European Climate Foundation

Charging Poland
Technical report

cambridge econometrics
clarity from complexity

Final Report

August
2018

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Authorisation and Version History

Version	Date	Authorised for release by	Description
2.0	13/08/18	Jon Stenning	Draft final edition of technical report
1.0	10/02/18	Jon Stenning	First edition of technical report

Acknowledgments

Background

This study on the impacts of low-carbon mobility in Poland builds on a series of previous studies examining the potential impacts of the transition to low-carbon mobility in the UK ('Fuelling Britain's Future', 2015), France ('En route pour un transport durable', 2016), Germany ('Low Carbon Cars in Germany', 2017) and in the wider EU ('Fuelling Europe's Future, 2012). The technology cost analysis published in Fuelling Europe's Future, developed by Ricardo-AEA and the core working group for that project, forms the starting point for this analysis.

Core analytical team

Cambridge Econometrics provided the lead for the analytical work presented in this report, principally relating to the development and application of the passenger car stock model for Poland and for the economic modelling undertaken in E3ME.

The Fundacja Promocji Pojazdów Elekrycznych convened and managed a core working group to advise and review the analysis and reporting. The authors would like to thank all members of the core working group for their respective inputs.

Disclaimer

The stakeholders who contributed to this study shared the aim of establishing a constructive and transparent exchange of views on the technical, economic and environmental issues associated with the development of low-carbon technologies for cars. The objective was to evaluate the boundaries within which vehicle technologies can contribute to mitigating carbon emissions from cars and buses in Poland. Each stakeholder contributed their knowledge and vision of these issues. The information and conclusions in this report represent these contributions, but should not be treated as binding on the companies and organisations involved.

Contents

Acronyms and Abbreviations

Table 1.1 sets out the acronyms and abbreviations commonly used in the report.

Table 1.1 Acronyms and abbreviations

	Abbreviation	Definition
Powertrain types		
Internal combustion engine	ICE	These are conventional petrol or diesel cars with an internal combustion engine. In the various scenarios modelled there is variation in the level of efficiency improvements to the ICE. Efficiency improvements cover engine options, transmission options, driving resistance reduction, tyres and hybridisation. Under our definition of an ICE, hybridisation is limited to micro-hybrids with start-stop technology and regenerative breaking.
Hybrid electric vehicles	HEV	This definition covers full hybrid electric vehicles that can be run in pure EV mode for some time. They have a larger battery than the micro-hybrids (that are classified as ICEs).
Plug-in hybrid electric vehicle	PHEV	Plug-in hybrid electric vehicles have a large battery and an internal combustion engine. They can be plugged in to recharge the vehicle battery. EVs with range extenders are not included in the study.
Battery electric vehicle	BEV	This category refers to fully electric vehicles, with a battery but no engine.
Fuel cell electric vehicle	FCEV	FCEVs are hydrogen fuelled vehicles, which include a fuel cell and a battery-powered electric motor.
Zero emissions vehicle	ZEV	Includes all vehicles with zero tailpipe emissions (e.g. FCEVs and BEVs).
Economic terminology		
Gross domestic product	GDP	A monetary measure of the market value of all final goods and services in the national economy
Gross Value added	GVA	A measure of the total value of goods and services in the economy netted from value of inputs and taxes.
Other acronyms		
Original equipment manufacturers	OEMs	Refers to equipment manufacturers of motor vehicles
Million barrels of oil equivalent	mboe	A unit for measuring oil volumes

Executive Summary

Poland is often regarded as something of a laggard by European standards in terms of environmental legislation. However, the mobility strategy published in 2017 set the ambitious goal of 1 million electric vehicles in the country by 2025. At the same time, Poland has experienced investment in battery production facilities, such as the extensive lithium-ion manufacturing plant being built by LG CHEM in Wroclaw, potentially position Poland's economy as a major winner from the shift to electric powertrains, and domestic firms such as Solaris are establishing themselves as amongst the leading developers of low-carbon vehicles in Europe.

Cambridge Econometrics were commissioned by the European Climate Foundation (ECF) to assess the likely economic impacts associated with, and the potential challenges to delivering, decarbonising the Polish car and bus fleet in the medium (to 2030) and long (to 2050) term.

This technical report sets out the findings from our analysis of the impacts of decarbonising transport in Poland. It provides details about the EV charging infrastructure requirements, technology costs and economic impacts of the transition to low-carbon mobility. A summary report, presenting the key messages from the study, is also available[1].

The study results show that, whilst there are potentially substantial economic and environmental benefits associated with decarbonising transport in Poland, there are also challenges to delivering this transition which must be addressed if the benefits are to be realised. In recent years, there has been a strong push to decarbonise transport in Europe and this change is coming irrespective of how transport policy in Poland evolves. Furthermore, there is the potential for substantial negative impacts if Polish decarbonisation policy lags substantially behind other EU Member States such as Germany, from whom Poland imports a large number of second-hand vehicles.

The potential benefits if Poland embraces the transition are substantial:

- The reduced dependence on imported oil and petroleum products will not only deliver benefits in terms of reduced energy dependence, but also large reductions in carbon emissions, particularly as Poland's electricity mix moves away from coal and towards low-carbon technologies
- Net economic and employment gains which increase as oil imports are reduced over the time frame assessed. By 2030, the TECH RAPID scenario would lead to an increase in GDP of 0.2% and an increase in net employment of around 50,000 jobs.
- For the consumer, we expect that the 4-year total cost of ownership of Zero-Emission Vehicles could converge towards that for conventional petrol and diesel cars by the year 2030.

However, there are a number of potential hurdles to delivering the transition:

[1] See: https://www.camecon.com/how/our-work/low-carbon-cars-in-germany/

- The Polish stock has a slow turnover and an aged fleet by European standards; as such any transition in sales will take a long time to substantially penetrate through the stock.
- Imported German second-hand cars form a large proportion of new registrations in Poland; in addition to slowing the transition, there is the potential for German policy (such as city centre diesel bans) to have negative spillover effects in Poland if it reduces the sell-on value of diesels and causes an increase in their penetration into the Polish market, pushing out sales of electric vehicles.
- The implementation of a rapid charging infrastructure in Poland will require annual investments reaching hundreds of millions of euros by 2050. A determined and joint effort of the industry, government and civil society is needed in order to deploy sufficient charging infrastructure. Timing, location, capability and interoperability are key issues.
- The transition to low-carbon mobility causes a wide range of impacts in employment across several sectors. Employment in the automotive sector will remain stable until 2030 in our central scenario, where climate goals are met through a balanced mix of hybrids, plug-in vehicles and increasingly efficient ICEs, although under a more ambitious scenario such a tipping point would be reached by 2025. After this point, the transition to electric mobility will increase employment in sectors such as construction and infrastructure, as well as services, but is likely to have an adverse impact on employment in the automotive value chain.

1 Introduction

1.1 Background

Low-carbon transport policy

In November 2013, the European Parliament and the Council of the European Union set out legislation to limit the emissions of new vehicles. The EU CO_2 standards required fleet-wide average vehicle emissions to be below 95g CO_2 per km by 2021. In 2017, the Commission announced[2] proposed new standards for 2025 and 2030; a 15% reduction in average new vehicle emissions between 2021 and 2025, and a 30% reduction in new vehicle emissions in 2030 compared to 2021. These aim to continue to move Europe along a low carbon pathway and to meet EU-wide targets for a 60% reduction in transport CO_2 emissions by 2050.

Announcements in 2017 by the French and UK governments to ban new sales of conventional petrol and diesel cars by 2040 has also sent a clear signal that change is coming. As well as supporting the curtailment of CO_2 emissions, the impetus for this change is, in part, due to increasing concern about the level of local air pollutants (such as NOx) emitted by vehicles and the negative health outcomes associated with this pollution, especially in densely populated urban areas.

Transport policy in Poland is moving towards a low carbon pathway. The Polish government's draft e-mobility legislation is targeting 1 million EVs on the road by 2025, and an increase in the deployment of supporting infrastructure. This trajectory is slower than that being targeted in Germany (where the government is aiming for 1 million EVs in 2020 and 6 million by 2030), and notably Polish policy does not currently include an explicit target for reducing emissions (either CO_2 or local air pollutants).

Motivation for the study

The transition towards lower emission vehicles is gaining momentum, driven by European and national policy (as well as firm commitments from other countries, such as China). It is becoming increasingly apparent that this transition is going to take place, with or without the actions of national policymakers. However, the Polish market has specificities which mark it as distinct from the more mature western European markets; new vehicle registrations in Poland are dominated by imported 2nd hand vehicles (primarily from Germany), rather than new vehicles, and the average age of vehicles in Poland is substantially higher than the European average. At the same time, the environmental benefits of the decarbonisation of passenger cars (at least in terms of CO_2) are less clear-cut, due to the extensive role that coal plays in electricity generation.

The purpose of this study is to shed light on the potential benefits and the transitional challenges of decarbonising passenger cars and buses within Poland. In doing so, it highlights some of the key issues that policy makers should focus on.

The study seeks to address questions about the nature of Polish demand for passenger cars and how the transition will affect supply chains, labour

[2] https://ec.europa.eu/clima/policies/transport/vehicles/proposal_en

requirements and the wider economic impacts brought about by this change: What will be the impact on traditional motor vehicle sector value chains and jobs? What is the potential for Poland to alter its competitive position within the European market? How will government tax revenues be affected due to reduced fuel duty? How might a transition in the electricity generation system interact with the shift in transport?

The study also addresses some of the key uncertainties about the transition: What if future oil prices are higher (or lower) than projected? What if technology costs and battery costs are different to expected? How does a different electricity generation mix impact upon the CO2 emissions from the stock?

1.2 Methodology

For this study, a set of scenarios were defined where it was assumed that a certain low-carbon vehicle technology mix would be achieved by vehicle CO_2 emissions regulations. The factors affecting consumers decisions to purchase alternative vehicle technologies was not assessed.

The methodology involved three key stages:

1) Stakeholder consultation to define the scenarios and agree on the key modelling assumptions
2) An integrated modelling framework that involved (i) application of the Cambridge Econometrics' vehicle stock model to assess the impact of alternative low-carbon vehicle sales mix on energy demand and emissions of passenger cars and buses, vehicle prices, technology costs and the total cost vehicle of ownership and (ii) application of the E3ME model to assess the wider socio-economic effects of the low-carbon vehicle transition, including an assessment of the tailpipe emissions of the vehicle stock under different electricity generation scenarios.

The two models that were applied in our framework are the Cambridge Econometrics' Vehicle Stock Model and E3ME.

Cambridge Econometrics' Vehicle Stock Model

Cambridge Econometrics' vehicle stock model calculates vehicle fuel demand, vehicle emissions and vehicle prices for a given mix of vehicle technologies. The model uses information about the efficiency of new vehicles and vehicle survival rates to assess how changes in vehicles sales affect stock characteristics. The model also includes a detailed technology sub-model to calculate how the efficiency and price of new vehicles are affected, with increasing take-up of fuel efficient technologies. The vehicle stock model is highly disaggregated, modelling 16 different technology types across three different size-bands (small, medium and large)[3] of passenger car, and two categories of bus (urban buses and long-distance coaches).

E3ME

Some of the outputs from the vehicle stock model (including fuel demand and vehicle prices) are then used as inputs to E3ME, an integrated macro-econometric model, which has full representation of the linkages between the energy system, environment and economy at a global level. The high regional and sectoral disaggregation (including explicit coverage of every EU Member

[3] See Section 3, Table 3.1 for more details.

State) allows modelling of scenarios specific to Poland and detailed analysis of sectors and trade relationships in key supply chains (for the automotive and petroleum refining industries). E3ME was used to assess how the transition to low carbon vehicles affected household incomes, trade in oil and petroleum, consumption, GDP, employment, CO_2, NOx and particulates.

For more information and the full model manual, refer to www.e3me.com. A summary description of the model is also available in Appendix A.

1.3 Structure of the report

The report is structured as follows:

- **Section 2** sets out the scenarios that were developed to inform the analysis and are required to answer the questions raised by the Core Working Group
- The main modelling assumptions and technology cost data are set out in **Section 3**
- New infrastructure requirements are a key consideration for the deployment of zero emission vehicles, these are considered in **Section 4**
- Above all, a transition requires consumers to adopt low and zero emission cars. In **Section 5** we look at the capital and fuel costs facing the consumer for new cars in the future
- The core analysis, focuses on the macroeconomic impact of the difference scenarios. The net impacts and transitional challenges are set out in **Section 6**.
- The main driver of low emission cars, is to reduce the harmful impact that road transport has on the local and global environment. The contribution of passenger cars to CO_2 emissions and local air quality pollutants is set out in **Section 7**.
- The potential role of low emission buses and coaches is explored in **Section 8**.
- The report finishes with our conclusions in **Section 9**. These are the views of the report's authors and do not necessarily represent the views of the European Climate Foundation or the members of the Core Working Group, either individually or collectively.

