emissions produced during manufacture than the batteries in BEVs, but their use should only be promoted and subsidised if their batteries are large enough to supply full motive power for a range that is sufficient for most trips in urban areas, for example at least 50–70 km under real driving conditions. PHEVs will, of course, produce fewer overall GHG emissions if they use biofuels in their ICEs, and in the long-term could potentially use synthetic fuels. However, it is unlikely that synthetic fuels will ever become cheap enough to compete with alternatives for passenger cars and LDVs.

The impact of digital technologies (ICT) and automatic driving on the decarbonisation of passenger cars and trucks is difficult to predict, even qualitatively. Smart

⁵ The performance of vehicles using ICEs powered by synthetic fuels depends on the engine design and application, as well as on the degree of hybridisation.

business models may be beneficial, but rebound effects due to cost reductions per journey and higher comfort levels may increase the demand for transport services. In the worst case, for example, these new technologies could lead to increased emissions through lower market shares for freight transport by rail and higher market shares for freight transport by road.

5.4 Promoting emission reductions with taxes, incentives and public financing

As the use of fossil fuels for road transport is reduced, governments will need to find alternative sources of income to replace those from fuel taxes, but they will also see important reductions in their import bills because more than 85% of petroleum products consumed in the EU are currently imported. In the past, EU governments have applied different tax levels to different fuels, for example to encourage the use of unleaded gasoline before the use of leaded gasoline was phased out, or to promote the use of diesel over gasoline to reduce carbon emissions from transport. Similar approaches may be needed during the transition phase to promote the use of low-carbon fuels.

However, as fossil fuels are phased out and the transport, buildings and industry sectors compete more actively for limited resources of sustainable biofuels and low-carbon electricity, it will become increasingly difficult to work with the three different fiscal tools that are currently being used to drive down carbon emissions, namely (1) taxation on the diminishing number of users of fossil fuels, (2) the ETS for electricity supplies and industrial energy demands and (3) the Effort Sharing Regulation for buildings and transport. As part of this challenge, the taxation of aviation fuels may also come back under scrutiny, although this is notoriously complicated by international agreements and lies outside the scope of this EASAC report ⁶. Given the complexity and the diversity of EU taxation regimes and energy markets, the EASAC working group has concluded that it is too early to predict how EU governments will react to the financial impacts of future fossil-fuel markets.

Long-term commitments should be adopted in future to build investor confidence and promote the transition to low-emission transport fuels or vehicle types, for example through special tax regimes or incentives such as low vehicle excise taxes, subsidies for vehicle purchase, payments to scrap old pollution-emitting (NO_x, carbon monoxide, hydrocarbons, and particulate matter) vehicles, reductions in congestion or

low-emission zone charges, access to special lanes on the road, reduced price parking in city centres, free electricity at public vehicle charging points or subsidies for home charging points. However, it is very important that sunset clauses be put in place for all such incentives and tax regimes to avoid escalating costs, negative reactions from taxpayers and new businesses going bankrupt when incentives come to an end. It is also important that the implementation of such measures be closely monitored and, when necessary, corrected for unwanted side effects, such as creating unfair competition with public transport or privileging wealthy vehicle owners at the expense of low-income travellers.

A zero-emission vehicle (ZEV) mandate, which requires manufacturers to sell a minimum number of ZEVs per year (PHEVs, BEVs and FCEVs), is a policy option for promoting low-carbon vehicles that was first implemented in California in 1990, later in other US states and, in 2017 with some differences, in China. In all cases, car manufacturers incur a fine if their target, based on total vehicle sales and accrued credits, is not met. Research suggests that California's ZEV Mandate has been successful in promoting innovation (Vergis and Mehta 2012; Melton *et al.* 2016), and those US states with a mandate offer a greater selection of ZEV models than other regions (Lutsey *et al.* 2015). The impact of mandates is difficult to estimate, but studies indicate that they have helped to deliver GHG reduction targets (Jenn *et al.* 2017; Sykes and Axsen 2017). However, mandates can have negative repercussions: for example, emissions of conventional vehicles may increase if manufacturers sell more ZEVs because targets depend on average emissions of the entire fleet (Jenn *et al.* 2016). Mandates can also be more expensive than other options (Fox *et al.* 2017). A ZEV mandate option was studied by the European Commission in the impact assessment for its proposed Regulation on emission performance standards for new passenger cars and LDVs (EC 2017j). This concluded that a crediting system would be a better option because it is more flexible than a mandate and, in addition to promoting the development of zero- and low-emission vehicles, it would improve the efficiency of conventional engines, support the competitiveness of the EU automotive industry, and benefit consumers and the environment.

Congestion charges, which are increasingly being applied by cities, are an effective means of reducing traffic congestion, and can be an effective way of reducing GHG emissions and improving air quality. However, as the numbers of low-carbon vehicles grow, it will also be important to ensure that incentives such

⁶ Aviation fuels used within the EU have been included in the EU Emission Trading System (ETS) since 2012, and in 2016 the International Civil Aviation Organization agreed to address CO₂ emissions from international aviation as of 2021. The Carbon Offsetting and Reduction Scheme for International Aviation aims to stabilise CO₂ emissions at 2020 levels by requiring airlines to offset the growth of their emissions after 2020. However, such a stabilisation aim is not sufficient to deliver the emission reduction commitments made in the Paris Agreement to limit global warming to 2°C.

as exemptions from congestion charges or free parking do not lead to a new form of traffic congestion caused by having too many low-carbon vehicles in city centres.

The EU is committed to using its own funding (e.g. the Connecting Europe Facility, European Fund for Strategic Investments, etc.) to support the financing of alternative fuels infrastructure, and to working with the European Investment Bank to attract additional investment (EIB 2017; EC 2018g). Such interventions must be carefully managed to avoid distorting the market in ways that might lead to 'lock-ins' or sub-optimal mixes of vehicles and fuels for the future.

Public authorities can play an important role by adopting common low-emission specifications when procuring new vehicle fleets, so that manufacturers can benefit from economies of scale and reduce prices for all future vehicles. For similar reasons, transport and fuel supply infrastructures should be harmonised across the EU. Valuable inputs to such initiatives may become available from the Member State reports that have to be produced for the 2014 EU Directive on alternative fuels infrastructure, because these should contain technical specifications for electric vehicle charging, natural gas, biofuels and hydrogen refuelling points (EU 2014a). In the future, international standards will also have a potentially important role to play in delivering economies of scale and lower prices for vehicle purchasers and users.

5.5 Promoting EU industries, jobs, skills and further research

The vehicle manufacturing industry in the EU is a major source of jobs and growth. It has an important role to play in the decarbonisation of transport both in the EU and in global markets with its rapidly emerging competitors from Asia and the USA. Recent initiatives by governments and industries outside the EU, notably in China, have helped Third Countries to develop strong positions in emerging global markets for batteries and electric vehicles, notably for electric passenger cars and buses. Future EU policies and initiatives should therefore help EU industries to face future competition at home and in export markets by building on economies of scale in domestic EU markets.

There is clearly a large potential opportunity for EU manufacturers to produce batteries as well as electric and hybrid vehicles for sales in global markets, although the choice of battery technology and of where batteries should be made remain subject to ongoing political debates. To produce batteries in the EU, rather than importing them, would bring several advantages in

addition to job creation and the provision of a solid base for future research and innovation. Local manufacturing of batteries in the EU would help to avoid the problems of scarcity of supply which have already been experienced in the rapidly growing EU BEV markets, and could also increase EU leverage for securing long-term sustainability in materials exploitation and refinery processes. Last but not least, as the EU electricity sector is decarbonised, batteries made in the EU should become increasingly competitive in markets that demand low levels of embedded emissions.

Policies to promote the use of clean fuels and infrastructure should also address the impacts on local communities of reduced demands for fossil fuels, for example in refineries and harbours, and the needs for investment to replace those plants and to retrain the personnel involved.

New skills will be needed for the manufacturing of low-emission vehicles (notably electric vehicles) and for the maintenance and repair of the new vehicles, but because the overall number of employees needed by the EU's automotive industry will be lower, new opportunities will need to be found for members of the existing workforce, who will be made redundant as existing vehicles are phased out. Vehicle manufacturers have estimated that it will require seven times fewer employees to produce an electric vehicle than a conventional vehicle, and that electric vehicles will require far fewer repairs and maintenance service providers.

ICT skills will be important in vehicle manufacturing and maintenance, but also to build on the growing demand for passenger information, traffic and congestion controls, coordination of intermodal transfers, coordination of the charging of electric vehicles, and support for the emerging Internet-based vehicle hire and management platforms.

As part of the transition to a decarbonised future for the transport sector, research and demonstration projects as well as pilot initiatives aiming to roll out new vehicle technologies (batteries, fuel cells, ERS, etc.), fuel production processes (advanced biofuels, hydrogen, synthetic fuels, etc.) and infrastructures are being funded by the EU and by industry. These will provide valuable business opportunities and help with the development of skills in the operation of low-emission technologies, schemes and systems. Public and private sectors at EU, national, regional and local levels will have important roles to play in supporting and monitoring the success of this transition.

6 Advice for policy-makers

The gap between the GHG emissions expected from business-as-usual in the EU Reference Scenario 2016 and the reduced level of emissions needed to limit global warming to less than 2°C or even further to 1.5°C (Paris Agreement) is huge. As part of its response to this challenge, the EU has already taken many steps, including the adoption of a strategy for low-emission mobility to promote the decarbonisation of transport at the same time as addressing poor air quality, traffic accidents and the introduction of innovative technologies (notably ICT), while also defending the competitiveness of EU transport industry.

In addition, the EU has strengthened the ETS as an investment driver by increasing the pace of annual reductions in allowances and reinforced the market stability reserve (the mechanism established in 2015 to reduce the surplus of emission allowances in the carbon market). The ETS does not directly address the transport sector, but will become increasingly important as transport is electrified because emissions from electricity generation are directly controlled (capped) by the ETS. The EU has also committed a growing fraction of its future budget to investments in infrastructure, and to research and innovation related to the transition to a more sustainable economy, including the transport sector.