2 Overview of scenarios

2.1 Scenario design

The analysis set out in this report is based on a set of scenarios developed by the Core Working Group, which each assume a different vehicle sales mix. To assess the economic impacts of the transition to low-carbon vehicles over 2015-2050, four scenarios were compared:

- A reference scenario **(REF)** which assumes no improvements to new vehicle efficiency after 2015. This is used as a clean baseline for comparison, to assess the impact of new 'current policy' vehicle emissions legislation. Despite no change to the vehicles sales mix over the projection period, total energy use in the vehicle stock falls in the short-term in this scenario, as the new vehicles replace older (less efficient) vehicles in the stock.
- A 'current policy initiative' scenario **(CPI)** which is based on the agreed European Commission legislation to regulate the new passenger car efficiency of cars to 95 g/km by 2021, with emissions savings predominantly driven by ICE efficiency improvements. Note that in the absence of announced standards for buses, there is no CPI scenario (as 'announced policy' requires no change from current vehicle efficiency levels).
- A low-carbon technology scenario **(TECH)**, which assumes a rapid take-up of advanced powertrains (PHEVs, BEVs and FCEVs) in the medium term. This is combined with ambitious deployment of fuel-efficient technologies (such as light-weighting and low rolling resistance tyres) in all new vehicles over the period to 2050.
- A low carbon technology scenario with a more ambitious deployment for advanced powertrains (**TECH RAPID**) where there are no new sales of ICEs from 2030 onwards, replaced predominately by BEVs.

For the most part, this technical report focusses on the impact of the **TECH RAPID** scenario, to explore the impact of an ambitious deployment of technology, although other variants are explored:

- **TECH IMPORT** is used to understand the impact of more advanced decarbonisation policies in Western Europe (particularly Germany). If policy such as Germany city-centre bans on diesel vehicles were enacted, it would reduce the 2^{nd}-hand value of such vehicles, and could potentially lead to them flooding into the Polish market in greater numbers. Such an outcome would slow the transition of the stock to advanced powertrains.
- In addition, the impact of different electricity generation scenarios, provided by Forum Energii, are used to explore the CO2 emissions from the vehicle stock in the **TECH** scenario under a coal-focussed, diversified and renewables-focussed generation mix.

2.2 Vehicle sales and stock

New vehicle sales

The composition of new vehicle sales in each scenario is shown in Figure 2.1.

In the TECH scenario in 2030, new vehicle sales are still predominately mild and micro hybrid ICEs (53%), but there is a large share of full hybrids (11%), plug-in hybrids (20%) and BEVs (10%). Post-2030, the market for BEVs takes off as sales grow to 49% by 2040 and 69% by 2050. Fuel cell vehicles are assumed to only capture a small share by 2050 as they are slowly introduced to target the 'longer range' market. PHEVs are taken up as a 'bridging' technology and are deployed initially but sales of PHEVs are gradually phased out by 2050.

Figure 2.1: Powertrain deployments in new sales for TECH scenario

Second-hand imports

However, new vehicle registrations only make up around 40% of new sales with the remaining 60% made up from second-hand imports. In our scenarios, we derived take up of advanced powertrains based on new vehicle deployment scenarios from our previous analysis of low carbon cars in Germany[4] which is the largest exporter of vehicles to Poland.

[4] https://www.camecon.com/how/our-work/low-carbon-cars-in-germany/

These German new vehicle deployments were then converted into deployments of second-hand vehicles using time lags reflecting the average age composition of second-hand imports in Poland.
In Figure 2.2, we show the second-hand sales deployments used. In almost all the scenarios we used an equivalent scenario from the German modelling. The exception was the TECH IMPORT scenario for which we assumed that cheap ICEs are dumped onto the polish market and so all imports remain ICE for the entire period.

Figure 2.2: Powertrain deployments in second hand imports for TECH scenario

In Figure 2.3, we see the impact of the new sales deployments on the vehicle stock. Despite the ambitious deployment of new advanced powertrains in the TECH scenario, ICEs continue to make up a large share of the stock in 2030 and BEVs only just achieve a majority in the vehicle stock by 2050. The stock of EVs (PHEV, BEV and FCEV) does not reach the Polish target of 1 million vehicles by 2025 but does meet the target of 6 million EVs by 2030. By 2040, the stock of EVs grows to 19 million and by 2050 reaches around 32 million.

In the TECH RAPID scenario, the majority of cars in the stock (86%) are advanced powertrains by 2040.

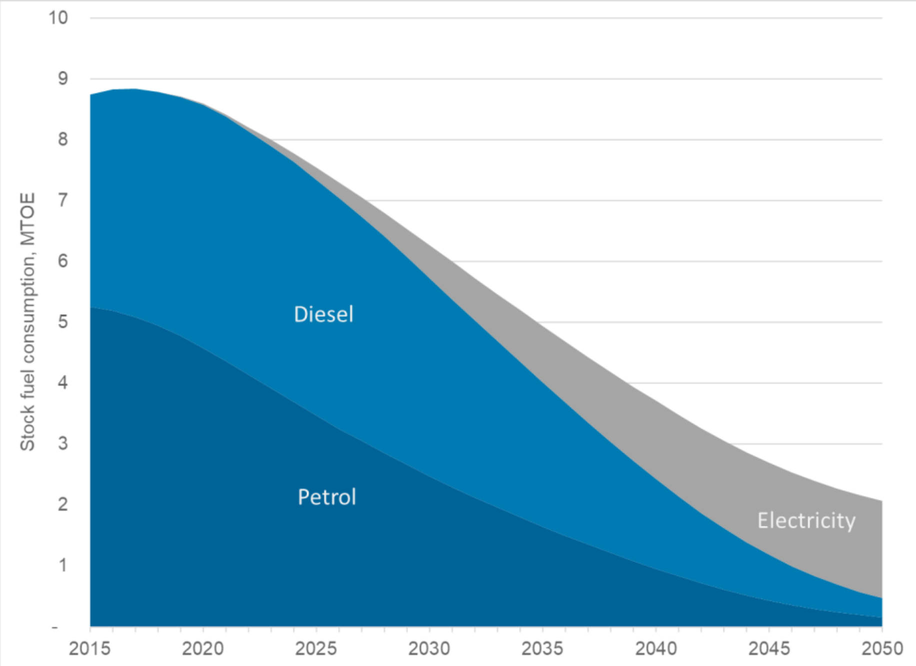
Figure 2.3: Composition of vehicle stock in TECH scenario

2.3 Fuel demand

Figure 2.4 shows the combined effects on efficiency improvements and deployment of advanced powertrains on fuel consumption by the Polish vehicle stock in the TECH RAPID scenario. By 2030, we see a substantial reduction in demand for fuel, with a 35% reduction in petrol and diesel demand relative to 2015 (equivalent to 26m barrels of oil saved by 2030). By 2050, the passenger car stocks oil and petroleum demand will have fallen by 95% compared to 2015 levels.

Electricity and hydrogen demand grow in line with rollout of the stock of PHEVs, BEVs and FCEVs and, by 2050, due to the relative efficiency of advanced powertrains, demand for these fuels makes up 78% of total fuel consumption, despite PHEVs and BEVs making up 94% of the vehicle stock. The additional electricity demand is around 19TWh by 2050 which is, equivalent to 8% of total Polish electricity demand in that year.

Figure 2.4: Stock Fuel consumption in TECH RAPID scenario



3 Modelling assumptions

This section sets out the key modelling assumptions underpinning the analysis.

The scenarios are defined by (i) the sales mix by vehicle powertrain type and (ii) the take-up of fuel efficient technologies. Key assumptions common to all scenarios and are briefly outlined in Section 3.1. The subsequent sections provide information about our technology costs, battery costs and power sector assumptions.

3.1 Key modelling assumptions

	Details of assumptions used
Vehicle sales	• Historical data taken from the SAMAR • Total new sales kept constant at 617,000 per year
Efficiency of new vehicles	• This is an outcome of the vehicle stock model, based on assumptions about the vehicle powertrain and the energy efficient technologies that are installed in the vehicle. For more information see Section 3.2.
Mileage by age cohort	• Based on TRACCS data averaged over 2005-2010, we assume that over the lifetime, average car travels around 8,000 km per year. We assume that average annual mileage falls gradually over the lifetime of the vehicle and we assume that the mileage for diesel cars is around 50% higher than that for petrol cars and EVs.
Vehicle survival rates	• Survival rate assumptions are based TRACCS data on stock and deregistrations averaged over 2005-2010. The survival rates have then been adjusted to calibrated to SAMAR estimate of the active Polish vehicle fleet.
Fuel prices	• Historical data for fuel prices is taken from the European Commission's Oil Bulletin[5] • For the central scenarios, we assume oil prices grow in line with the IEA's 2016 World Energy Outlook Current Policies Scenario (and a constant percentage mark-up is applied to derive the petrol and diesel fuel price)
Electricity prices	• Generation mixes are based upon ongoing analysis from Forum Energii • The electricity price for EV users is assumed to be the same as that paid by households at 25-30 cents/KWh over the period to 2050 (in 2014 prices) • The impact of additional demand on electricity prices will be explored later in the project
Rest of world	• In each scenario, we assume that low-carbon transport policy in the rest of Europe is consistent with that in Poland • Rest of world assumptions on low carbon transport policy affect the global oil price and are tested through sensitivity analysis
Value chains	• In all scenarios, we assume that Poland captures a consistent share of the vehicle value chain for conventional ICEs. For the central scenarios, we assume that, for EVs, battery modules

[5] http://ec.europa.eu/energy/en/data-analysis/weekly-oil-bulletin

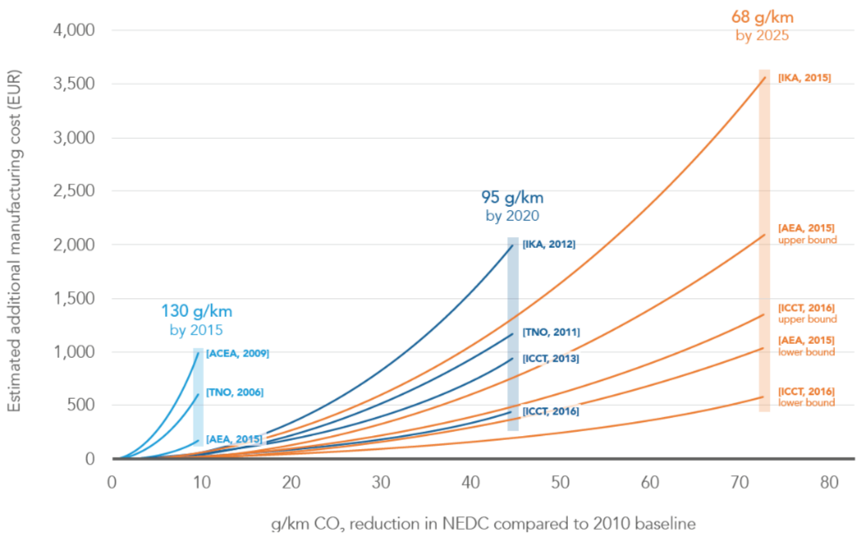
	and battery packs are assembled in Poland but that the battery cells are manufactured in Asia.
Trade in motor vehicles	• We assume the same volume of vehicle imports and exports between the EU15 and EU13 in each scenario (with the exception of TECH IMPORT). The price of vehicle imports changes in line with the change in domestic vehicle prices, reflecting that transport policy is assumed to be consistent across the EU, with the exception of the TECH IMPORT scenario.

3.2 Cost of fuel-efficient technologies

To achieve the vehicle emissions targets, as well as a transition to advanced low-carbon powertrains, the low-carbon scenarios also assume efficiency improvements through use of low-carbon technologies and lighter materials.

There is considerable uncertainty about the future cost of vehicle technologies. Recent studies reflect a wide range of costs of carbon abatement technologies for vehicles, ranging from IKA (2015) figures[6], at the top end of the range, to the ICCT (2016) analysis[7] at the low end of the range. For this study, values from a cost analysis for the European Commission by Ricardo-AEA (2015)[8] were used, which falls roughly in the middle of this range of cost estimates, above that of the ICCT and below that of IKA. The range of costs of fuel-efficient technologies are shown in Figure 3.1.

Figure 3.1 Alternative technology cost assumptions



Source: Mock, P., '2020–2030 CO_2 standards for new cars and light-commercial vehicles in the European Union', 2016

Definitions

[6] IKA (2015), Institut für Kraftfahrzeuge, "CO2-Emissionsreduktion bei Pkw und leichten Nutzfahrzeugen nach 2020," http://www.bmwi.de/DE/Mediathek/publikationen,did=686692.html

[7] ICCT (2016), '2020–2030 CO_2 standards for new cars and light-commercial vehicles in the European Union' http://www.theicct.org/sites/default/files/publications/ICCT_EU-CO2-stds_2020-30_brief_nov2016.pdf

[8] Ricardo-AEA (2015), Ricardo-AEA, "Improving understanding of technology and costs for CO2 reductions from cars, and LCVs in the period to 2030 and development of cost curves," 28 July 2015 draft version, distributed at a stakeholder workshop of the European Commission DG CLIMA

Building on the definitions of the TNO 2011 study "Support for the revision of Regulation (EC) No 443/2009 on CO_2 emissions from cars", we use the following set of definitions for downsizing options, compared to a comparable 2010 car (without downsizing).

Definitions:

- mild downsizing (15% cylinder content reduction)
- medium downsizing (30% cylinder content reduction)
- strong downsizing (45% cylinder content reduction)

Other engine options include:

- Direct injection (homogenous)
- Direct injection (stratified charge)
- Thermodynamic cycle improvements (e.g. homogenous charge compression injection HCCI)
- Cam phasing
- Variable valve actuation and lift

While other transmission options include:

- optimising gearbox ratios
- automated manual transmission
- dual clutch transmission
- continuously variable transmission

The scale of hybridisation included in the modelling is as follows:

- start-stop hybridisation
- start-stop hybridisation with regenerative breaking
- full and mild hybrid (modelled as a powertrain switch)

Technology costs and energy savings

Our cost assumptions are based on Ricardo-AEA (2015), with high and low variants based on IKA (2015) and ICCT (2016) respectively.

The costs in Table 3.1 are sourced from the latest R-AEA (2016) datasets developed for the European Commission. Table 3.1 summarises the main technologies included, and the associated energy savings and cost increase compared to a 2015 new car without those same features.

Table 3.1: Engine and transmission options – 2015 cost curve data

Downsizing options	Energy saving	Cost (€)		
		Small car	Medium car	Large car
Mild (15% cylinder content reduction)	4-6%	88	110	115
Medium (30% cylinder content reduction)	10-13%	120	180	180
Strong (45% cylinder content reduction)	15-19%	165	195	195

Combustion improvements (petrol)	5%	224	224	314
Combustion improvements (diesel)	2%	204	204	285
Cylinder deactivation	5%	155	155	155
Other engine options (petrol only)	Energy saving	Cost (€)		
		Small car	Medium car	Large car
Direct injection (homogenous)	4.5-5.5%	130	130	184
Direct injection (stratified)	10-14%	250	350	435
Thermodynamic cycle improvements	11-13%	280	300	400
Cam phasing	5%	50	50	80
Variable valve actuation and lift (petrol and diesel)	9%	144	150	235
Transmission options	Energy saving	Cost (€)		
		Small car	Medium car	Large car
Optimising gearbox ratios / downspeeding	4%	40	40	40
Automated manual transmission	2-5%	220	220	230
Dual clutch transmission	3-6%	233	250	257
Partial hybridisation	Energy saving	Cost (€)		
		Small car	Medium car	Large car
Start-stop	2.5-5%	66	80	96
Start-stop with regenerative breaking	6-10%	219	235	300

Note: Costs are at mass production levels.

There remains much more that can be done to improve the efficiency of the internal combustion engine and transmission system, and many of the technologies that are already available on the marketplace can make a significant impact on fuel consumption in the 2020-2025 timeframe. Start-stop technology using advanced lead-based batteries is perhaps the most cost-effective way of achieving reductions of 5-10 per cent in CO_2 emissions (depending on whether the system is able to recapture braking energy). Ricardo-AEA has estimated that the cost per gram of CO_2 reduction is about half that of improving the fuel efficiency of the internal combustion engine, and less than a quarter of that for hybridisation.

Other options that are likely to be applied first include engine downsizing coupled with boost (e.g. combination of turbo- and super-charging) and direct injection for petrol engines. For example, there has already been a 31 per cent reduction in g/km of CO_2 between 2010 petrol Ford Focus variants (at 159 g/km) and 2012 EcoBoost branded variants (at 109 g/km), achieved mainly through the use of downsized engines (from 1.6 litres to 1.0 litres) with turbo-charging, direct injection and start-stop technologies. Systems combined also with increasing levels of hybridisation offer even greater potential benefits – e.g. 52 per cent reduction in CO2 going from the 2010 petrol Toyota Yaris (at 164 g/km) to the 2012 Toyota Yaris hybrid (at 79 g/km). Most recently Mazda announced the possibility of increasing fuel efficiency in petrol cars by up to 30%, through the elimination of spark plugs in its SkyactiveX engines.

Efficiency improvements in the CPI and TECH scenario

Table 3.2 highlights the efficiency improvements in the ICE that come about from engine improvements, transmission improvements and partial hybridisation in the CPI and TECH scenarios respectively. In the post 2030 period relatively little is done to improve the efficiency of the ICE, as sales in advanced powertrains dominate the market and few additional improvements are deemed cost effective.

In 2030, nearly all new ICE vehicles have the following features (as applicable[9]):

- start-stop (all) plus regenerative breaking (75%)
- between 30% and 45%-cylinder content reduction
- variable valve actuation and lift
- gear box optimisation
- direct injection or HCCI

In the period to 2050 the additional improvements to ICE efficiency that can be attributed to the engine and transmission (rather than light-weighting and improved rolling resistance) are the mainstreaming of dual clutch transmissions, regenerative breaking and 45% cylinder content reduction across the board.

The data suggests less technological potential to improve the efficiency of a diesel engine than petrol engines.

Table 3.2: New car efficiency CPI Scenario and TECH Scenario (% reduction in MJ/km to 2010)

		CPI				TECH		
Size	Fuel	2010	2015	2020		2020	2030	2050
Small	Petrol	-	11%	22%		24%	41%	45%
Medium	Petrol	-	12%	23%		25%	43%	47%
Large	Petrol	-	12%	24%		26%	45%	48%
Small	Diesel	-	4%	12%		13%	24%	27%
Medium	Diesel	-	4%	12%		13%	24%	27%
Large	Diesel	-	4%	12%		13%	24%	27%

The impact of full hybridisation in the TECH scenario

In 2015, full hybridisation adds around €2,000 to the cost of a car compared to a like-for-like ICE and delivers 22%-25% reductions in energy consumption per kilometre driven. The cost of a full hybrid falls to around €1,000 by 2030 and €750 by 2050. These costs are in line with the ICCT's latest data, but are lower than the 2015 cost data from Ricardo-AEA which puts the cost of full hybridisation for a medium car at €2,500. The ICCT's lower cost estimates for hybrids assume that 'P2' hybrids are introduced by OEMs. These systems have one electric motor and two clutches, and hence are cheaper than the Toyota power-split system which uses two electric motors and a planetary gear system. As noted by ICCT, the current hybrid market is dominated by Toyota,

[9] Some technologies are not applicable to diesel cars

but the majority of other OEMs now offering full hybrids (Kia/Hyundai, VW Group, BMW, Nissan etc.) offer P2 solutions. Hence the costs assumptions in this study reflect the lower cost solution favoured by a greater number of OEMs, while recognising that the two systems (and variations within each) could continue to exist in the market place.

In the short term, the TECH scenario includes a rapid adoption of the lower cost 48-volt mild hybrid, which delivers around two-thirds of the efficiency improvement of a full hybrid for around one-third of the current cost.

In the long term in the TECH scenario, the relative efficiency gap between ICE's and standard hybrids (non-plugin) closes because of ICE engine improvements that can only be considered as additional technologies applied to non-hybrid engines[10]. However, this is partially offset by improvement in the performance of hybrid engines which are expected to improve in line with the development of electric motor systems. The net effect is that the efficiency gap closes by 3 percentage points, so that new hybrids offer a 19-22% efficiency improvement relative to a new ICE from 2030.

[10] As an example, hybrids include start-stop technology and so while it is possible to add start-stop to an ICE, it is not possible to add it to a hybrid as defined by this framework because it is already included

3.3 Battery costs

Definitions

Table 3.3 shows the battery size assumptions for hybrid, plug-in hybrid and battery electric vehicles between 2020 and 2050. There is currently considerable uncertainty on future battery pack sizes, as these will depend both on future reductions in battery costs and OEM design choices to balance vehicle driving ranges against cost based on customer preferences. The battery electric vehicle market in particular is beginning the transition from first generation vehicles such as the Nissan Leaf and VW Golf with driving ranges of 150-200km to second generation models such as the Chevrolet Bolt and Tesla Model 3 and new entrants from German OEMs in the premium sector such as the Audi E-tron/Q8 and Porsche Mission E concepts. OEM statements suggest that medium size next generation BEVs will target driving ranges of 200 miles (320km) or more, while large vehicles will have longer ranges of 500km or more, similar to the Tesla Model S. In smaller segments, Renault indicated that it expects to double the range of the B-segment Zoe by 2018, with an implied battery pack size of around 45kWh.

Given the costs of increasing BEV driving ranges through additional battery capacity, it is expected that OEMs will offer multiple battery configurations to allow customers to make a trade-off between vehicle price and range. This is already seen in the new Nissan Leaf, where two battery size configurations are available, and in the BMW i3, where a new battery with a c.50% increase in driving range will be offered alongside the existing model range. To account for this, we assume 'short range' and 'long range' (standard) versions of BEVs in the modelling in the short term before battery costs fall to the point where the shorter-range option is no longer a likely mass-market option.

Beyond 2020, we have used different assumptions for PHEVs and BEVs on changes in battery capacity. For PHEVs, we assume that OEMs maintain an electric driving range of c.50km, and decrease pack sizes over time as efficiency improvements lead to reductions in energy use per km. For BEVs, we assume that pack sizes are held constant, and vehicle driving ranges increase over time as improvements in battery energy density reduce pack weight (currently over 400kg for the 60kWh pack in the Chevrolet Bolt) and vehicle-level efficiency improvements reduce energy consumption per kilometre.

The battery sizes are intended to be representative, since in practice there are a wide range of options and specifications available to manufacturers, leading to a wide range of costs, performance and range.

Table 3.3: Assumed battery sizes

		Battery sizes (kWh)			
Powertrain	Market segment	2020	2030	2040	2050
HEV	Small	0.86	0.69	0.53	0.43
HEV	Medium	1.05	0.84	0.65	0.52
HEV	Large	1.43	1.15	0.89	0.71
PHEV	Small	7.00	6.30	5.60	4.90
PHEV	Medium	10.00	9.00	8.00	7.00
PHEV	Large	15.00	13.50	12.00	10.50
BEV – Short range	Small	21.00			
BEV – Short range	Medium	28.00			
BEV – Long range	Small	45.00	45.00	45.00	45.00
BEV – Long range	Medium	60.00	60.00	60.00	60.00
BEV – Long range	Large	90.00	90.00	90.00	90.00

Costs and energy savings

The primary influence on plug-in vehicle cost and performance is battery technology, since other components such as electric motors are already well developed and have more limited potential for future improvements. Battery cost projections are based on a recent Element Energy study for the European Climate Foundation and BEUC (the European Consumer Association). That study employed Element Energy's component-level model of battery costs, which takes into account cell costs and performance developments over time, as well as packing costs such as thermal management, wiring harnesses, containers and the Battery Management System (BMS).

There are four key areas of battery technology where breakthroughs are needed:

- Reducing the cost
- Increasing the specific energy (to improve vehicle range/performance for a given battery weight or reduce weight for a given battery kWh capacity)
- Improving usable operational lifetime
- Reducing recharging time, for example allowing rapid charging at 150kW+ with no impact on battery state of health

In the short- to medium-term, lithium ion battery technology is expected to form the principal basis of batteries for use in full HEVs and more advanced plug-in vehicles (i.e. PHEVs, BEVs). Discussions with OEMs and cell suppliers have confirmed there is significant scope for innovation within lithium ion chemistries, such as increasing use of silicon in the anode, use of solid state electrolytes and improved packaging efficiency. In the medium-term, lithium-sulphur holds perhaps the most promise (up to five times the energy density of lithium ion) with lithium-air having greater potential (up to ten times lithium ion energy density), but these technologies are believed to be relevant only in 2030 and beyond.

Results from Element Energy's latest battery cost model suggest strong reductions in battery costs between now and 2030, reaching a cost of €138 per kWh for a large (>60kWh) pack. This is based on materials and manufacturing costs plus a margin and does not account for short term strategic pricing such as incurring losses in early deployments to build market share. These strategic pricing decisions could take place either at the OEMs or their suppliers, for example with cell manufacturers offering low prices to build market share and maximise throughput in new plants, or OEMs cross-subsidising zero emission models with profits from conventional vehicles,

Our baseline estimates are conservative and are higher than some more optimistic cost projections recently published. These include estimates from GM that the cost of the Chevrolet Bolt battery is $145 per kWh at the cell level (equivalent to €175 per kWh at a pack level assuming that packing costs add 33% to the cell cost)[11]. GM also published a roadmap for cell costs suggesting that a cell cost of $100 per kWh is expected by 2022. The most optimistic recent estimates suggest that battery packs from the Tesla Gigafactory could reach $125 per kWh by 2020 at a pack level ($88 per kWh cell cost plus $38 per kWh for packing costs)[12]. Tesla itself expects a 33% reduction in cost from the approximately $250 per kWh pack costs in the current Model S.

To test the impact of these more optimistic estimates, we used a sensitivity based on these recent cost estimates and targets. In this sensitivity, we assume that battery costs reach $150/kWh at a pack level by 2020, falling to $100/kWh by 2030. This is equivalent to achieving the 2030 baseline battery costs 10 years early, in 2020. Under this low-cost scenario, only long range BEVs are assumed to be sold since vehicles would be cost effective even with relatively large battery packs. The two cost scenarios are shown in Table 3.4 and Table 3.5.

The costs above refer to relatively high capacity batteries used in Battery Electric Vehicles. For PHEV, batteries cost more than BEV batteries, per kWh. This is because the power requirements place a proportionally larger demand on the smaller battery pack in a PHEV, so batteries with higher power are needed at a somewhat higher cost.

The costs presented in Table 3.4 and Table 3.5 refer to both the battery and the battery system (or pack), but not the electric drive powertrain (see Table 3.5. The costs are therefore lower per kWh for a large battery than a small battery. In addition, PHEV and HEV batteries cost more than BEV batteries on a per kWh basis. This is due to the use of different chemistries to allow high current draws from a comparatively small battery, and the fact that fixed battery costs (e.g. thermal management, BMS) are spread over fewer kilowatt-hours of capacity.