Nevertheless, it is clear that much more needs to be done to move away from the EU Reference Scenario 2016 (in which CO₂ emissions from the passenger car sector are projected to decrease by about 10%, while those from the truck and bus sector are projected to increase by about 15%, such that overall CO₂ emissions from the EU transport sector, including aviation but not maritime freight, will remain roughly stable or only marginally reduced at a level of around 1,000 Mt CO₂ per year until 2050). Indeed, much more needs to be done even to deliver the target set in the European Commission's White Paper on transport of 2011 to reduce emissions from the transport sector by 60% (compared with 1990 levels) by 2050 to ensure that EU emissions are firmly on the way to zero by that date.

Future policy options

EASAC has looked closely at the initiatives taken by the EU to tackle transport emissions when compiling this report, and its advice is intended to build on those initiatives both during the transition to low-carbon transport, which should take place over the next 10–15 years, and in the long term.

Are current EU policies sufficient to deliver GHG emission reduction targets?

Current EU policies are unlikely to deliver emission reductions quickly enough to limit global warming to

less than 2°C (Paris Agreement). Emission reductions should be accelerated urgently over the next 10–15 years because it is the cumulative GHG emissions over the coming years that lead to global warming, not specific emissions levels in 2030 or 2050. With the average age of EU vehicles being 11 and 12 years, it could take up to about 20 years to renew the current fleet. Nevertheless, emissions from the transport sector could be reduced more quickly than from some other sectors, such as buildings and industry, where the rate of technology renewal is typically lower and many decision-makers need to be convinced to make unusual investments with long payback periods.

Decarbonisation of the transport, industry and buildings sectors depends to a large extent on electrification, so the electricity sector needs to be decarbonised as quickly as possible, especially over the next 10–15 years. In addition, there should be urgent policy support for other short-term options that are independent of the decarbonisation of electricity and could quickly make modest but nevertheless important reductions in transport GHG emissions, such as containing transport demand and shifting passengers and freight to transport modes that produce fewer emissions (e.g. buses, trains and ships), while improving vehicle design and the efficiency of combustion-based powertrains, mainly through hybridisation.

Current EU policies do not adequately and visibly commit to and plan for the timely phase-out of fossil fuels. Stronger fossil-fuel phase-out policies, regulations and incentives need to be implemented as soon as possible and coordinated at all levels across the competing sectors of transport, energy, buildings and industry, such that the biggest potential emission reductions at affordable costs are prioritised and addressed first. International collaboration (e.g. through the ETS and Effort Sharing Regulation) and citizen engagement on policies, regulations and incentives to address the phasing out of fossil fuels will become increasingly important in the future because market forces will cause oil and gas prices to become more volatile and fall as their consumption is reduced.

What should be done to facilitate the transition to a decarbonised future?

No 'silver bullet' policy can deliver the EU's commitments to transport emission reductions, so a combination of transport policy options must be implemented over different periods, some being implemented quickly during a transition period, and others inevitably taking longer. However, all options should be supported at EU, national, regional and local authority levels. Individual citizens are often preoccupied with other issues, so

awareness campaigns together with public sector investments and incentive schemes will be particularly important, recognising that some of the required policies will be difficult for some citizens to accept, especially those on low incomes. Targeted measures and investments will therefore be needed to facilitate and incentivise change, as well as increased resources to inform and engage with local decision-makers, citizen groups and individual consumers throughout the transition period.

EASAC's policy recommendations are split into three groups (also suggested by the IEA):

- (1) *avoiding* demand for passenger and freight transport services;
- (2) *shifting* passengers and freight to transport modes with lower emissions;
- (3) *improving* performance through vehicle design, deploying more efficient powertrains, and substituting fossil fuels with low-carbon energy carriers.

EASAC's recommended actions by policy-makers are summarised below.

1. **Avoid and contain the demand for motorised transport, and reverse EU policy that 'curbing mobility is not an option'.** The urgent need to reduce GHG emissions should be reflected in urgent short-term policies to limit and, where possible, to reverse the growth in motorised transport demand. More policies, regulations and investments should be put in place by businesses, cities, towns, and local authorities using sustainable urban mobility plans to discourage the use of passenger cars in urban areas by promoting walking, cycling, car sharing, working from home, teleconferencing, etc. by using ultra low-emission zones, congestion charges, pedestrian areas and cycle lanes. Such schemes should also be actively promoted and endorsed by EU and national authorities, highlighting the potential health benefits from improving urban air quality. In cities and other urban areas, policies for freight transport should be coordinated using sustainable urban logistics plans (SULPs). Freight transport and aviation both have unsustainable growth rates. The long-standing EU policy that 'curbing mobility is not an option', which was emphasised in the European Commission's White Paper on transport (EC 2011a), should be replaced by innovative EU policies for containing passenger and freight transport demand without jeopardising economic development, regional cohesion, consumer services or the competitiveness of EU industries.
2. **Shift passengers from private cars to public transport services (trains, buses, trams, etc.).** Less than 20% of passenger transport today is

carried by public transport (or privately operated communal transport). This fraction should be increased in the short term by using incentives to raise the occupancy levels of existing public/communal transport, introducing more park and ride schemes for rural commuters, and making better use of emerging business models to deliver transport services (such as Mobility as a Service). Occupancy levels should be raised by making wider use of information technologies to inform potential travellers about the arrival, departure and journey times of existing services. The performance of public transport should also be improved by investing in new bus lanes, increased frequency of trains and buses, and more reliable inter-modal transfers, for example between buses and trains. For the long term, major investments in new train, tram and other public transport services are needed to extend the capacities, routes and options for travellers. There could also be a role in the long term for autonomous buses, taxis and cars, which could be accelerated by incentives and regulations.

3. **Shift more freight off the road and onto railways or waterways.** Most businesses would need to build new infrastructure before they could use rail, inland waterway or maritime transport, so public and private sectors should jointly invest urgently in more and better access points for intermodal containers to transport freight by rail, inland waterways or maritime services. In many parts of Europe, railways are already heavily loaded but nevertheless, with better targeted policies and incentives, together with substantially bigger investments in new infrastructure, rail, inland waterways and maritime transport could offer substantial GHG emission reductions compared with those from transporting by road. Infrastructure building takes time, so (public and private) investments should begin immediately (during the transition period) in preparation for the long term, when they will become increasingly important, because long-haul freight transport is more difficult to decarbonise than short haul urban transport.
4. **Improve/introduce regulations during the transition period to limit consumer demand for oversized vehicles and oversized ICEs.** The European Commission has published recommendations on vehicle labelling, and EU regulations require manufacturers to reduce the annual fleet average emissions from their vehicle sales. However, new oversized passenger cars and LDVs with oversized fossil-fuelled ICEs are still widely available and typically driven longer distances than small vehicles, which are often used mainly for short journeys in urban areas.

Awareness campaigns together with tougher regulations are needed in addition to taxation of fossil fuels to discourage demand for new oversized vehicles and oversized fossil-fuelled engines.

5. Improve the average emissions performance of all passenger cars and LDVs during the transition period. This can be achieved by setting binding target dates for phasing out the use of fossil fuels (gasoline, diesel, compressed natural gas and LPG) for road transport and introducing subsidised scrapping schemes to accelerate vehicle renewal. To avoid wasting embedded energy, scrapping schemes should focus on old vehicles with high carbon emissions. In parallel, because it will take up to 20 years to renew most of the vehicle fleet, it will also be important to continue to reduce GHG emissions from new ICEVs through optimised vehicle and powertrain design, together with hybridisation. This will require increasingly demanding testing, legislation and standards for both embedded and tailpipe emissions on an LCA basis, together with campaigns to promote high-visibility vehicle emission labelling.

6. Improve/increase the rate of market penetration of BEVs and PHEVs for passenger transport as soon as possible. Overall emissions from the electricity generating sector are capped by the ETS, but emissions attributed to the transport sector will decrease as more low-carbon electricity is supplied by the grid. This is important because it will trigger economies of scale in BEVs and investments in electricity supply infrastructure which are needed for the future. Market growth of BEVs and PHEVs can be accelerated by incentivising the purchase of BEVs and certified low-carbon PHEVs (including buses), by imposing regulations in urban areas to limit the use of fossil fuels, by improving the accessibility of public charging points and by providing recycling facilities for batteries. BEVs and PHEVs should be certified and labelled for embedded emissions on a life cycle basis (including emissions from vehicle and battery manufacturing, recycling and disposal) because this will limit carbon leakage through overseas manufacturing in countries with largely fossil-fuel-based power generation, and it will support the manufacture and recycling of batteries with low-carbon footprints, produced using low-carbon electricity within the EU.

In parallel, increasingly strict regulations should be imposed on the relative sizing of PHEV batteries and ICEs, so that PHEVs with oversized ICEs can more easily be excluded from incentive schemes and credits for low-emission vehicles. In accordance with the 'polluters and infrastructure

users pay' principle, PHEVs should not benefit from incentives for low-carbon transport unless they are certified as being appropriately designed with batteries and electric motors that are large enough to allow electric driving for at least 50–70 km. On this basis, rapid electrification of passenger and light duty freight transport would be a 'no regrets' option for the short term, offering reduced emissions of GHG, NO_x and particulate matter, and better air quality in urban areas.

7. Improve/increase the penetration rate of low-carbon electricity generation in the grid urgently. BEVs, ERS, FCEVs and synthetic fuels (for aviation, maritime transport and long-haul HDVs) have the potential to offer GHG emission savings and other benefits to society at the same time. However, to reap those benefits, the rate of growth of low-carbon electricity generation must be higher than the total growth in the demand for electricity from electric vehicles, industry and buildings. Targeted legislation, codes and incentives in addition to the ETS are needed to deliver the required growth of low-carbon electricity generation together with decommissioning of fossil-fuelled generation during the transition period.

8. Improve and adapt the design and regulation of electricity markets and tariffs that apply to electric vehicles. The potential benefits of synergies between managing flexibility on the grid and managing the charging and discharging of BEVs should be maximised as soon as possible. The costs and benefits of new infrastructure and flexibility on electricity networks should be fairly shared between the users of electric vehicles and other consumers through improved time-of-day and power-related tariffs. The use of aggregators and innovative ICT solutions should be encouraged for the benefit of grid operators and of all electricity consumers including industry, buildings, BEV owners and producers of hydrogen for FCEVs and synthetic fuels.