[11] http://cleantechnica.com/2015/10/05/chevy-bolt-battery-cells-145kwh-new-chevy-volt-with-autonomous-driving/
[12]http://www.streetinsider.com/Analyst+Comments/Jeffereis+Sees+1%2C000bps+of+GM+Tailwind+for+Tesla+%28TSLA%29%3B+PT+Up+to+%24365/10899606.html

Table 3.4: Battery system costs – baseline costs

		Battery system costs (€/kWh)			
Powertrain	Market segment	2020	2030	2040	2050
HEV	Small	490	326	256	222
HEV	Medium	490	326	256	222
HEV	Large	490	326	256	222
PHEV	Small	411	278	227	185
PHEV	Medium	411	278	227	185
PHEV	Large	301	215	176	144
BEV – Short	Small	264			
BEV – Short	Medium	235			
BEV – Long	Small	202	132	97	72
BEV – Long	Medium	202	132	97	72
BEV – Long	Large	202	132	97	72

Table 3.5: Battery costs - low cost scenario based on OEM announcements

		Battery system costs (€/kWh)			
Powertrain	Market segment	2020	2030	2040	2050
HEV	Small	490	326	256	222
HEV	Medium	490	326	256	222
HEV	Large	490	326	256	222
PHEV	Small	411	278	227	185
PHEV	Medium	411	278	227	185
PHEV	Large	301	215	176	144
BEV – Long	Small	132	88	72	72
BEV – Long	Medium	132	88	72	72
BEV – Long	Large	132	88	72	72

Table 3.6: Electric powertrain costs

		Electric powertrain costs (€)			
Powertrain	Market segment	2020	2030	2040	2050
HEV	Small	728	655	589	532
HEV	Medium	890	800	720	650
HEV	Large	1,214	1,091	982	886
PHEV	Small	844	761	687	622
PHEV	Medium	1,031	930	840	760
PHEV	Large	1,406	1,268	1,145	1,036
BEV – Short range	Small	844			
BEV – Short range	Medium	1,031			
BEV	Small	844	761	687	622
BEV	Medium	1,031	930	840	760
BEV	Large	1,406	1,268	1,145	1,036

The powertrain costs range by approximately a factor of two between the powertrain required for a small HEV and a large BEV. Overall, the total battery system and powertrain costs are show below for the total electric system and powertrain for each of the different market segments based on the derived battery size.

Table 3.7: Total cost of electric powertrain and battery

		Total cost of electric powertrain and battery €			
Powertrain	Market segment	2020	2030	2040	2050
HEV	Small	1,149	880	725	627
HEV	Medium	1,405	1,074	886	765
HEV	Large	1,915	1,466	1,210	1,044
PHEV	Small	3,721	2,512	1,958	1,529
PHEV	Medium	5,141	3,432	2,656	2,055
PHEV	Large	5,921	4,171	3,257	2,548
BEV – Short range	Small	6,388			
BEV – Short range	Medium	7,611			
BEV – Long	Small	10,384	7,151	5,907	4,897
BEV – Long	Medium	13,151	8,850	7,260	6,040
BEV – Long	Large	19,586	13,148	10,775	7,920

Note: The cost difference between BEV and PHEV will be smaller than the battery cost difference, since a BEV system entirely displaces an ICE, whereas a PHEV only allows for a smaller ICE engine to support it. An ICE has a cost of around €2,000 in the medium category. BEV costs are consistent with the stated ranges, but we should discuss the trade-off between ranges and costs.

Table 3.8: Total cost of electric powertrain and battery (OEM announcement cost assumptions)

		Total cost of electric powertrain and battery €			
Powertrain	Market segment	2020	2030	2040	2050
BEV – Long	Small	6,784	4,721	3,927	3,862
BEV – Long	Medium	8,951	6,210	5,160	5,080
BEV – Long	Large	13,286	9,188	7,625	7,516

Note: The cost difference between BEV and PHEV will be smaller than the battery cost difference, since a BEV system entirely displaces an ICE, whereas a PHEV only allows for a smaller ICE engine to support it. An ICE has a cost of around €2,000 in the medium category. BEV costs are consistent with the stated ranges, but we should discuss the trade-off between ranges and costs.

Battery range

In line with Fuelling Europe's Future and Element Energy (2012) and recent vehicle cost modelling for ECF and BEUC (2016), we apply State of Charge (SOC) assumptions (Table 3.9) to derive the useable energy of the battery. The expected range (Table 3.10) is then derived based on the test cycle efficiency of the vehicle (in all electric mode).

Table 3.9: Battery usable State of Charge (SOC)

		Battery usable SOC for electric range (%)			
Powertrain	Market segment	2020	2030	2040	2050
PHEV	Small	70%	72%	74%	75%
PHEV	Medium	70%	72%	74%	75%
PHEV	Large	70%	72%	74%	75%
BEV – Short range	Small	85%			
BEV – Short range	Medium	85%			
BEV – Long range	Small	85%	90%	90%	90%
BEV – Long range	Medium	85%	90%	90%	90%
BEV – Long range	Large	85%	90%	90%	90%

Table 3.10: Vehicle range in all electric mode

		All electric range (km – NEDC)			
Powertrain	Market segment	2020	2030	2040	2050
PHEV	Small	42	44	46	46
PHEV	Medium	49	51	53	54
PHEV	Large	61	64	67	67
BEV – Short range	Small	176			
BEV – Short range	Medium	223			
BEV – Long range	Small	377	378	397	414
BEV – Long range	Medium	477	473	501	534
BEV – Long range	Large	556	554	589	624

The values in Table 3.10 for 2020 reflect announced ranges of next generation models. For example, a Chevrolet Bolt or Tesla Model 3 with a range of 200 miles on the US EPA test cycle would have a range of 460-480km on the NEDC, since the NEDC gives an approximately 40-45% increase in range for a given vehicle[13]. Ranges continue to increase after 2020 due to improvements in

13 For example, the NEDC range for the Nissan Leaf 30kWh is 155 miles, compared with 107 on the EPA test.

energy use per km (from light-weighting, improved ancillaries, aerodynamics etc.). PHEV ranges increase modestly beyond 2020 for the same reason, but it is assumed that the majority of reduced energy consumption is used to reduce the pack size and cost, since a range of 40-60km is considered sufficient for a large proportion of daily driving.

In 2020, we assume that EV sales are split evenly between the short range and long-range option. By 2030, the long range (large battery options) are much more cost effective than the short-range options and so at this point, we make the assumption that BEV sales are dominated entirely by the long-range option.

3.4 Power sector assumptions

The structure of the power sector and the renewable content of electricity generation has three important implications for the results of the study:

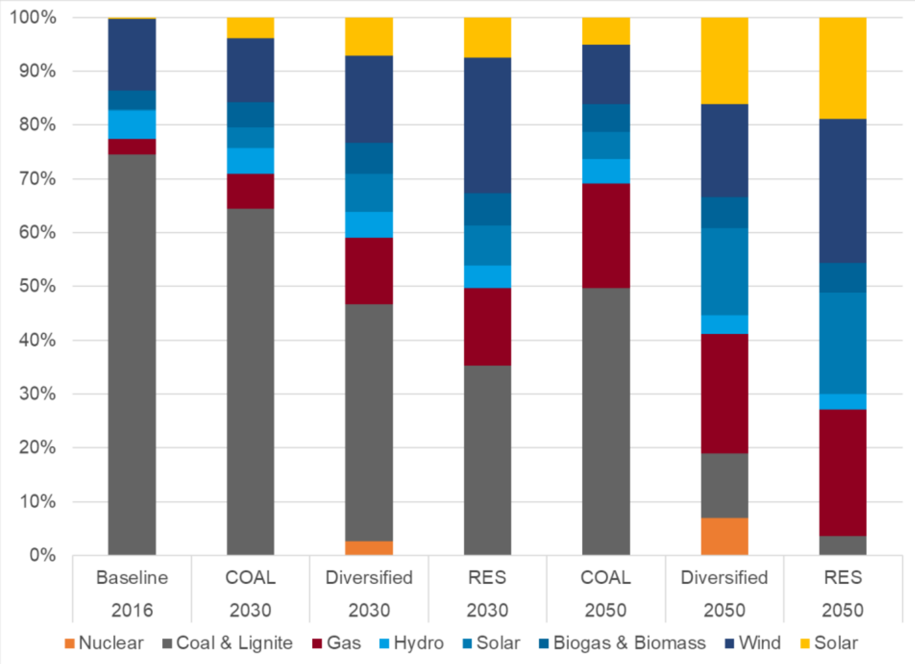
- it determines the net environmental impact of electrification of the vehicle fleet
- it determines the price of electricity that EV owners will be charged, which has implications for the Total Cost of Ownership (TCO) for an EV relative to a conventional ICE
- it could affect net electricity system costs negatively (distribution costs and additional power requirements) or positively (through synergies between EV and the power grid)

Our power sector projections were provided by Forum Energii[14]. We used the “Diversified scenario with nuclear power” for the modelling of TCOs and all economic modelling. However, we also calculated the implied emissions associated with use of an EV in two alternate scenarios; “Coal”, which maintains a dominant position for coal in the future energy mix, and “Renewable”, which foresees a gradual withdrawal of carbon-based generation and replacement with RES.

Figure 3.2 below shows the capacity mixes in the three difference scenarios.

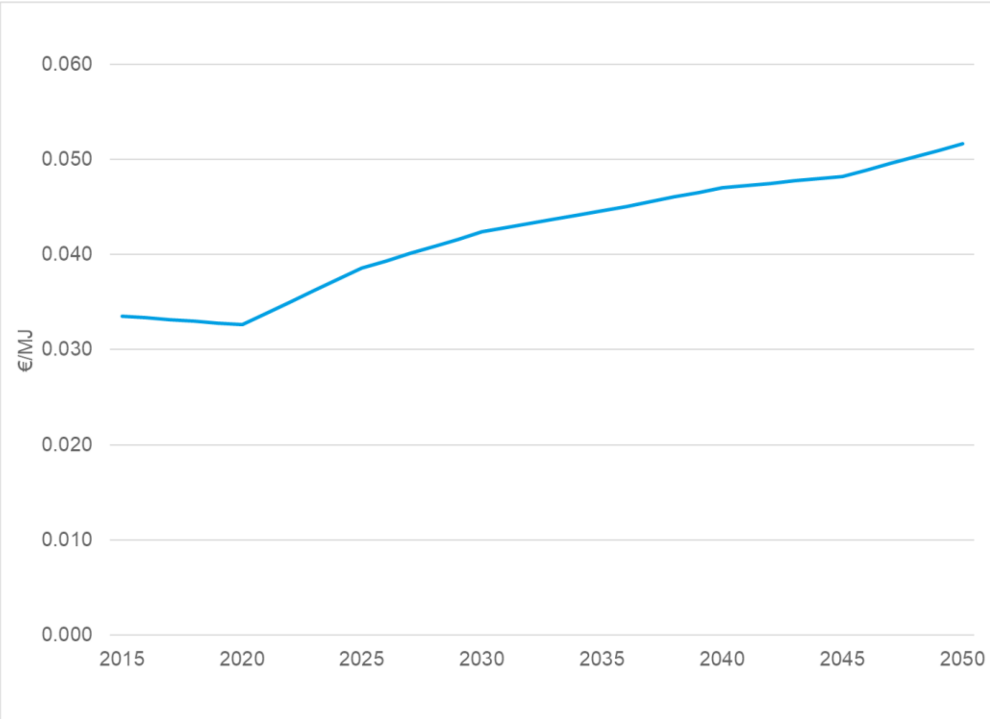
[14] From the publication *Polish energy sector 2050. 4 scenarios*, October 2017

Figure 3.2 Capacity mix in the different power scenarios



Due to the difficulty in charging different electricity prices to EV users and other final consumers, the price of electricity paid by vehicle users is assumed to be the same to the rate paid by households. In Poland, this is expected to increase, as cheap domestic coal is replaced by other sources of energy.

Figure 3.3 Electricity price paid for vehicle charging in Poland



4 Infrastructure requirements

This section describes the definition, costs and deployment of electric charging posts. It also provides a breakdown of our calculation for total charging infrastructure requirements.

4.1 Definition and cost

Building on the definitions implemented in Fuelling Europe's Future, and following comments from ABB and ERDF for the ECF-funded study 'En Route pour un Transport Durable' published in 2015, the definitions and costs for charging points used in this study are shown in Table 4.1. The table is intended to represent the range of charging archetypes available to end users to illustrate the characteristics and costs of charging posts. For example, each 'archetype' represents a typical option but in reality there will be a range of options in each market with variations in price and features. For the residential sector, the standard option is a wall box with a Type 2 connector and a charging capacity of 3.7kW (16 amp single phase) or 7.4kW (32 amp). This solution is often offered through OEM dealerships either with an OEM-branded charging point or through a partnership with an independent provider. For example, BMW offers the Wallbox Pure (3.7kW) and Wallbox Pro (7.4kW) solutions for the i3.

For residential sites with no access to a private driveway or garage, solutions are similar to a private domestic charge point with the addition of options for metering electricity and controlling access to authorised users. In the workplace we consider that two plug ground-mounted charging posts will prevail in the short term, but these could be replaced in the market by 11kW accelerated recharging posts in the medium term.

For public stations in public places such as on-street parking spaces, dedicated car parks and retail car parks, a rate of 11kW is assumed. This reflects the transition to 11KW on-board chargers observed among car OEMs. A 22kW rate is not relevant because the few EV model compatible with this rate are transitioning to a different solution (e.g. Renault Zoe going to a Combined Charging System).

For stations on motorways, a multi-standard AC/DC rapid recharging unit is proposed allowing for an 80% recharge in 20-30 minutes for a BEV with a c.25kWh pack . Future rapid charging power is likely to increase, given the agreement on a 150kW Combined Charging System (CCS) standard in late 2015. Higher powers are necessary to maintain acceptable charging times for vehicles with large batteries (above 50kWh), expected in 2nd generation BEVs. The CharIN initiative (launched in 2016 by BMW, Audi, VW, Porsche, Daimler, Ford, Mennekes, GM, Phoenix contact, TUV) is aiming at developing and establishing the CCS as the standard for charging battery-powered electric vehicles of all kinds. It envisages using CCS for rates up to 350 kW.

Table 4.1: Charging post definition and costs

Main application	Charging point features	Power (kW)	Charge time - 25kWh battery (approx.)	Cost (€)	
				Production	Installation
Residential - individual	Wall box (+ inductive pad in future) One plug User protection during charging Options for metering	3 kW /7kW	4-8 hours	400	1000
Residential - collective	Wall box One plug Choice of access control systems	3 kW /7kW	4-8 hours	800	2000
Workplace	Ground mounted Two plugs Choice of access control systems	7 kW	4 hours	800	1000
Parking (on-street and shopping centres)	Ground mounted Two plugs High resilience Different access options	11 kW	2.5 hour	2,500	5,000
Stations on motorways	Rapid charging Three plugs High resilience	50 kW DC Likely to shift to 150kW by 2020 (and higher kW after)	30 minutes (for 80% charge)	25,000	15,000

4.2 Deployment

For deployment, we assume that each EV sold has, on average, either a residential wall box or a workplace charging post in place. In addition, we assume that there will be two public charging posts in urban areas for every ten EVs on the road. These assumptions are in line with the approach developed and reviewed by industry players for previous studies in France and Germany 2015.

For rapid charging, Our previous analysis of EU driving statistics suggests that 80-90% of total EV energy use could be supplied by home or destination charging. Assuming that 15% of annual kilometres are supplied by rapid charging suggests an annual demand of 300kWh per vehicle per year (based on 15,000km per year and 0.2kWh/km in real world driving). A 50kW rapid charger could supply 1200kWh per day if 100% utilised, or c. 600 kWh if 50% utilised (allowing for lower traffic levels over night and less than full utilisation during the day). This implies that a single rapid charger could support the en-route charging needs of c.500 vehicles, and hence a large vehicle parc of 10 million battery electric vehicles would require 20,000 unique charge points (or approximately c.10-15 charging bays for each of the 1,200 sites on the motorway and major road network).

Changing the power of rapid chargers to 150kW may not have a large impact on the number of vehicles that can be supported by each charging point in the short term, because existing BEVs will not support the higher power and new vehicles are likely to have significantly larger batteries (e.g. 60kWh plus) that offsets any potential reduction in charging time. For this reason, the analysis does not differentiate 50kW and 150kW posts. However, even higher powers of 350kW are likely to significantly decrease charging times as battery pack sizes are unlikely to continue to grow rapidly beyond 60kWh (or 80kW-100kW in larger vehicles). This means that 350kW chargers could potentially support larger numbers of vehicles, and hence fewer of them are required for a given EV parc, but the reduced number of sites is likely to be offset by the increased cost of the chargers and related grid connection costs. Finally, a shift towards larger batteries and longer driving ranges between charges will make BEVs viable for longer range duty cycles, but could reduce proportion of annual energy use supplied by rapid chargers if the ranges were sufficient to allow long trips to be completed with charging before and after the journey. This trend is likely to be stronger if the prices of delivered energy from rapid chargers are higher than domestic or destination charging. The combination of very high-power charging in future and relatively high range BEVs mean that the estimated infrastructure numbers below are likely to over-estimate rather than under-estimate the numbers needed to support a given fleet of BEVs.

We have assumed the number of rapid charge points is in proportion to the number of BEVs in the parc, with a ratio of 500 BEVs per charging point. This number is subject to significant uncertainty. There is also debate about whether rapid chargers will be used exclusively for long journeys, or whether they will provide a substantial fraction of a vehicle's annual energy demand during local trips, and even allowing people without access to dedicated home charging spaces to own an EV.

Table 4.2: EV charging post deployment

		2020	2030	2040	2050
Charging posts per EV (PHEV +BEV)	Residential	0.7	0.6	0.6	0.6
	Workplace	0.2	0.2	0.2	0.2
	Parking	0.2	0.2	0.2	0.2
BEVs per rapid charging post		Fixed number of charging points required for geographic coverage	500	500	500

4.3 Calculating total charging infrastructure requirements

The total number of residential, workplace and public slow charging posts required each year is calculated by multiplying the total number of EVs (PHEVs +BEVs) in the stock by the density assumptions outlined in Table 4.2. For rapid charging infrastructure, we assume deployment grows in line with the BEV fleet. The number of charging points (plugs) is then calculated based on our assumptions about the number of plugs on each post (see Table 4.1).

From the total infrastructure requirements, we calculate the net additional charging posts installed each year and add to this replacement of charging posts that are retiring from the stock.

The additional charging requirements in each year are then multiplied by the cost per post in that year. To project changes in charging infrastructure costs out to 2050, we apply a 10% learning rate (ie a 10% cost reduction for each doubling of cumulative charging capacity.

Appendix C shows the key steps in our calculations to derive the total number of charging posts (and plugs) in each scenario, and the total investment requirements.

5 Consumers' Perspective

5.1 Vehicle costs

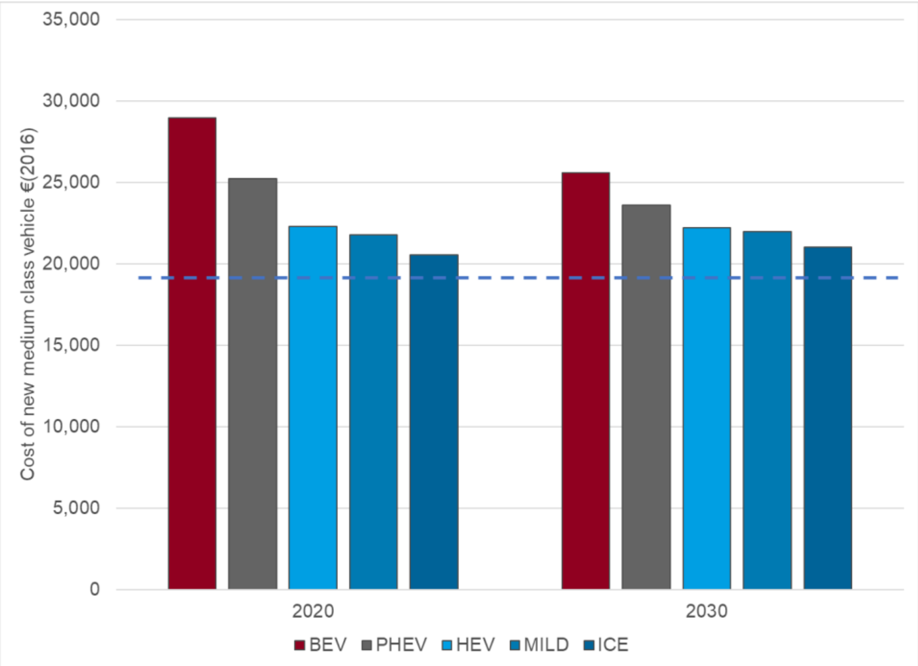
The capital cost of each vehicle in the model is derived by combining projections of the powertrain and glider cost (by market segment) with estimates of the cost of fuel-efficient technologies installed in the car (including low-rolling resistance tyres, aerodynamic improvements, weight reductions).

Margins, distribution costs and VAT are added to the vehicle production costs in order to derive the retail price. In 2030 it is assumed that, in monetary terms, the additional retail and distribution costs for ICEs, EVs, PHEVs and FCEVs are broadly equivalent.

VAT is added at 23% and is charged on consumer sales of all vehicle types over the period to 2050. As VAT is applied as a percentage of the final sale price, the VAT component for (relatively expensive) BEVs, PHEVs and FCEVs is higher than that for conventional petrol and diesel cars.

We assume that car owners would pay for the capital cost of a car over its lifetime (13 years, on average) in monthly instalments with a 3.5% interest rate (other rates of interest are assessed). The retail price of new vehicles in the TECH scenario is shown in the Figure 5.1 Capital and financing cost of a new medium sized vehicle in the TECH scenarios.

Figure 5.1 Capital and financing cost of a new medium sized vehicle in the TECH scenarios



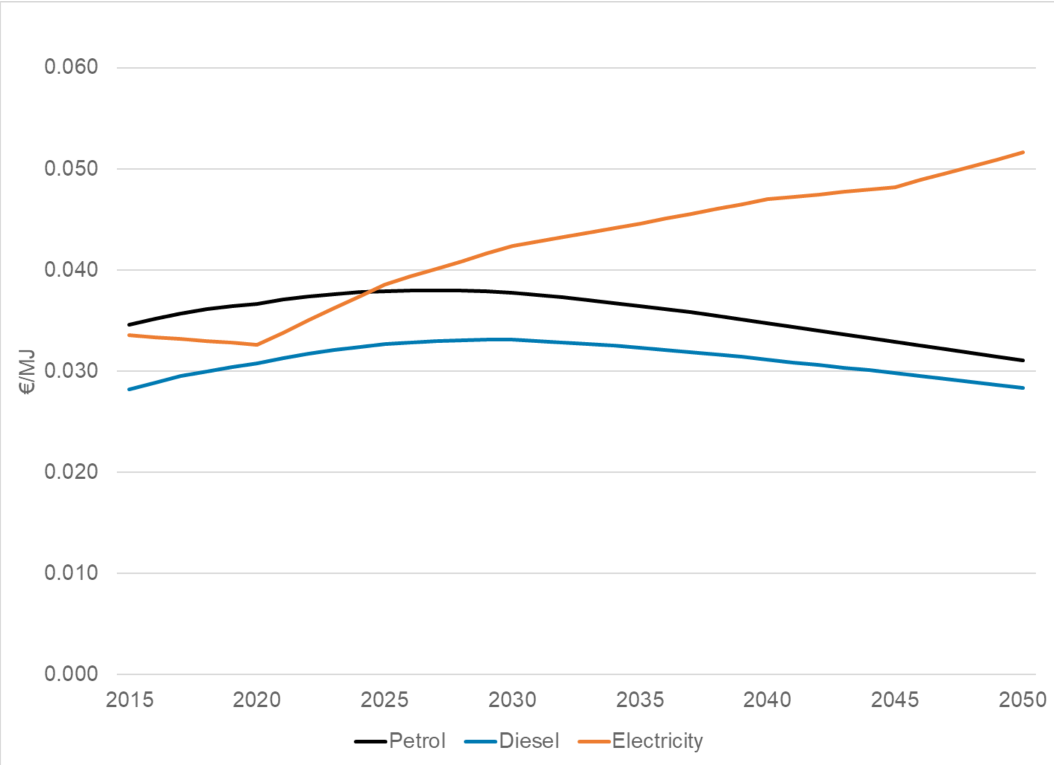
The cost of technologies to reduce CO_2 from cars will reduce over time as scale economies are achieved, but the aggregate costs will increase as more technologies are added to reach tighter CO_2 limits. In 2020, battery-electric vehicles are projected to be significantly more expensive than diesel and gasoline vehicles and their hybrid variants. But by 2030, the difference in price will be narrowed, as the cost of diesel and petrol cars increase to meet environmental goals and as zero-emissions cars get cheaper as they start being manufactured at scale.

5.2 Fuel costs

One feature of the TECH scenario is a substantial improvement to the efficiency of conventional ICEs, leading to fuel bill savings for owners of petrol and diesel cars. In addition, the transition towards an increase in the share of PHEVs, BEVs and FCEVs has implications for fuel bills in the TECH scenario due to the differences in the costs of these alternative fuels, as well as the improvements in the efficiency of energy conversion in an electric powertrain relative to a conventional ICE.

The oil price projections used for this analysis are taken from IEA's November 2016 World Energy Outlook and the cost of petrol and diesel production is assumed to grow in line with these oil prices over the period to 2050.