9. Improve and simplify guidance on the use of biofuels, biogas, natural gas and methane for transport. Improved guidance should be given to industry and consumers through EU policies and directives as quickly as possible. The use of all biofuels for transport should continue to be subjected to strict sustainability criteria, and there should continue to be a cap on the use of conventional biofuels made from food or feed crops. In addition, to protect the Earth's carbon stocks, all forest biomass used for bioenergy should come from sustainably managed forests, and biogenic GHG emissions from advanced biofuels should not be zero-rated

when determining incentives or contributions to targets, if those biofuels were produced from forest biomass with long carbon-payback times. The use of natural gas in ICEVs can typically produce 20–25% lower tailpipe emissions than diesel or gasoline, respectively, but methane has a global warming potential that is between 28 and 36 times higher than that of CO₂, so natural gas should only be used for transport if all upstream ‘fugitive’ leakages during its collection, processing, transmission, storage and distribution are properly monitored, certified and limited to less than about 1%.

10. **Improve/increase resources for the development of technologies for producing synthetic fuels.** Allocate adequate resources throughout the transition period to the development of synthetic fuel production technologies, despite their low efficiencies and high costs. Work on large-scale production technologies for synthetic fuels (hydrogen, methane, other hydrocarbons and possibly ammonia) should be strengthened because of the short- to medium-term needs for ‘drop-in’ substitute fuels to replace fossil fuels in conventional ICEs as well as the long-term needs for liquid fuels in long-haul transport (aviation, marine and HDVs). Research on the use of synthetic fuels for the storage and long-distance transport of electricity should also be strengthened.
11. **Improve/increase the levels of investments in ICT and autonomous vehicles.** Increased investment and policy support are needed to deliver car sharing, traffic management, road pricing, transportation planning, electric vehicle charging and discharging solutions, automatic driving and interconnected vehicles, which lead to reduced GHG emissions. ICT solutions can be implemented in the short term, but progress should be closely monitored because recent evidence suggests that digital technologies can not only affect the operations, management and charging/discharging of vehicles in many different ways, but also have ‘rebound effects’. For example, in some situations, ICT and vehicle autonomy could lead to the introduction of smarter supply chains and consequent emission reductions, whereas in others it could lead to increased transport demand and consequent emission increases. The impacts of policies relating to ICT and autonomous vehicles need therefore to be monitored and, when necessary, adapted to

ensure that containment of mobility demand is not jeopardised, and that mobility pricing incentives, regulations, codes and standards are suitably adjusted as these emerging sectors develop.

12. **Improve/strengthen preparations for long-term emission reductions by making long-term policy commitments to invest in innovation, jobs, skills and interdisciplinary research.** The EU automotive industry, which is a major contributor to GDP in the EU, must remain competitive in both EU and global markets as it decarbonises its products and services, but it faces high commercial risks during the transition to a decarbonised future. These risks could be reduced by investing in innovation, for example in a wide range of innovative and potential breakthrough technologies as well as in the establishment of low-carbon footprint battery manufacturing within the EU. To manufacture batteries with low-carbon footprints (low embedded emissions) in the EU would require low-carbon electricity supplies to the manufacturing plant, but would give EU batteries an important competitive advantage in future global markets. It could also strengthen EU leverage in securing long-term sustainability for rare element exploitation and refinery processes.

In addition, experience should be shared across the EU in several topic areas through collaborative innovation, training and research activities to meet the expected growth in demand for skills in ICT, LCA, electrical system management, and in low-carbon vehicle manufacture, maintenance and repair. Market uptake of low-carbon emission mobility (public transport, BEVs, FCEVs, ERS, synthetic fuels, etc.) should be promoted by supporting well-targeted collaborative projects on how to facilitate and manage behavioural change related to sustainable mobility, the successful delivery of innovative socio-economic policy options for transport, and standards. Such work should aim to share experience and explore new solutions, institutional initiatives and business models for all viable decarbonisation options, including regulations, incentives and investments. In addition, long-term initiatives should be put in place to strengthen international cooperation on certifying, labelling and using synthetic fuels in aviation and shipping, and to exploit the potential synergies that might emerge in the long term between the production of synthetic fuels and the seasonal storage and long-distance transportation of electricity.

References

- Aatola H, Larmi M and Sarjovaara T (2008) Hydrotreated vegetable oil (HVO) as a renewable diesel fuel: trade-off between NO_x, particulate emission, and fuel consumption of a heavy duty engine. Report 2008-01-2500. SAE International.
http://www.etipbioenergy.eu/images/SAE_Study_Hydrotreated_Vegetable_Oil_HVO_as_a_Renewable_Diesel_Fuel.pdf
- Abánades A, et al. (2016) Development of methane decarbonisation based on liquid metal technology for CO₂-free production of hydrogen. *International Journal of Hydrogen Energy* **41** (19), 8159–8167.
<https://www.sciencedirect.com/science/article/pii/S0360319915027421>
- Abánades A (2018) Natural gas decarbonization as tool for greenhouse gases emission control. *Frontiers in Energy Research* **6**, 47.
<https://doi.org/10.3389/fenrg.2018.00047>
- Abraham D (2015). *The Elements of Power*. Yale University Press.
<https://yalebooks.yale.edu/book/9780300196795/elements-power>
- ACEA (2011) Discussion Paper – 17th ACEA SAG meeting – October 2011; Modal Shift Target for Freight Transport Above 300 km: An Assessment.
https://www.acea.be/uploads/publications/SAG_17.pdf
- ACEA (2017a) Passenger car fleet by fuel type.
<http://www.acea.be/statistics/article/Passenger-Car-Fleet-by-Fuel-Type>
- ACEA (2017b) Truck platooning.
<https://www.acea.be/industry-topics/tag/category/truck-platooning>
- ACEA (2018) – Vehicles in use in Europe (2018).
https://www.acea.be/uploads/statistic_documents/ACEA_Report_Vehicles_in_use-Europe_2018.pdf
- Agora Verkehrswende, Agora Energiewende and Frontier Economics (2018) The future cost of electricity-based synthetic fuels.
https://www.agora-energiewende.de/fileadmin2/Projekte/2017/SynKost_2050/Agora_SynKost_Study_EN_WEB.pdf
- An R, Ji M and Zhang S (2017) Global warming and obesity: a systematic review. *Obesity Reviews* **19** (2), 150–163.
<https://www.ncbi.nlm.nih.gov/pubmed/28977817>
- Barkenbus JN (2010) Eco-driving: an overlooked climate change initiative. *Energy Policy* **38** (2), 762–769
<https://www.sciencedirect.com/science/article/pii/S0301421509007484>
- Bassett D, et al. (2008) Walking, cycling, and obesity rates in Europe, North America, and Australia. *Journal of Physical Activity and Health* **5**, 795–814.
<http://www.cycle-helmets.com/walk-bike-obesity-rates.pdf>
- Bauer C, Hofer J, Althaus H-J, Del Duce A, Simons A (2015) The environmental performance of current and future passenger vehicles: life cycle assessment based on novel scenario analysis framework. *Applied Energy* **157**, 871–883.
https://econpapers.repec.org/article/eeeappene/v_3a157_3ay_3a2015_3ai_3ac_3ap_3a871-883.htm
- Bayram I, Michailidis G, Papapanagiotou I and Devetsikiotis M (2013) Decentralized control of electric vehicles in a network of fast charging stations. In *IEEE Global Communications Conference (GLOBECOM), Atlanta, GA, 2013*, pp. 2785–2790.
<https://ieeexplore.ieee.org/document/6831496>
- Berggren C, Magnusson T and Sushandoyo D (2015) Transition pathways revisited: established firms as multi-level actors in the heavy vehicle industry, 2015. *Research Policy* **44** (5), 1017–1028.
<http://dx.doi.org/10.1016/j.respol.2014.11.009>
- Bloomberg NEF (2018) Electric vehicle outlook 2018.
<https://about.bnef.com/electric-vehicle-outlook/>
- Boffey D (2018) Luxembourg to become first country to make all public transport free. *The Guardian*, 5 December.
<https://www.theguardian.com/world/2018/dec/05/luxembourg-to-become-first-country-to-make-all-public-transport-free>
- Boriboonsomsin K, Barth M, Zhu W and Vu A (2012) Eco-routing navigation system based on multisource historical and real-time traffic information. *IEEE Transactions on Intelligent Transportation Systems* **13** (4), 1694–1704.
<https://ieeexplore.ieee.org/document/6236175>
- Boulouchos K et al. (2017) Towards an energy efficient and climate compatible future swiss transportation system. SCCER Mobility.
https://www.researchgate.net/publication/317560008_Towards_an_Energy_Efficient_and_Climate-Compatible_Future_Swiss_Transportation_System
- Bruun EC (2014) *Characterizing and Influencing Modal Relationships, Better Public Transit Systems: Analysing Investments and Performance*, 2nd edition, chapter 5. Routledge.
<https://www.routledge.com/Better-Public-Transit-Systems-Analyzing-Investments-and-Performance-2nd/Bruun/p/book/9780415706001>
- C40 cities (2018) Fossil fuel free streets declaration.
www.c40.org/other/fossil-fuel-free-streets-declaration
- Çabukoglu E, Georges G, Küng L, Pareschi G and Boulouchos K (2018) Battery electric propulsion: an option for heavy-duty vehicles? Results from a Swiss case-study. *Transportation Research C* **88**, 107–123.
<https://www.sciencedirect.com/science/article/pii/S0968090X18300470?via%3Dihub>
- Çabukoglu E, Georges G, Küng L, Pareschi G and Boulouchos K (2019) Fuel cell electric vehicles: an option to decarbonize heavy-duty transport? Results from a Swiss case-study. *Transportation Research C* (submitted).
- City of Copenhagen (2011) Good, better, best: the City of Copenhagen's bicycle strategy 2011-2025. Technical and Environmental Administration Traffic Department, City of Copenhagen.
https://policytransfer.metropolis.org/system/images/1556/original/Copenhagen_Bicycle_Strategy_2011-2025.pdf
- CE Delft (2017) STREAM Freight transport 2016: emissions of freight transport modes (version 2).
<https://www.cedelft.eu/en/publications/download/2260>
- Connolly D (2016) eRoads: a comparison between oil, battery electric vehicles, and electric roads for Danish road transport in terms of energy, emissions, and costs. Aalborg University.
http://vbn.aau.dk/files/237844907/David_Connolly_eRoads_2016.pdf
- COWI, et al. (2013) Study to support an impact assessment of the urban mobility package. Activity 31 Sustainable Urban Mobility Plans. Final report.
https://ec.europa.eu/transport/sites/transport/files/themes/urban_studies/doc/2013-10-urban-mobility-package-activity-31.pdf
- Cox B (2018) Mobility and the energy transition: a life-cycle assessment of Swiss passenger transport technologies including developments until 2050. PhD thesis. ETH no. 25081.
https://www.sccer-mobility.ch/export/sites/sccer-mobility/capacity-areas/dwn_capacity_areas/B.Cox_PhD-Thesis_embargo-free_ETH-Zurich_2018.pdf
- Cox B, Mutel C, Bauer C, Beltran A and van Vuuren D (2018) Uncertain environmental footprint of current and future battery electric vehicles. *Environmental Science and Technology* **52**, 4989.
<https://pubs.acs.org/doi/abs/10.1021/acs.est.8b00261>

- Cruetzig F, et al. (2012) Decarbonizing urban transport in European cities: four cases show possibly high co-benefits. *Environmental Research Letters* **7**, 044042.
<https://iopscience.iop.org/article/10.1088/1748-9326/7/4/044042/pdf>
- Creutzig F, et al. (2015) Bioenergy and climate change mitigation: an assessment. *Global Change Biology Bioenergy* **7** (5), 916–944.
<https://onlinelibrary.wiley.com/doi/10.1111/gcbb.12205>
- David W, et al. (2014) Hydrogen production from ammonia using sodium amide. *Journal of the American Chemical Society* **136** (38), 13082–13085.
<https://pubs.acs.org/doi/abs/10.1021/ja5042836>
- Deilami S, Masoum A, Moses P and Masoum M (2011) Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile. *IEEE Transactions on Smart Grid* **2** (3), 456–467.
<https://ieeexplore.ieee.org/document/5986769>
- Dena (2018) dena-Leitstudie Integrierte Energiewende.
https://shop.dena.de/fileadmin/denashop/media/Downloads_Dateien/esd/9261_dena-Leitstudie_Integrierte_Energiewende_lang.pdf
- Department for Transport (2016) Road use statistics Great Britain 2016.
<https://www.licencebureau.co.uk/wp-content/uploads/road-use-statistics.pdf>
- EASAC (2012) The current status of biofuels in the European Union, their environmental impacts and future prospects.
<https://easac.eu/publications/details/the-current-status-of-biofuels-in-the-european-union-their-environmental-impacts-and-future-prospect/>
- EASAC (2016a) Indicators for a circular economy.
https://easac.eu/fileadmin/PDF_s/reports_statements/Circular_Economy/EASAC_Indicators_web_complete.pdf
- EASAC (2016b). Priorities for critical materials for a circular economy.
https://easac.eu/fileadmin/PDF_s/reports_statements/Circular_Economy/EASAC_Critical_Materials_web_corrected_Jan_2017.pdf
- EASAC (2017a) Valuing dedicated storage in electricity grids.
<https://easac.eu/publications/details/valuing-dedicated-storage-in-electricity-grids/>
- EASAC (2017b) Multi-functionality and sustainability in the European Union's forests.
<https://easac.eu/publications/details/multi-functionality-and-sustainability-in-the-european-unions-forests/>
- EASAC (2018a) Negative emission technologies.
<https://easac.eu/publications/details/easac-net/>
- EASAC (2018b) Project on climate change and health.
<https://easac.eu/projects/details/climate-change-and-health/>
- EASAC (2018c) Commentary on forest bioenergy and carbon neutrality.
<https://easac.eu/publications/details/commentary-on-forest-bioenergy-and-carbon-neutrality/>
- EASAC (2018d) Project on carbon neutrality.
<https://easac.eu/projects/details/carbon-neutrality/>
- EC (1995) A Community strategy to reduce CO₂ emissions from passenger cars and improve fuel economy.
<http://aei.pitt.edu/4992/1/4992.pdf>
- EC (2011a) EU White Paper on Transport.
https://ec.europa.eu/transport/sites/transport/files/themes/strategies/doc/2011_white_paper/white-paper-illustrated-brochure_en.pdf
- EC (2011b) COM 112. A roadmap for moving to a competitive low carbon economy in 2050.
<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52011DC0112>
- EC (2013) SWD 529. Final executive summary of impact assessment accompanying EU Communication Together towards competitive and resource-efficient urban mobility.
<https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:52013SC0529>
- EC (2014a) Marco Polo programme.
https://ec.europa.eu/transport/marcopolo/about/index_en.htm
- EC (2016a) EU reference scenario.
https://ec.europa.eu/energy/sites/ener/files/documents/20160713%20draft_publication_REF2016_v13.pdf
- EC (2016b) Paris Agreement on climate action (December 2015).
https://ec.europa.eu/clima/policies/international/negotiations/paris_en#tab-0-0
- EC (2016c) Clean Energy for All Europeans package.
http://europa.eu/rapid/press-release_IP-16-4009_en.htm
- EC (2016d) A European strategy for low-emission mobility, COM(2016) 501 final.
<https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1476374593053&nduri=CELEX:52016DC0501>
- EC (2016e) Cooperative intelligent transport systems, EC COM (2016) 766.
<http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2016%3A766%3AFIN>
- EC (2017a) Europe on the move.
<http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0283>
- EC (2017b) Delivering on low-emission mobility, COM(2017) 675 final.
<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52017DC0675>
- EC (2017c) Smart Cities initiatives.
<https://ec.europa.eu/inea/en/horizon-2020/smart-cities-communities>
- EC (2017d) Digital Transformation Monitor. Autonomous cars: a big opportunity for European industry.
https://ec.europa.eu/growth/tools-databases/dem/monitor/sites/default/files/DTM_Autonomous%20cars%20v1.pdf
- EC (2017e) Electrification of the transport system.
http://ec.europa.eu/newsroom/horizon2020/document.cfm?doc_id=46372
- EC (2017f) Statistical Pocketbook 2017 – EU transport in figures.
<https://ec.europa.eu/transport/sites/transport/files/pocketbook2017.pdf>
- EC (2017g) European Battery Alliance.
https://ec.europa.eu/growth/industry/policy/european-battery-alliance_en
- EC (2017h) Supporting innovative solutions for smart grids and storage. Project examples. Innovation and Networks Executive Agency.
https://ec.europa.eu/inea/sites/inea/files/h2020_sgs_brochure_2017_web.pdf
- EC (2017j) Impact assessment accompanying Proposal for a Regulation setting emission performance standards for new passenger cars and for new light commercial vehicles {COM(2017) 676 final} - {SWD(2017) 651 final}.
<http://ec.europa.eu/transparency/regdoc/rep/10102/2017/EN/SWD-2017-650-F1-EN-MAIN-PART-1.PDF>
- EC (2017k). List of critical raw materials for the EU. COM (2017) 490 final.
<https://ec.europa.eu/transparency/regdoc/rep/1/2017/EN/COM-2017-490-F1-EN-MAIN-PART-1.PDF>
- EC (2018a) Public consultation on the strategy for long-term EU greenhouse gas emissions reduction.
https://ec.europa.eu/clima/news/public-consultation-strategy-long-term-eu-greenhouse-gas-emissions-reduction_en