Figure 5.2 Fuel price assumptions (2014 prices)

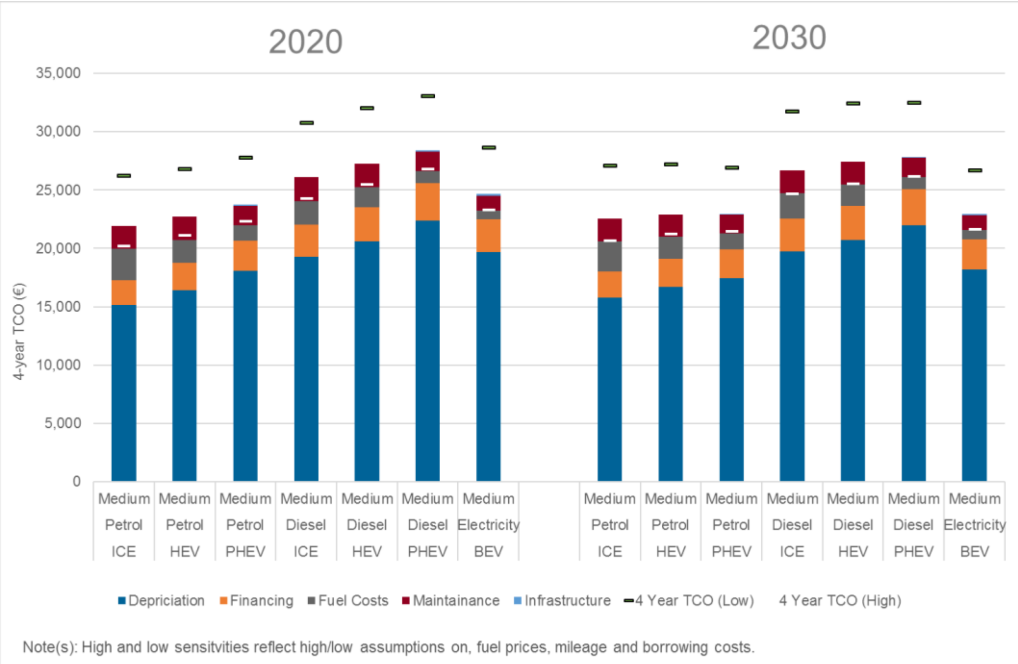


As PHEVs, EVs and FCEVs, become more prevalent in the vehicle mix, assumptions about the price of electricity becomes more important. The electricity price is taken from Forum Energii's "Diversified scenario with nuclear power" scenario. Electricity prices are expected to increase in the future, as cheap domestic coal is replaced by nuclear and renewables at a high cost to consumers, while fossil fuel prices fall in real terms, with fuel duty kept constant in nominal terms (and therefore falling in real terms).

5.3 Total cost of ownership (TCO)

To evaluate the impact of the low carbon transition on consumers, it is also important to look at the total cost of owning a vehicle. In Poland, given the scale of imports of second-hand vehicles, it is important to assess this both purchasers of new vehicles, but also of older imported vehicles. To understand this requires considering not just the purchase price, but also the costs of fuelling the vehicle, the financing costs, the charger cost if it is an electric vehicle, and the amount for which it can be resold at the end of the ownership period. Figure 5.3 shows this perspective for a new vehicle over a 4-year ownership period, in the TECH RAPID case.

Figure 5.3: 4-year TCOs for new vehicles across different powertrains in Poland under the TECH RAPID scenario

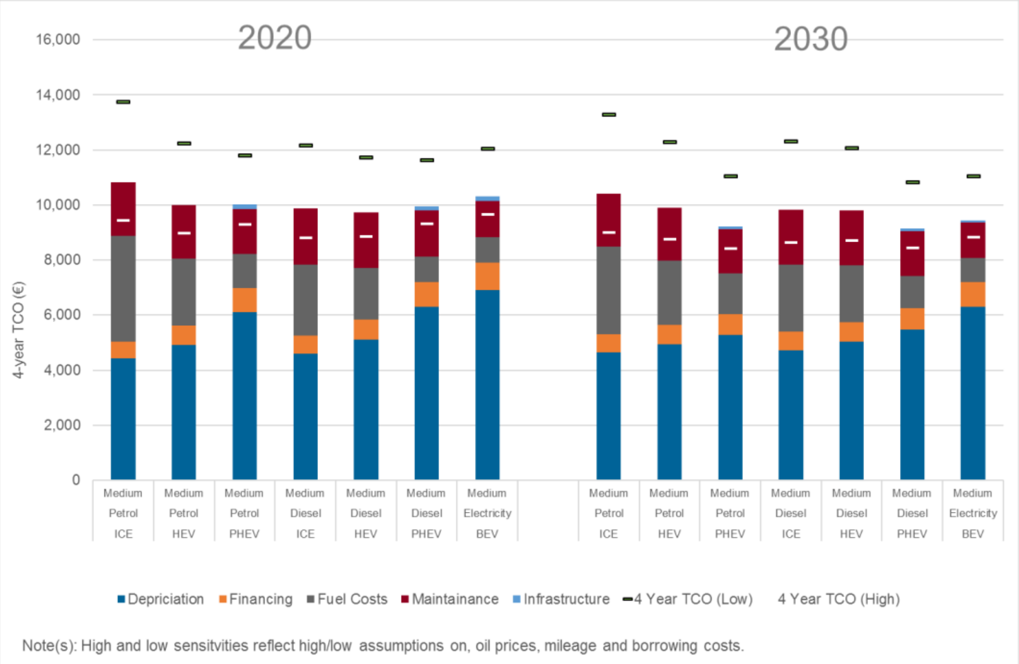


Note(s): High and low sensitivities reflect high/low assumptions on electricity prices, fuel prices, mileage, borrowing costs and technology costs.

The main finding of the TCO analysis is that there is strong convergence in the cost of owning and running all types of vehicles, and this convergence is much stronger than for the purchase price alone.

For second-hand vehicles, the TCO balance between the different powertrains is to some extent dependent upon the age of the vehicle; the newer the vehicle, the higher the purchase price, and therefore the bigger the disparity between ICEs and advanced powertrains (which have higher new purchase prices) in terms of depreciation and financing (both of which are a function of the purchase cost). However, typically there is much closer parity between the different powertrains, as can be seen in Figure 5.5.

Figure 5.4 4-year TCOs for average second-hand imported vehicles across different powertrains in Poland under the TECH RAPID scenario



Note(s): High and low sensitivities reflect high/low assumptions on electricity prices, fuel prices, mileage, borrowing costs and technology costs.

As these second-hand vehicles have already experienced some depreciation, the depreciation and financing costs over a 4-year period of ownership are much lower, negating to some extent the higher initial purchase price of an advanced powertrain vehicle. In both 2020 and 2030, the total cost of ownership of a hybrid, plug-in hybrid and battery-electric vehicle over four years are all lower than the equivalent cost of an internal combustion engine vehicle.

As outlined in Section 4 on the key assumptions, there is fair degree of uncertainty about how cost for low carbon technologies will develop and as such it is important to understand how these uncertainties could potentially impact on the consumer adoption of advanced powertrains. This is reflected in us testing the impact of high and low-cost sensitivities of technology and battery costs.

Further to this, we also consider sensitivities to customer behaviour and external factors which includes the sensitivity of TCO to annual mileage, the interest rate in financing car purchases, electricity prices and oil prices.

Table 5.1 Range of tested assumptions for 4-year TCO, shows the full set of assumptions that were used to define the potential upper and lower bounds on the total cost of ownership.

Table 5.1 Range of tested assumptions for 4-year TCO

Variable	Range		
	Low	Central	High
Car size	Medium	Medium	Medium
Depreciation	66%	66%	66%
Annual mileage (km)	6,000	8,000	12,000
Interest rate	1.5%	3.5%	8%
Oil Price	Low	Central	High
Electricity prices	EU	Poland	Poland

Technology costs	Low (adjusted in line with ICCT)	Central (Ricardo AEA)	High (adjusted in line with IKA)
Battery Costs	Low OEM costs (see Table 3.5	Central (see Table 3.4)	Central (see Table 3.4)

The results of testing this wide range of assumptions suggest that the overall trend of a convergence of cost of owning and running all types of vehicles to 2030 persists under extreme cases.

5.4 Characteristics of Polish Vehicles

The Polish vehicle fleet has a number of specificities which have the potential to make the transition to advanced powertrains happen more slowly.

The average age of a vehicle in Poland is much older than the European average, at 17 years[15]. Typical ownership periods are substantially higher than the European average, which has the potential to make battery electric vehicles a more attractive proposition (as the higher purchase price has more time over which to be counteracted by cheaper refuelling costs). However, it is also likely to slow the rate of transition, as the turnover of the stock happens much more slowly.

Furthermore, around 60% of vehicles registered for the first time in Poland are not factory-new cars, but are second-hand vehicles that have been imported from other EU Member States, with the vast majority coming from Germany. If this continues to be the case, it has two important implications; first, that the transition in Poland will depend to a large extent upon the transition happening in Germany and the German vehicle stock, and second that the transition is likely to take place later in Poland than in other countries such as Germany, because only one the EVs in the Germany stock age, and become vehicles ready to be exported to Poland, will they enter the Polish stock.

There is also an important policy conclusion to be drawn from Poland's current reliance upon second-hand imports from Germany. In a case whereby Germany introduced policies which reduced the value of second-hand ICE vehicles (such as a city-centre ban on diesel vehicles), this could reduce the sale price of these vehicles in Poland. Such action is likely to encourage greater take-up of second-hand ICE vehicles, and will further delay the speed with which Poland could transition to advanced powertrains. Our TECH IMPORT scenario explores just such a scenario.

[15] Transport Activity results in 2015, Polish Central Statistics office

6 Economic impacts

The economic impact of decarbonising Poland's passenger vehicles, compared to a reference case (REF) in which cars remain unchanged from today, was modelled using E3ME[16].

Whilst, in isolation, the increasing cost of vehicles has a negative impact on the consumers and the economy, leading to price inflation and putting downward pressure on real incomes and spending, it also diverts spending towards the value chain for manufacturing vehicles and their component parts and away from all other sectors of the economy. While many vehicles are constructed in other Member States, there are some automotive supply chains in Poland, meaning that increased spending on vehicles can create domestic jobs and activity.

However, better fuel-efficiency lowers the cost of living, with positive consequences for the economy, and diverts spending away from oil supply chains and towards other areas of the economy. Since oil is imported to Poland, the positive impact on the economy of lower spending on fuel is further improved by an improvement in the balance of trade. A summary of the main economic indicators in presented in Table 6.1.

Table 6.1: Main macroeconomic indicators

	CPI	TECH	TECH RAPID	TECH IMPORT
2030 Impacts				
GDP (%)	0.2%	0.3%	0.3%	0.3%
Employment (000's)	27	49	51	48
Oil Imports (mboe)	-10	-20	-27	-19
Tailpipe CO_2 emissions from passenger cars ($mtCO_2$)	-3.9	-7.7	-10.4	-7.4
	CPI	TECH	TECH RAPID	TECH IMPORT
2050 Impacts				
GDP (%)	0.3%	0.8%	1.1%	0.7%
Employment (000's)	23	78	81	68
Oil Imports (mboe)	-13	-57	-68	-45
Tailpipe CO_2 emissions from passenger cars ($mtCO_2$)	-5.2	-22.3	-26.3	-17.6

The economic impact is highly uncertain and is dependent on a number of competing factors: the cost of vehicles, low-carbon technologies and EV

[16] https://www.camecon.com/how/e3me-model/

batteries, the location of vehicle supply chains and future oil prices, to name a few of the key uncertainties. However, the overriding impact arises from the reduction in oil imports. This is noticeable in the macroeconomic results whereby the GDP impact tends to follow oil imports in all scenarios.

In the TECH RAPID scenario, although expenditure on motor vehicles are higher, the amount of oil taken out of the Polish economy is greater, leading to a larger positive economic impact over time. Conversely, in the TECH IMPORT case, the accelerated import of second-hand ICEs reduces the rate of deployment of advanced powertrains, and leads to higher consumption of oil than in the TECH or TECH RAPID scenario; as such, the economic gains are smaller, despite lower expenditure on purchasing vehicles.

6.1 Sectoral impacts

The costs and benefits are not evenly distributed among different socio-economic groups, with some benefitting and some adversely affected by the transition.

Oil and petroleum refining

In the TECH RAPID scenario, spending on road fuel is €5.4bn lower than in the reference scenario by 2030. Whilst much of this spending in the REF scenario flows out of the Polish economy (in the form of import spending), reduced spending has an adverse impact on the domestic refining industries. In the TECH RAPID scenario, gross output in the petroleum refining sector is considerably lower than in the reference scenario by 2030.

Other energy industries

Electricity (and hydrogen) sectors gain directly through investment in charging infrastructure and through consumers' expenditure on electricity & hydrogen. In the TECH RAPID scenario, gross output in the electricity sector is €0.5bn higher than in the reference scenario by 2030.

The automotive supply chain

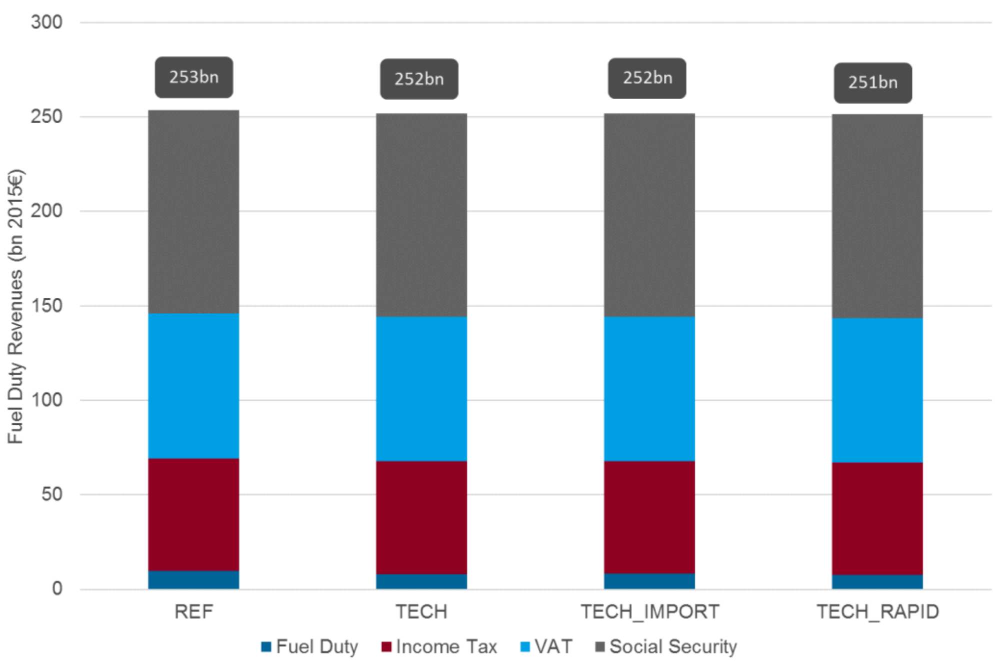
In the TECH RAPID scenario, the automotive supply chain shows a net increase in gross output of almost €0.7 bn and around 3,000 more jobs in 2030 compared to the reference scenario, due to the rapid transition from ICEs to the manufacture of BEVs. Within the supply chain there is a substantial transition from traditional motor vehicles production to electrical equipment. As such, in 2030, electrical equipment output is almost €1bn above baseline in the TECH RAPID scenario in 2030 whereas output in the traditional motor vehicles sector falls by 0.4bn.

6.2 Government revenues

In many countries (including Poland), fuel tax is levied to pay for road infrastructure improvements. By reducing spending on petrol and diesel fuels, vehicle efficiency improvements and a switch to EVs could have profound impacts on government tax revenues and the model for financing road maintenance and road infrastructure improvements.

Our analysis shows that in the TECH RAPID scenario, there is a shortfall in fuel tax revenues in 2030 of just less than €3 billion, compared to slightly more than €2 billion in the TECH scenario. While, as described above, the structural shifts created by this transition leads to an economic boost, and taxation of this additional economic activity increases the tax take elsewhere in the economy, these have little impact in Poland, due to the relatively low tax rates.

Figure 6.1 Fuel duty revenues (€2015bn)



It can be expected that the Polish finance ministry would seek to recoup the lost revenue, potentially through taxes aimed at the same user group (e.g. through a road tax). Such an additional tax would cause a small reduction in the overall GDP impact due to an additional cost faced by consumers reducing their expenditure on other goods and services in the economy.

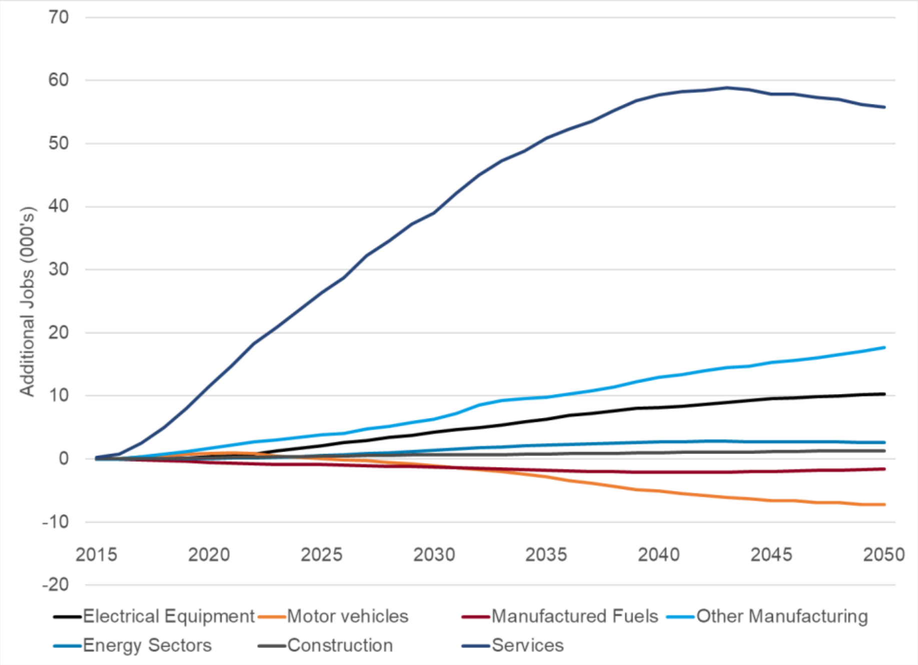
Nonetheless, it is worth noting these two important trends during the transition to low-carbon mobility. And as stated earlier, this highlights the importance of industry, government and civil society working together to find consensus on the optimal approach.

6.3 Employment

The impact on employment, while linked to the overall economic impact, is somewhat different. To measure the impact on employment, we also need to take account of the different employment intensities in the various sectors that are affected. There is a trend in increasing automation of the auto industry, leading to lower jobs overall, regardless of the low-carbon transition. Building battery-electric vehicles is expected to be less labour-intensive than building the gasoline and diesel vehicles they will replace. Meanwhile, building hybrids and plug-in hybrids is expected to be more labour intensive. Our modelling shows that the net employment impact for the auto sector from this transition will depend on the balance achieved between these various technologies, and the degree to which they are imported or produced in Poland.

Figure 6.2 shows the evolution of jobs in Poland as a result of the transition to low-carbon cars in 2030 and 2050 under our TECH RAPID scenario, relative to the Reference case. As a result of the economic shifts described above, there is a net increase in employment in the following sectors: construction, electricity, hydrogen, services and most manufacturing sectors. Employment in the fuels sector is reduced. Employment in the automotive manufacturing sector is increased in the short term, but decreases from the mid-2020s. Note that this is a direction function of the speed of the transition; in a slower transition, where PHEVs and HEVs continue to be manufactured in greater numbers (such as the TECH scenario), employment in the automotive sector would not be expected to become negative until after 2030.

Figure 6.2 The employment impact per sector of the transition to low-carbon cars (thousands)



The increase in auto sector jobs is driven by the fact that diesel and gasoline engines are built to greater levels of sophistication and efficiency to meet climate goals; and because of the increasing deployment of hybrids; plug-in hybrids and fuel-cell vehicles, which also contain increasing technological complexity. However, once hybrids are replaced by battery-electric vehicles which are simpler to build, fewer jobs are generated.

6.4 The economic risks and opportunities of a different transition speeds

In this report, we present most of the analysis exploring the TECH RAPID scenario, which is a transition of ambitious speed towards low-carbon mobility. At a macro level, this transition shows the largest economic benefits, and achieves the most rapid reduction in oil imports and emissions.

However, it should be noted that such a transition can also create challenges. In a more rapid transition, there are small negative economic impacts in the short term, as the higher cost of electric vehicles are not immediately counteracted by the benefits from reduced oil imports (which accumulate over time). In addition, early adopters are likely to face higher purchase prices for vehicles, as battery technology is less mature.

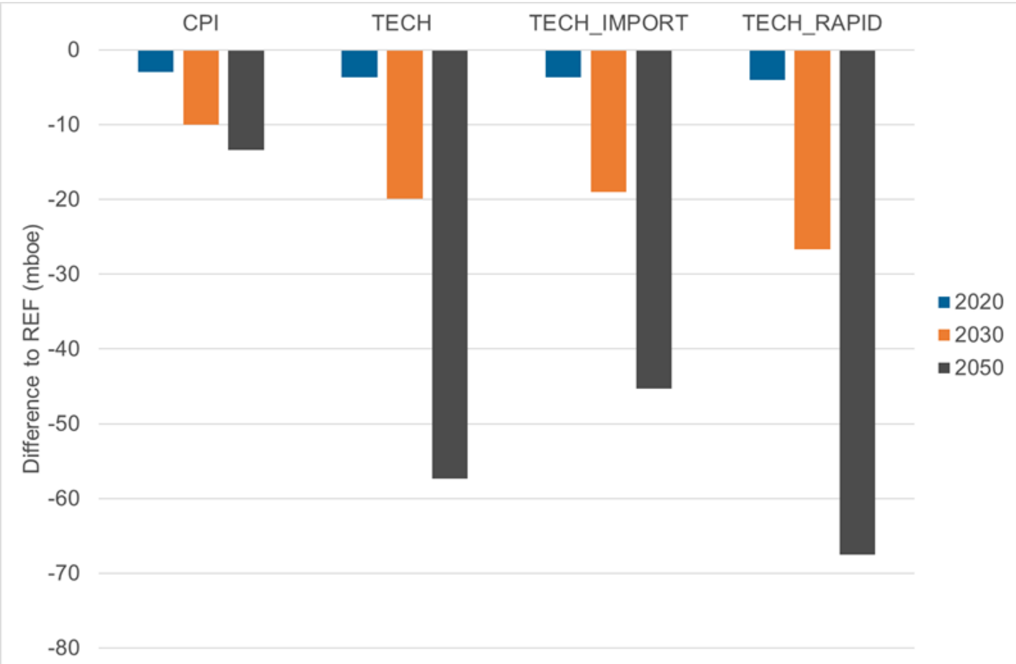
In the Polish context, however, there are also some first-mover advantages that could come with a rapid transition. LG CHEM are already constructing a large battery plant in Poland, and creating early (by European standards) domestic demand for motor vehicle batteries could present some early opportunities to strengthen the domestic battery manufacturing industry. Because Poland's traditional motor vehicle sector is relatively small, and there is already production of electric vehicles (such as Solaris) in Poland, the domestic economy is relatively well-placed to benefit from the transition.

6.5 Oil imports

By 2030, In the TECH RAPID scenario, oil imports are reduced by around 26 mboe annually. By 2050, the reduction in oil imports compared to the REF has increased to 68 mboe. In 2030, there is not a substantial difference between the scenarios, because it takes the new powertrains time to achieve penetration into the stock (and therefore to have a sizeable impact on oil demand); in 2030, even in the TECH-RAPID scenario, ICEs are over 80% of the stock of vehicles. However, by 2050 the differences are more pronounced, and in the TECH scenario imports are reduced by only 58 mboe per year.

The reduction in oil imports is the main economic driver and explains the levelling off of economic benefits in the CPI scenario relative to the REF from 2030 onwards, compared to the increasing GDP benefits in the TECH and TECH RAPID scenarios out to 2050.

Figure 6.3 Oil imports

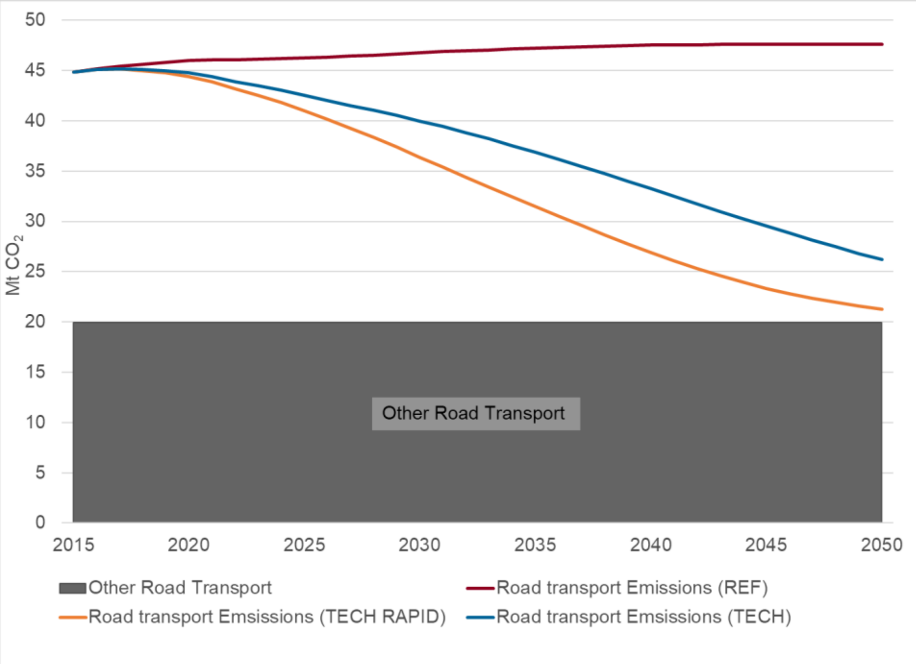


7 Environmental impacts

7.1 Impacts on CO_2 emissions

In the TECH RAPID scenario, CO_2 emissions from cars are reduced from around 25 Mt per annum in 2017 to about 1 Mt per annum in 2050 (Figure 7.1). This is achieved via a combination of increased fuel efficiency and switching the energy source from diesel and gasoline to low-carbon electricity and hydrogen. In the less ambitious TECH scenario, CO_2 emissions from cars are 6 Mt in 2050, i.e. still around 75% lower than current levels.

Figure 7.1 Road Transport CO_2 emissions in the TECH and TECH RAPID scenarios



7.2 The implied emissions in electricity

Figure 7.1 above does not include the implied emissions in electricity; that is, the CO_2 emissions created in the generation of the electricity. This is a particularly acute issue in Poland, where the electricity generation mix is currently dominated by coal.