- EC (2018b) Sustainable Mobility for Europe: safe, connected, and clean, COM/2018/293 final.
<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52018DC0293>
- EC (2018c) Horizon 2020 Transport programme.
<https://ec.europa.eu/programmes/horizon2020/en/area/transport>
- EC (2018d) SUMPS Sustainable Urban Mobility Plans.
https://ec.europa.eu/transport/themes/urban/urban_mobility/urban_mobility_actions/sump_en
- EC (2018e) EU Emission Trading System ETS.
http://ec.europa.eu/clima/policies/ets_en
- EC (2018f) Reducing CO₂ emissions from passenger cars.
https://ec.europa.eu/clima/policies/transport/vehicles/cars_en#tab-0-0
- EC (2018g) Connecting Europe Facility.
<https://ec.europa.eu/inea/en/connecting-europe-facility>
- EC (2018h) A clean planet for all, COM (2018) 773.
https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_en.pdf
- EC (2018i) Final Report of the High-Level Panel of the European Decarbonisation Pathways Initiative.
https://ec.europa.eu/info/sites/info/files/rec-18-002-decarbonisation_booklet_27112018.pdf
- EC (2018k) Proposal for post-2020 CO₂ targets for cars and vans.
https://ec.europa.eu/clima/policies/transport/vehicles/proposal_en
- EC (2018l) Reducing CO₂ emissions from heavy-duty vehicles.
https://ec.europa.eu/clima/policies/transport/vehicles/heavy_en
- EC (2018m) Reducing CO₂ emissions from vans.
https://ec.europa.eu/clima/policies/transport/vehicles/vans_en
- Ecola L and Wachs M (2012) Exploring the relationship between travel demand and growth. The Rand Corporation.
https://www.fhwa.dot.gov/policy/otps/pubs/vmt_gdp/vmt_gdp.pdf
- EEA (2016a) Electric vehicles in Europe.
https://www.google.co.uk/url?sa=t&andct=j&andq=andesrc=sandsou rce=webandcd=6&andved=2ahUKewi8qd_RiKreAhUOsAKHX5_B8wQfjAFegQIAxAC&andurl=https%3A%2F%2Fwww.eea.europa.eu%2Fpublications%2Felectric-vehicles-in-europe%2Fdownloadandus g=AovVaw1KDWynj8Sz0DQKLMlOkW5u
- EEA (2016b) Occupancy rates.
<https://www.eea.europa.eu/publications/ENVISSUENO12/page029.html>
- EEA (2016c) Explaining road transport emissions.
<https://www.google.co.uk/url?sa=t&andct=j&andq=andesrc=sandsou rce=webandcd=16&andved=2ahUKEwio8cGgvPXeAhXKDMAKHeeZCQsQFjAPegQIEhAC&andurl=https%3A%2F%2Fwww.eea.europa.eu%2Fpublications%2Fexplaining-road-transport-emissions%2Fdownload%2Ffileandusg=AovVaw362peHRHAIrVga3ggpYN9y>
- EEA (2017a) Statistics on passenger transport demand.
<https://www.eea.europa.eu/data-and-maps/indicators/passenger-transport-demand-version-2/assessment-9>
- EEA (2017b) Statistics on freight transport demand.
<https://www.eea.europa.eu/data-and-maps/indicators/freight-transport-demand-version-2/assessment-7>
- EEA (2017c) Overview of electricity production and use in Europe.
<https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-2/assessment-4>
- EEA (2018a) Greenhouse gas emissions from transport.
<https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-11>
- EEA (2018b) Average CO₂ emissions from newly registered motor vehicles.
<https://www.eea.europa.eu/data-and-maps/indicators/average-co2-emissions-from-motor-vehicles/assessment>
- EIB (2017) Annual investment report.
http://www.eib.org/attachments/efs/economic_investment_report_2017_key_findings_en.pdf
- Elgowainy A, et al. (2018) Current and future United States light-duty vehicle pathways: cradle-to-grave lifecycle greenhouse gas emissions and economic assessment.
<https://pubs.acs.org/doi/abs/10.1021/acs.est.7b06006>
- Ellingsen L, et al. (2016) Nanotechnology for environmentally sustainable electromobility. *Nature Nanotechnology* **11**, 1039–1051.
<https://www.nature.com/articles/nnano.2016.237>
- Eltis (2003) The first hydrogen bus of the CUTE project delivered to the public transport authorities.
<http://www.eltis.org/discover/news/first-hydrogen-bus-cute-project-delivered-public-transport-authorities-0>
- Eltis (2017) European Platform.
<http://www.eltis.org/mobility-plans/european-platform>
- Eltis (2018) Sustainable urban logistics planning guidelines.
<http://www.eltis.org/resources/tools/planning-sustainable-urban-logistics>
- EP (2016) Boosting building renovation: what potential and value for Europe?
[http://www.europarl.europa.eu/RegData/etudes/STUD/2016/587326/IPOL_STU\(2016\)587326_EN.pdf](http://www.europarl.europa.eu/RegData/etudes/STUD/2016/587326/IPOL_STU(2016)587326_EN.pdf)
- EP (2018) European Parliament launch of All Policies for a Healthy Europe initiative.
https://gallery.mailchimp.com/b46e253741edc9e116149e0ea/files/062f8550-5e1f-41b9-b4d5-55b60fc7d93b/181114_AP4HE_Agenda_22_November.pdf
- eRoadArlanda (2018) Electrified roads – a sustainable transport solution of the future.
https://eroadarlanda.se/?gclid=EAlaQobChMIgbi00N6I3AIVyasYCh285Q9NEAAYASAAEgJpHfD_BwE
- EU (2008) Consolidated version of the Treaty on the Functioning of the European Union - Part three: Union policies and internal actions. Title XXI: Energy - Article 194. *Official Journal* **115**, 9.5.2008, 134.
<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:12008E194>
- EU (2009) Directive 2009/12/EC on Airport Charges.
<https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:070:0011:0016:EN:PDF>
- EU (2014a) Alternative Fuels Infrastructure Directive.
<http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014L0094&andfrom=EN>
- EU (2014b) Directive 2014/45/EU on Periodic roadworthiness tests for motor vehicles and their trailers.
<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32014L0045>
- EU (2017a) Regulation (EU) 2017/2392 amending Directive 2003/87/EC to continue current limitations of scope for aviation activities and to prepare to implement a global market-based measure from 2021.
<https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32017R2392>
- EU (2017b) Commission delegated regulation (EU) 2017/1502 of June 2017 amending annexes I and II to Regulation (EC) No 443/2009 for the purpose of adapting to the change in the regulatory test procedure for the measurement of CO₂ from light duty vehicles.
<https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017R1502&andfrom=LV>

- EU (2017c). Regulation (EU) 2017/821 laying down supply chain due diligence obligations for Union importers of tin, tantalum and tungsten, their ores, and gold originating from conflict-affected and high-risk areas.
<https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32017R0821>
- EU (2018a) Directive on the promotion of the use of energy from renewable sources (recast).
<https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32018L2001&from=EN>
- EU (2018b) Recast Energy Performance of Buildings Directive.
<https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0844&from=EN>
- European Platform on SUMPS (2016) The economic benefits of urban sustainability measures - independent review of evidence.
http://www.eltis.org/sites/default/files/report_summary_reviews_of_measures.pdf
- Eurostat (2017) Greenhouse gas emission statistics.
http://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_statistics
- Eurostat (2018a) Greenhouse gas emissions by sector.
[https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Greenhouse_gas_emissions,_analysis_by_source_sector,_EU-28,_1990_and_2016_\(Percentage_of_total\).png](https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Greenhouse_gas_emissions,_analysis_by_source_sector,_EU-28,_1990_and_2016_(Percentage_of_total).png)
- Eurostat (2018b) Freight transport statistics – modal split.
https://ec.europa.eu/eurostat/statistics-explained/index.php/Freight_transport_statistics_-_modal_split
- Eurostat (2018c) Renewable energy statistics.
https://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics#7.25_of_renewable_energy_used_in_transport_activities_in_2016
- Fan Z (2012) A distributed demand response algorithm and its application to PHEV charging in smart grids. *IEEE Transactions on Smart Grid* **3** (3), 1280–1290.
<https://ieeexplore.ieee.org/document/6168819>
- FCH JU (2018) Fuel cells and hydrogen – joint undertaking.
<http://www.fch.europa.eu>
- FSO (Federal Statistical Office of Switzerland) (2017) Population's travel behaviour 2015.
https://www.are.admin.ch/dam/are/en/dokumente/verkehr/dokumente/mikrozensus/verkehrsverhalten-der-bevolkerung-2015.pdf.download.pdf/Verkehrsverhalten%20der%20Bev%C3%B6lkerung%202015_en.pdf
- Fox J, Axsen J and Jaccard M (2017) Picking winners: modelling the costs of technology-specific climate policy in the US passenger vehicle sector. *Ecological Economics* **137**, 133–147.
<https://ideas.repec.org/a/eee/ecolec/v137y2017i1p133-147.html>
- Figenbaum E and Kolbenstvedt M (2016) Learning from Norwegian battery and plug-in vehicle users – results from a survey of vehicle users. *TØI Report* 1492/2016.
<https://www.toi.no/getfile.php/1343167/Publikasjoner/TØI%20rapporter/2016/1492-2016/Summary.pdf>
- Fridstrøm L et al. (2018) *Decarbonization of Transport. A Position Paper Prepared by MoZEEES and CenSES*.
<https://www.ntnu.no/documents/7414984/1282007173/Decarbonization+of+transport.pdf/9fe253e9-ac91-4968-bc4a-e1f93376a6f7>
- Gerding E, et al. (2011) Online mechanism design for electric vehicle charging. In *Proceedings of the 10th International Conference on Autonomous Agents and Multiagent Systems (AAMAS 2011)* (editors Yolum, Tumer, Stone and Sonenberg), 2–6 May 2011, Taipei, Taiwan, pp. 811–818.
http://www.ifaamas.org/Proceedings/aamas2011/papers/B6_B70.pdf
- Global Covenant of Mayors (2018) Implementing climate ambition. Global Covenant of Mayors 2018 Global Aggregation Report.
https://www.globalcovenantofmayors.org/wp-content/uploads/2018/09/2018_GCOM_report_web.pdf
- Göransson L, Karlsson S and Johnsson F (2010) Integration of plug-in hybrid electric vehicles in a regional wind-thermal power system. *Energy Policy* **38** (10), 5482–5492.
<https://www.sciencedirect.com/science/article/pii/S0301421510002740>
- Göransson L and Johnsson F (2018) A comparison of variation management strategies for wind power integration in different electricity system contexts. *Wind Energy* **21** (10), 837–854.
<https://onlinelibrary.wiley.com/doi/full/10.1002/we.2198>
- Gough R, Dickerson C, Rowley P and Walsh C (2017) Vehicle-to-grid feasibility: a techno-economic analysis of EV-based energy storage. *Applied Energy* **192**, 12–23.
<https://doi.org/10.1016/j.apenergy.2017.01.102>
- Grigoratos T and Martini G (2014) Non-exhaust traffic related emissions. Brake and tyre wear PM. JRC Science and Policy report. EC Joint Research Centre.
<http://publications.jrc.ec.europa.eu/repository/bitstream/JRC89231/jrc89231-online%20final%20version%202.pdf>
- Haszeldine RS, Flude S, Johnson G and Scott V (2018) Negative emissions technologies and carbon capture and storage to achieve the Paris Agreement commitments. *Philosophical Transactions of the Royal Society A* **376**, 20160447.
<https://royalsocietypublishing.org/doi/full/10.1098/rsta.2016.0447>
- Holladay J, Hu J, King D and Wang Y An overview of hydrogen production technologies. *Catalysis Today* **139** (4), 244–260.
<https://www.sciencedirect.com/science/article/pii/S0920586108004100#aep-section-id42>
- ICLEI (2018) Call to urban policy makers: build a secure future by aligning your climate strategies to the latest science.
<https://iclei.org/en/media/call-to-urban-policymakers-build-a-secure-future-by-aligning-your-climate-strategies-to-the-latest-science>
- IEA (2017) World energy outlook 2017.
https://www.iea.org/publications/freepublications/publication/WEO_2017_Executive_Summary_English_version.pdf
- IEA (2018) International energy agency transport activities.
<https://www.iea.org/topics/transport/>
- IEA/IRENA (2017) Perspectives for the energy transition.
<https://www.irena.org/publications/2017/Mar/Perspectives-for-the-energy-transition-Investment-needs-for-a-low-carbon-energy-system>
- IMO (2009) Second IMO GHG study 2009.
<http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/SecondIMOGHGStudy2009.pdf>
- IPCC (2014a) Climate change 2014: mitigation of climate change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_frontmatter.pdf
- IPCC (2014b) Assessment report ar5. Annex 3. Technology-specific cost and performance parameters.
https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_annex-iii.pdf
- IPCC (2018) Global warming of 1.5 °C, an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways.
<http://www.ipcc.ch/report/sr15/>

- IRENA (2018a) Biogas for road vehicles – technology brief. http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Mar/IRENA_Biogas_for_Road_Vehicles_2017.pdf?la=en&hash=9261CA2381C7847A515E230D03C9487AE4392B88
- IRENA (2018b) Renewable energy prospects for the European Union. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Feb/IRENA_REmap_EU_2018.pdf
- Irlé R (2018) Europe plug-in vehicle sales for Q3 of 2018. <http://www.ev-volumes.com/country/total-eu/fta-plug-in-vehicle-volumes-2/>
- ITF (2015a) Transport outlook 2015. https://read.oecd-ilibrary.org/transport/itf-transport-outlook-2015_9789282107782-en#page1
- ITF (2015b) Urban mobility system upgrade. How shared self-driving cars could change city traffic. https://www.itf-oecd.org/sites/default/files/docs/15cpb_self-drivingcars.pdf
- ITF (2017) Transport outlook 2017. <https://www.itf-oecd.org/sites/default/files/docs/transport-outlook-2017-presentation.pdf>
- ITF (2018) International transport forum – road transport. [https://www.itf-oecd.org/search/policy-insights?f\[0\]=field_publication_type%3A3096andf\[1\]=field_theme_tax%3A1andf\[2\]=field_category_tax%3A10andf\[3\]=field_publication_type%3A637](https://www.itf-oecd.org/search/policy-insights?f[0]=field_publication_type%3A3096andf[1]=field_theme_tax%3A1andf[2]=field_category_tax%3A10andf[3]=field_publication_type%3A637)
- Jenn A, Azevedo IM and Michalek JJ (2016) Alternative fuel vehicle adoption increases fleet gasoline consumption and greenhouse gas emissions under United States corporate average fuel economy policy and greenhouse gas emissions standards. *Environmental Science and Technology*, **50** (5), 2165–2174. <https://pubs.acs.org/doi/10.1021/acs.est.5b02842>
- Jenn A, Azevedo I and Michalek J (2017) a tale of two policies: interactions of US federal and state policies for promoting alternative fuel vehicles increase in greenhouse gas emissions (no. 17-05278). <https://trid.trb.org/view/1439076>
- JRC (2013) Analysis of national travel statistics in Europe. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC83304/tch-d2.1_final.pdf
- Kane M (2018) There are 6,500 hydrogen fuel cell cars worldwide (half in California). <https://insideevs.com/there-is-only-6500-hydrogen-fuel-cell-cars-in-the-world-half-in-california-report/>
- Keith D, Holmes G, St Angelo D and Heidel K (2018) A process for capturing CO₂ from the atmosphere. *Joule* **2** (8), 1573–1594. <https://doi.org/10.1016/j.joule.2018.05.006>
- Kemp R (2016) Scope for reduction in transport CO₂ emissions by modal shift. <https://s3-eu-west-1.amazonaws.com/assets.eti.co.uk/legacyUploads/2016/02/Scope-for-reduction-in-transport-CO2-emissions-by-modal-shift-ETI-Comms.pdf>
- Kramers A, Höjer M, Lövehagen N and Wangel J (2014) Smart sustainable cities – exploring ICT solutions for reduced energy use in cities. *Environmental Modelling and Software* **56**, 52–62. <https://doi.org/10.1016/j.envsoft.2013.12.019>
- Le Fevre CN (2017) Methane emissions from blind spot to spotlight. Oxford Institute For Energy Studies. <https://www.oxfordenergy.org/publications/methane-emissions-blind-spot-spotlight/>
- Nationale Akademie der Wissenschaften Leopoldina, Deutsche Akademie der Technikwissenschaften und Union der deutschen Akademien der Wissenschaften (2017) 'Sektorkopplung' – Optionen für die nächste Phase der Energiewende. https://www.acatech.de/wp-content/uploads/2018/06/ESYS_Stellungnahme_Sektorkopplung.pdf
- Lewis AM, Kelly JC and Keoleian GA (2014) Vehicle light weighting vs. electrification: life cycle energy and GHG emissions results for diverse powertrain vehicles. *Applied Energy* **126**, 13–20. <https://www.sciencedirect.com/science/article/pii/S0306261914002530>
- LIPASTO Transport Emission Database (2009a) Average passenger aircraft emissions and energy consumption per passenger kilometre in Finland 2008. <http://lipasto.vtt.fi/yksikkopaastot/henkiloliikenne/ilmaliikenne/ilmah.htm>
- LIPASTO Transport Emission Database (2009b) Average freight air transport emissions and energy consumption per tonne kilometer. http://lipasto.vtt.fi/yksikkopaastot/tavaraaliikenne/ilmaliikenne/ilma_tavarae.htm
- LIPASTO Transport Emission Database (2017a) Energy use of electric intercity train in Finland in 2016. <http://lipasto.vtt.fi/yksikkopaastot/henkiloliikenne/raideliikenne/intercitysahkoe.htm>
- LIPASTO Transport Emission Database (2017b) Emissions and energy use of diesel driven railcar in Finland in 2016. <http://lipasto.vtt.fi/yksikkopaastot/henkiloliikenne/raideliikenne/dm12diese.htm>
- LIPASTO Transport Emission Database (2018) Average coach+bus in 2016. <http://lipasto.vtt.fi/yksikkopaastot/henkiloliikenne/tieliikenne/injautote/bussilinjaautokeskimaarine.htm>
- Liu Q, Xiong D, Petibon R, Du C and Dahn J (2016) Gas evolution during unwanted lithium plating in Li-ion cells with EC-based or EC-free electrolytes. *Journal of The Electrochemical Society* **163** (14), A3010–A3015. https://www.researchgate.net/publication/309877212_Gas_Evolution_during_Unwanted_Lithium_Plating_in_Li-Ion_Cells_with_EC-Based_or_EC-Free_Electrolytes
- Lutsey N, Searle S, Chambliss S and Bandivadekar A (2015) Assessment of leading electric vehicle promotion activities in United States cities. International Council on Clean Transportation. https://www.theicct.org/sites/default/files/publications/ICCT_EV-promotion-US-cities_20150729.pdf
- Martin E and Shaheen S (2011) Greenhouse gas emission impacts of carsharing in North America. *IEEE Transactions on Intelligent Transportation Systems* **12** (4) 1074–1086. <https://ieeexplore.ieee.org/document/5951778>
- Mason J *et al.* (2015) Global high shift cycling scenario, ITDP. https://www.itdp.org/wp-content/uploads/2015/11/A-Global-High-Shift-Cycling-Scenario_-_Nov-12-2015.pdf
- McKinnon A (2018) *Decarbonising Logistics*. Kogan Page. <https://www.koganpage.com/product/decarbonising-logistics-9780749483807>
- Melton N, Axsen J and Sperling D (2016) Moving beyond alternative fuel hype to decarbonize transportation. *Nature Energy* **1**, 16013. <https://www.nature.com/articles/nenergy201613>
- Miotti M *et al.* (2016) Personal vehicles evaluated against climate change mitigation targets. *Environmental Science & Technology* **50**, 10795–10804. <https://pubs.acs.org/doi/pdf/10.1021/acs.est.6b00177>
- Mwasilu F, Justo J, Kim E, Do T and Jung J (2014) Electric vehicles and smart grid interaction: a review on vehicle to grid and renewable energy sources integration. *Renewable and Sustainable Energy Reviews* **34**, 501–516. <https://doi.org/10.1016/j.rser.2014.03.031>

- Nelldal B and Andersson E (2012) Mode shift as a measure to reduce GHG emissions. *Procedia - Social and Behavioral Sciences* **48**, 3187–3197.
<https://core.ac.uk/download/pdf/81934490.pdf>
- Newman P and Kenworthy J (2015) *The End of Automobile Dependence: How Cities are Moving Beyond Car-Based Planning*. Island Press.
<https://islandpress.org/books/end-automobile-dependence>
- Nordenholz F, Winkler C and Knorr W (2017) Analysing the modal shift to rail potential within the long-distance passenger travel market in Germany. *Transportation Research Procedia* **26**, 2017, 81–91.
<https://www.sciencedirect.com/science/article/pii/S2352146517308694>
- NPE (2018a) National electro-mobility platform, Germany: high power charging.
<http://nationale-plattform-elektromobilitaet.de/en/anwendung/high-power-charging/>
- NPE (2018b) German national platform for electric mobility. Progress Report 2018 – Market ramp-up phase.
http://nationale-plattform-elektromobilitaet.de/fileadmin/user_upload/Redaktion/Publikationen/NPE_Progress_Report_2018.pdf
- NYC Streetsblog (2017) Road pricing in London, Stockholm and Singapore – a way forward for New York City.
http://nyc.streetsblog.org/wp-content/uploads/2018/01/TSTC_A_Way_Forward_CPreport_1.4.18_medium.pdf
- Odyssee-Mure (2018) sectoral profile – transport.
<http://www.odyssee-mure.eu/publications/efficiency-by-sector/transport/passenger-mobility-per-capita.html>
- Onder CH, Ott T and Guzzella L (2011) How much fuel can a hybrid electric vehicle save? In *International Advanced Mobility Forum (IAMF) 2011*.
<https://doi.org/10.3929/ethz-a-006886477>
- Ortega-Vazquez M (2014) Optimal scheduling of electric vehicle charging and vehicle-to-grid services at household level including battery degradation and price uncertainty. *IET Generation, Transmission and Distribution* **8** (6), 1007–1016.
<https://digital-library.theiet.org/content/journals/10.1049/iet-gtd.2013.0624>
- Ott T, Zurbruggen F, Onder C and Guzzella L (2013) Cycle-averaged efficiency of hybrid electric vehicles. *Proceedings of the Institution of Mechanical Engineers D* **227** (1), 78–86.
<https://doi.org/10.1177/0954407012447508>
- Plevin R (2017) Assessing the climate effects of biofuels using integrated assessment models, part I: methodological considerations. *Journal of Industrial Ecology* **21** (6), 1478–1487.
<https://doi.org/10.1111/jiec.12507>
- Ploetner KO, Urban M, Roth A, Tay G, Habersetzer A (2018) Fulfilling long-term emission reduction goals in aviation by alternative fuel options: an evolutionary approach. In *2018 Aviation Technology, Integration, and Operations Conference Atlanta, Georgia*.
https://www.bauhaus-luftfahrt.net/fileadmin/user_upload/2018_AIAA_Aviation_Ploetner_CO2Emissions_O.pdf
- Replogle MA and Fulton LM (2014) A global high shift scenario: impacts and potential for more public transport, walking, and cycling with lower car use. ITDP.
https://www.itdp.org/wp-content/uploads/2014/09/A-Global-High-Shift-Scenario_WEB.pdf
- Rogelj J, et al. (2016) Differences between carbon budget estimates unravelled. *Nature Climate Change* **6**, 245–252.
<https://www.nature.com/articles/nclimate2868>
- SAPEA (2018) Novel carbon capture and utilisation technologies.
<https://www.sapea.info/wp-content/uploads/CCU-report-web-version.pdf>
- Schafer A (2000) Regularities in travel demand – an international perspective. *Journal of Transportation and Statistics* **3** (3), 1–31.
https://www.bts.gov/archive/publications/journal_of_transportation_and_statistics/volume_03_number_03/paper_01/index
- Schiebbahn S, et al. (2015) Power to gas: technological overview, systems analysis and economic assessment for a case study in Germany. *International Journal of Hydrogen Energy* **40**, 4285.
<https://www.sciencedirect.com/science/article/pii/S0360319915001913>
- Scholtes H, Hage S, Hoppenbrouwers J, de Looor H (1998) Transport prevention – a new concept in Netherlands' logistics. Bakkenist Management Consultants, Amsterdam. Annex to OECD report of Workshop on Innovation for Environmentally Sustainable Transport: Mobility Services and Logistics for Passenger and Freight Transport, Berlin, 27–28 September 1999.
[http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV/EPOC/WPNEP/T\(2001\)6&addoCLanguage=En](http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV/EPOC/WPNEP/T(2001)6&addoCLanguage=En)
- Schuller A, Dietz B, Flath C and Weinhardt C (2014) Charging strategies for battery electric vehicles: economic benchmark and V2G potential. *IEEE Transactions on Power Systems* **29** (5), 2014–2022.
<https://ieeexplore.ieee.org/document/6730964>
- SETIS (2017) Strategic energy technologies information system.
<https://setis.ec.europa.eu/low-carbon-technologies/sustainable-transport>
- Small K and Gómez-Ibáñez J (1998) Road pricing for congestion management: the transition from theory to policy. In *Road Pricing, Traffic Congestion and the Environment. Issues of Efficiency and Social Feasibility* (editors K Button and E Verhoef), pp. 213–246. Cheltenham, UK: Edward Elgar.
<https://econpapers.repec.org/paper/cdluctwcp/qt8kk909p1.htm>
- Spath PL and Mann MK (2001) Life cycle assessment of hydrogen production via natural gas steam reforming (no. NREL/TP-570-27637). Golden, CO: National Renewable Energy Laboratory.
<https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/27637.pdf>
- Statistics Netherlands (2016) Transport and mobility 2016.
https://www.google.co.uk/url?sa=t&andct=j&andq=andsrc=sandsou rce=web&andcd=1&andved=2ahUKEwjBm9aO37jeAhVMAsAKHZ7HD9oQFjAAegQIARAC&andurl=https%3A%2F%2Fwww.cbs.nl%2F-%2Fmedia%2F_%2Fpdf%2F2016%2F38%2F2016-transport-and-mobility.pdf&andusg=AOvVaw2s9_yrKde-GRCBX3g-ibo5
- Sykes M and Axsen J (2017) No free ride to zero-emissions: simulating a region's need to implement its own zero-emissions vehicle (ZEV) mandate to achieve 2050 GHG targets. *Energy Policy* **110**, 447–460.
<https://ideas.repec.org/a/eee/enepol/v110y2017icp447-460.html>
- Taljegård M (2017) The impact of an electrification of road transportation on the electricity system in Scandinavia. Thesis, Chalmers University of Technology.
<http://publications.lib.chalmers.se/records/fulltext/253394/253394.pdf>
- Taljegård M, Göransson L, Odenberger M and Johnsson F (2019). Impacts of electric vehicles on the electricity generation portfolio – a Scandinavian-German case study. *Applied Energy* **235**, 1637–1650.
<https://www.sciencedirect.com/science/article/pii/S03606261918316970>
- Tilton JE (2002). *On Borrowed Time? Assessing the Threat of Mineral Depletion*. Washington, DC: RFF Press.
<https://www.routledge.com/On-Borrowed-Time-Assessing-the-Threat-of-Mineral-Depletion-1st-Edition/Tilton/p/book/9781891853586>
- Timmers V and Achten P (2016) Non-exhaust PM emissions from electric vehicles. *Atmospheric Environment* **134**, 10e17
<http://www.soliftec.com/NonExhaust%20PMs.pdf>
- Toll M (2018) Are you killing your lithium batteries? *electrek*, 4 May.
<https://electrek.co/2018/05/04/are-you-killing-your-lithium-batteries/>
- Transport and Environment (2018) Electric buses arrive on time. Marketplace, economic, technology, environmental and policy perspectives for fully electric buses in the EU.

<https://www.transportenvironment.org/sites/te/files/publications/Electric%20buses%20arrive%20on%20time.pdf>

Transport Systems Catapult (2016) Mobility as a service. https://ts.catapult.org.uk/wp-content/uploads/2016/07/Mobility-as-a-Service_Exploring-the-Opportunity-for-MaaS-in-the-UK-Web.pdf

Tsugawa S and Kato S (2010) Energy ITS: another application of vehicular communications. *IEEE Communications Magazine* **48** (11), 120–126. <https://ieeexplore.ieee.org/document/5621978>

US Geological Survey (2018). Mineral commodity summaries 2018. <https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/lithium/mcs-2018-lithi.pdf>

van Basshuysen R (2015) *Erdgas und erneuerbares Methan für den Fahrzeugantrieb*. Springer. <https://www.springer.com/de/book/9783658071585>

Vassallo JM and Fagan M (2005) Nature or nurture: why do railroads carry greater freight share in the United States than in Europe? Harvard University, WP05–15. https://web.archive.org/web/20060902215734/http://www.ksg.harvard.edu/taubmancenter/pdfs/working_papers/fagan_vassallo_05_rail.pdf

Vergis S and Mehta V (2012) Technology innovation and policy: a case study of the California ZEV mandate. https://www.google.co.uk/url?sa=t&drct=jandq=andesrc=sandsource=webandcd=2andved=2ahUKEwiMyKawu5jgAhVwThUIHU-PAyAQFjABegQICBACandurl=https%3A%2F%2Fitspubs.ucdavis.edu%2Fwp-content%2Fthemes%2Fucdavis%2Fpubs%2Fdownload_pdf.php%3Fid%3D1940andusg=AOvVaw3TWi8PCrBQpzH3_OghZrvk

Visser J, Nemoto T and Browne M (2014) Home delivery and the impacts on urban freight transport: a review. *Procedia - Social and Behavioral Sciences* **125**, 15–27. <https://doi.org/10.1016/j.sbspro.2014.01.1452>.

Wadud Z, et al. (2016) Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. *Transportation Research A* **86**, 1–18. <https://www.sciencedirect.com/science/article/pii/S0965856415002694>

Wang Y, Sanchez Rodrigues V and Evans L (2015) The use of ICT in road freight transport for CO₂ reduction – an exploratory study of UK's grocery retail industry. *International Journal of Logistics Management* **26** (1), 2–29. <https://doi.org/10.1108/IJLM-02-2013-0021>

Watts N, et al. (2018) The 2018 report of the *Lancet* Countdown on health and climate change: shaping the health of nations for centuries to come. *Lancet* **392**, 2479–2514. [https://www.thelancet.com/journals/lancet/article/PIIS0140-6736\(18\)32594-7/fulltext](https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(18)32594-7/fulltext)

Wernet G, et al. (2016) The ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment* **21** (9), 1218–1230. <https://lca-net.com/publications/show/ecoinvent-database-version-3-part-overview-methodology/>

Abbreviations

BEV	Battery electric vehicle
CCS	Carbon capture and storage
EASAC	European Academies' Science Advisory Council
EIB	European Investment Bank
ERS	Electric road systems
ETS	EU Emission Trading System
EU	European Union
EU-28	Twenty-eight Member States of the European Union
FCEV	Fuel cell electric vehicle
GDP	Gross domestic product
GHG	Greenhouse gas
HDV	Heavy-duty vehicle
IEA	International Energy Agency
ICE	Internal combustion engine
ICEV	Internal combustion energy vehicle
ICT	Information and communications technologies
IGCC	Integrated gasification combined cycle
ILUC	Indirect land use change
IPCC	Intergovernmental Panel on Climate Change
ITF	International Transport Forum
JRC	European Commission Joint Research Centre
LCA	Life cycle analysis
LDV	Light-duty vehicle
LPG	Liquefied petroleum gas
Mt CO ₂ -eq	Million tonnes of carbon dioxide equivalents
Mtoe	Million tonnes of oil equivalent
NO _x	Nitrogen oxides
PEV	Plug-in electric vehicle
PHEV	Plug-in hybrid electric vehicle
pkm	Passenger-kilometre
SDG	Sustainable development goal
SULPs	Sustainable Urban Logistics Plans
SUMPs	Sustainable Urban Mobility Plans
tkm	Tonne-kilometre
vkm	Vehicle-kilometre
ZEV	Zero-emission vehicle

Annex 1 2014 IPCC assessment report

Emissions of selected electricity supply technologies (IPCC 2014b).

Life cycle CO₂ equivalent from selected electricity supply technologies (g CO₂-eq./kWh)

Technology	Minimum	Median	Maximum
Currently commercially available technologies			
Pulverised coal	740	820	910
Biomass: co-firing with coal	620	740	890
Gas: combined cycle	410	490	650
Biomass: Dedicated	130	230	420
Solar photovoltaics: utility scale	18	48	180
Solar photovoltaics: rooftop	26	41	60
Geothermal	6.0	38	79
Concentrated solar power	8.8	27	63
Hydropower	1.0	24	2,200*
Wind offshore	8.0	12	35
Nuclear	3.7	12	110
Wind onshore	7.0	11	56
Pre-commercial technologies			
CCS: pulverised coal	190	220	250
CCS: coal, IGCC	170	200	230
CCS: gas, combined cycle	94	170	340
CCS: coal, oxyfuel	100	160	200
Ocean (tidal and wave)	5.6	17	28

*Includes methane emissions from reservoirs (notably in tropical sites).
CCS, carbon capture and storage.

Annex 2 Expected evolution of autonomous vehicles

The levels of automation in road vehicles are steadily increasing, from the initial introduction of cruise controls to the more advanced self-parking options and beyond. The five levels of automation, which are commonly used to identify the degree of automation of a given vehicle, are listed below:

Level 0. The driver (human) controls it all: steering, brakes, throttle, etc.

Level 1. Most functions are still controlled by the driver, but a specific function (like steering or accelerating) can be done automatically by the car.

Level 2. At least one driver assistance system (e.g. steering or acceleration) is automated, such as cruise control or lane-centring. The driver must always be ready to take control of the vehicle.

Level 3. Drivers are still necessary, but can completely shift 'safety-critical functions' to the vehicle, under certain traffic or environmental conditions. The driver will nevertheless intervene if necessary.

Level 4. Vehicles are designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. However, the system does not cover every driving scenario.

Level 5. A fully autonomous system which expects the vehicle's performance to equal that of a human driver, in every driving scenario.

The higher levels of autonomy involve interactions between the vehicle systems and those of the transport infrastructure, and highly reliable connections between these will be required for level 5. This implies a growing need for excellent coverage of global positioning system signals and of mobile network signals (e.g. 5G), which does not exist in many parts of Europe today.

Annex 3 Future availability of rare element resources

Many of the new technologies for the generation and utilisation of sustainable energy also require – fortunately in small amounts – rare elements that have hitherto been virtually unused. 'Rare' elements are normally defined as those that have a concentration in the Earth's crust of less than 0.1%. Examples are cobalt and lithium for batteries as well as rare-earth elements, in particular neodymium, for the strong permanent magnets used in electric vehicle powertrains.

The Congo is the largest global supplier of (partly refined) cobalt; Australia, followed by Chile, are the largest producers of lithium (US Geological Survey 2018). The production of cobalt and other metals in the Congo is subject to ethical questions. In the EU, there is appropriate legislation in force concerning so-called conflict minerals (EU 2017c).

In recent years, concern has been expressed about potentially critical supply situations that could develop, or in some cases perhaps have already developed, in connection with such mineral resources. These range from alarmist articles in the popular press, to well-researched reports by various bodies, including learned societies, to papers in the scientific literature, and books (Abraham 2015). The JRC has defined those elements that it deems 'critical' in a list which has been revised twice in recent years (EC 2017k). EASAC has also recently discussed critical materials within the context of the circular economy (EASAC 2016b).

There are several factors potentially contributing to supply risk, including the political situation in producer countries, international conflicts, the existence of monopolies or oligopolies, other high-tech applications of the element concerned, inadequate recycling measures and 'geochemical scarcity'. This last indicator covers the possible decline in ore grades, increasingly more difficult mining conditions and the increasing demand for energy and/or water.

Generally speaking, the actual physical depletion of mineral resources is not (yet) a significant factor (Tilton 2002), although attention often focuses on the so-called static reach, namely the ratio of *identified* global reserves and resources to annual production rate. In view of the enormous quantities of elements, even of rare elements, in the Earth's crust, a significant effect of mineral depletion on supply risk is not expected in the coming decades. However, the serious environmental consequences of more extensive and increasingly complex mining operations should not be ignored. Moreover, large increases in the annual production of rare metals, for example of platinum-group metals for hydrogen production by electrolysis, are difficult to achieve at short notice because disused or hitherto untapped deposits must be exploited.

Annex 4 Working group composition and timetable

The report was prepared by a working group of experts nominated by member academies of EASAC, with valuable inputs from experts who contributed to project meetings and workshops.

Chairperson

Konstantinos Boulouchos, ETH Zurich, Switzerland

Working group members

Peter-Johann Sturm, Graz University of Technology, Austria
Jan Kretzschmar, Royal Flemish Academy of Belgium (KVAB), Belgium
Neven Duic, University of Zagreb, Croatia
Juhani Laurikko, Helsinki University of Technology, Finland
Alex Bradshaw, Max Planck Society, Germany
Thomas Hamacher, Technical University of Munich, Germany
Marc Oliver Bettzüge, University of Cologne, Germany
George Giannopoulos, Academy of Athens, Greece
Han La Poutré, Delft University of technology, The Netherlands
Kornelius Blok, TU Delft, The Netherlands
Øystein Ulleberg, Institute for Energy Technology, Norway
Harry Frank, The Royal Swedish Academy of Sciences, Sweden
Filip Johnsson, Chalmers University of Technology, Sweden
Gil Georges, ETH Zurich, Switzerland
Kirsten Oswald, ETH Zurich, Switzerland
Thomas Justus Schmidt, Paul Scherrer Institute, Switzerland
Peter Bruce, University of Oxford, UK
William Gillett, EASAC energy programme director

The first working group meeting was hosted by the Royal Academies for Science and the Arts of Belgium on 5 July 2017 in Brussels, preceded by a workshop on 4 July 2017 with invited speakers from the European Commission and other leading stakeholders, including Alois Krasenbrink from JRC, Elisabeth Windisch from ITF-OECD, Peter Vis from DG Move, Tudor Constantinescu from DG ENER, Stefaan Vergote from DG CLIMA, François Wakenhut from DG ENV, Jaroslav Straka from DG REGIO, Erik Jonnaert from ACEA and Wolfgang Teubner from ICLEI.

The second working group meeting was held in Zurich on 13 November 2017, hosted by ETH Zurich.

The third working group meeting was held in Zagreb on 10 April 2018, hosted by the Croatian Academy of Arts and Sciences.

The fourth meeting was held in Berlin, hosted by the German National Academy of Sciences, Leopoldina.

Annex 5 Acknowledgements

EASAC thanks Konstantinos Boulouchos and Kirsten Oswald from ETH Zurich for their extensive contributions to the drafting of this report.

EASAC is grateful to the Royal Academies for Science and the Arts of Belgium, ETH Zurich, the Croatian Academy of Arts and Sciences, and the German National Academy of Sciences, Leopoldina, for hosting working meetings, and the Swiss Government for supporting the work at ETH Zurich through the Swiss Academies of Arts and Sciences.

EASAC also thanks its working group members for their contributions, and the members of the EASAC energy and environment steering panels, and Michael Norton (EASAC environment programme director), for their advice and guidance.

Peer reviewers

Graham Hutchings, Cardiff University, UK

Asgeir Tomasgard, NTNU, Norway

Maria do Rosário, Instituto Superior Técnico, Universidade de Lisboa, Portugal

Igor Emri, University of Ljubljana, Slovenia

Bálint Hartmann, MTA Centre for Energy Research, Hungary

Bart Somers, Technical University of Eindhoven, The Netherlands

Christian Bach, EMPA, Switzerland

Oliver Kröcher, Paul Scherrer Institute, Switzerland

Christopher Onder, ETH Zurich, Switzerland

Stefan Hirschberg, Paul Scherrer Institute, Switzerland

Christian Berggren, Linköping University, Sweden

EASAC, the European Academies' Science Advisory Council, consists of representatives of the following European national academies and academic bodies who have issued this report:

The Austrian Academy of Sciences
The Royal Academies for Science and the Arts of Belgium
The Bulgarian Academy of Sciences
The Croatian Academy of Sciences and Arts
The Czech Academy of Sciences
The Royal Danish Academy of Sciences and Letters
The Estonian Academy of Sciences
The Council of Finnish Academies
The Académie des sciences (France)
The German National Academy of Sciences Leopoldina
The Academy of Athens
The Hungarian Academy of Sciences
The Royal Irish Academy
The Accademia Nazionale dei Lincei (Italy)
The Latvian Academy of Sciences
The Lithuanian Academy of Sciences
The Royal Netherlands Academy of Arts and Sciences
The Norwegian Academy of Science and Letters
The Polish Academy of Sciences
The Academy of Sciences of Lisbon
The Romanian Academy
The Slovak Academy of Sciences
The Slovenian Academy of Sciences and Arts
The Spanish Royal Academy of Sciences
The Swiss Academies of Arts and Sciences
The Royal Swedish Academy of Sciences
The Royal Society (United Kingdom)

Academia Europaea
ALLEA

For further information:

EASAC Secretariat
Deutsche Akademie der Naturforscher Leopoldina
German National Academy of Sciences
Postfach 110543
06019 Halle (Saale)
Germany

tel +49 (0)345 4723 9833
fax +49 (0)345 4723 9839
secretariat@easac.eu

EASAC Brussels Office
Royal Academies for Science and the
Arts of Belgium (RASAB)
Hertogsstraat 1 Rue Ducale
1000 Brussels
Belgium

tel +32 (2) 550 23 32
brusseloffice@easac.eu

The affiliated network for Europe of



EASAC contributes to the implementation of the