Our analysis explores three potential evolutions of the electricity mix, taken from existing work from Forum Energii[17]. These are;

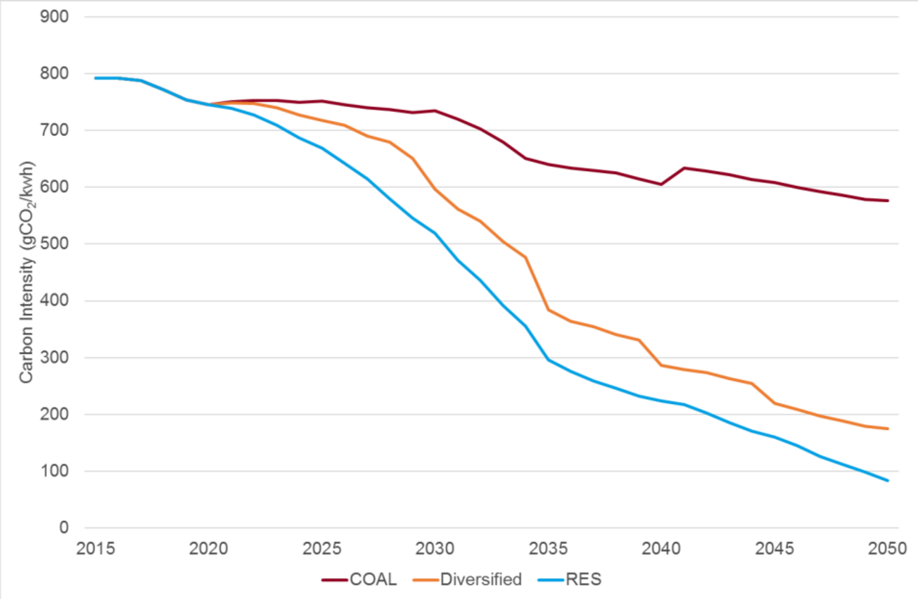
- Coal scenario, where coal continues to play a major role in electricity generation (albeit declining over time)
- Diversified scenario, with nuclear generation, where electricity is generated through a balanced mix of technologies, including some coal, gas, nuclear and renewables

[17] *Polish energy sector 2050. 4 scenarios*, October 2017

- RES scenario, where the future generation mix is focussed on renewable technologies.

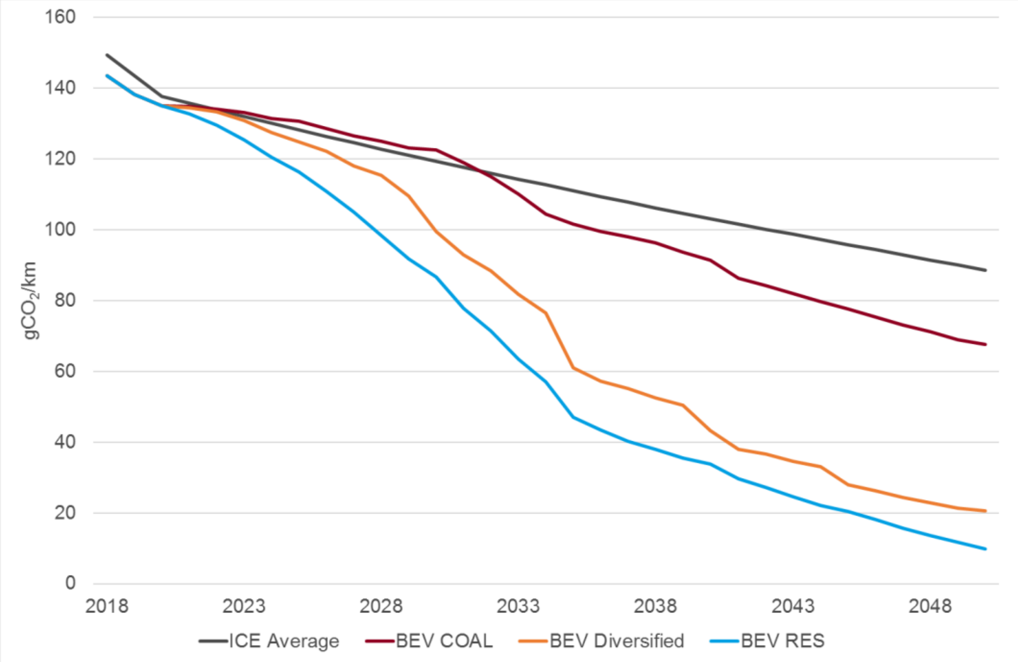
The different generation mixes, and their associated carbon footprints, were used to calculate the implied emissions associated with the use of EVs, and the results are shown in Figure 7.2.

Figure 7.2 The carbon intensity of different electricity mixes



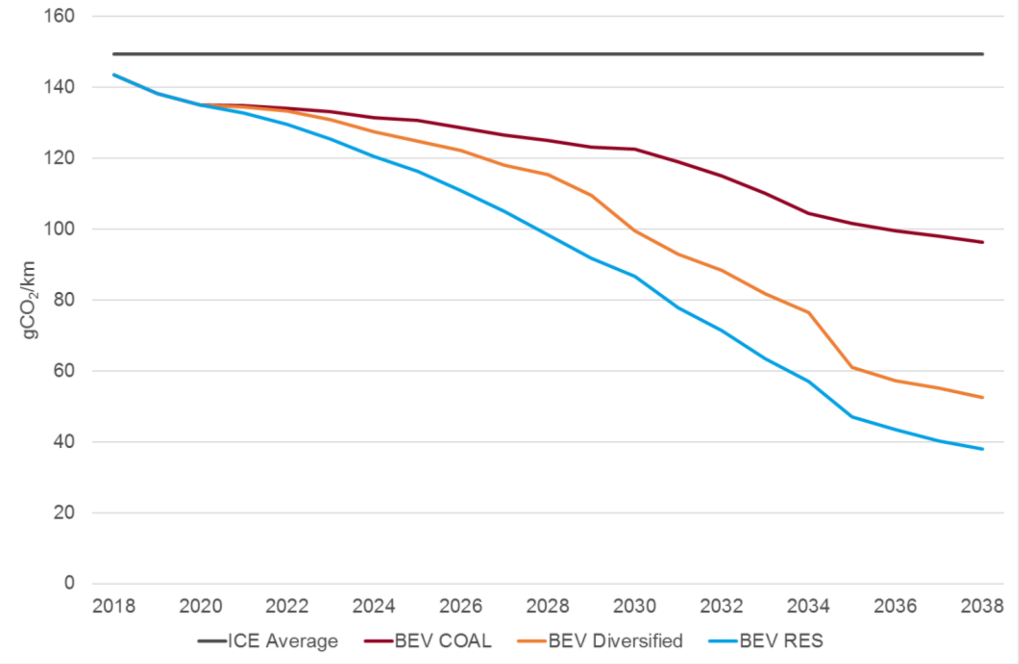
This demonstrates how, in a future where electricity remains dominated by coal-fired generation, emissions associated with electricity use would fall only slightly, whereas they would fall much more substantially under a diversified or RES-focussed mix. However, the key question around implied emissions is under what conditions an EV fuelled by Polish electricity has a smaller in-use emissions footprint than an ICE. This is shown in Figure 7.3; between 2020 and 2030, the average new ICE has emissions which are lower than a BEV under a coal fired generation mix *in the first year of operation*. However, if the generation mix evolves away from coal, then in all years a BEV has lower emissions.

Figure 7.3 Real world emissions of new vehicles under different generation mixes



Considering the specific case of a vehicle purchased in one of these years where it is possible for a BEV to have higher in-use emissions than an ICE, it should be noted that the chart above shows only the difference in emissions in the first year of operation. This is significant because while the in-use emissions associated with an ICE cannot change after manufacture (on a per km basis), the same is not true of a BEV. As the electricity mix continues to decarbonise, the in-use emissions of the same BEV can continue to fall. This is shown in , where we consider the real world emissions associated with a new vehicle purchased in 2018. In this case, while the ICE maintains emissions of around 149g CO_2 per km, the implied emissions associated with a BEV continue to fall over time; so even under a coal-focussed generation mix, while emissions are similar to an ICE in the first year of operation, as more coal is pushed off-line, the carbon intensity of the electricity used falls, and lifetime in-use emissions from the BEV, even under this unfavourable mix, are substantially lower than the ICE (see Figure 7.4).

Figure 7.4 Real world emissions of a 2018 new vehicle over time



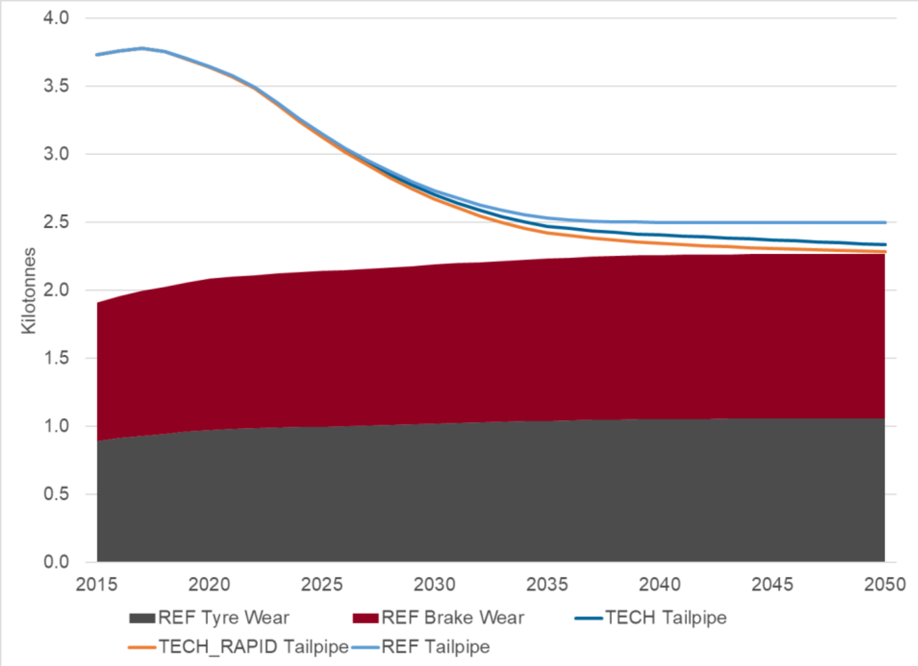
7.3 Impacts on particulate matter

Particulate matter ($PM_{2.5}$ and PM_{10}) emitted from road transport can have a substantial impact on local air quality which has led to harmful consequences for human health in many urban centres.

At the same time as reducing CO_2 emissions, a substantial co-benefit of decarbonising passenger cars is achieved as emissions of PM_{10} from vehicle exhausts would be cut from around 1,800 tonnes per year in 2017 to 200 tonnes in 2050.

Much of the reduction seen across all scenarios is through the impact from the Euro 5 and Euro 6 emissions standards. As these standards are already in place and set out to 2020 for ICEs, as shown in Figure 7.5, the reduction to 2035 is through these more efficient ICE-based vehicles gaining a larger share of the vehicle stock and the least efficient vehicles retiring. However, beyond 2030, PM_{10} emissions in the REF scenario remain almost constant at around 400 tonnes whereas the TECH RAPID scenario reaches 300 tonnes by 2050. This is predominately achieved through the transition away from petrol and diesel vehicles towards zero emission electricity and hydrogen.

Figure 7.5: Stock tailpipe particulate emissions (PM_{10}) in REF, TECH and TECH RAPID



However, these particulate emissions that we model only refer to tailpipe emissions. While substantial, it is only part of the issue for local air pollutants from road transport. For road transport, the largest source of emission of particulates, is through tyre & brake wear and road abrasion, as shown in Figure 7.5.

8 Low carbon buses

8.1 Introduction

Alongside the work on passenger cars, an analysis of the potential for reducing carbon emissions from buses was also undertaken. This chapter provides a summary of that work.

A similar approach was taken as outlined for passenger cars in the rest of this report; a stock model was developed to understand the potential role of fuel efficient technologies, as well as the deployment of advanced powertrains, to reduce emissions and fuel consumption. Macroeconomic analysis was also carried out, to assess the impact of a transition of buses on the Polish economy; however, the impacts on the economy proved to be negligible, and as such are not included in this analysis.

8.2 Future sales mixes

In the analysis of buses, we consider just two scenarios; a reference scenario (REF), with no change from current technologies (i.e. no improvement in fuel efficiency or additional deployment of advanced powertrains from today) and a TECH scenario, which includes a moderately ambitious rollout of fuel efficient technologies and advanced powertrains.

The analysis covers both urban buses, which operate in and around cities, typically on circular or short linear routes and coaches, used for long-distance point-to-point routes (such as between cities). In the TECH scenario, we consider different technologies being deployed between these two vehicle types; urban coach ICEs will be replaced primarily by battery electric vehicles and plug-in hybrids (with a smaller role for HEVs), reflecting the availability of charging infrastructure geared towards regular and low mileage routes (see Figure 8.2). Long distance coaches, on the other hand, will instead transition to a mix of plug-in hybrids in the short/medium term (in order to reduce emissions without requiring lengthy charging during routes), while during the 2040s sales will transition to fuel cell vehicles, with hydrogen offering sufficient range and speed of refuelling to meet the demands of long-distance routes (see).

Figure 8.2 Sales shares of urban buses in the TECH scenario

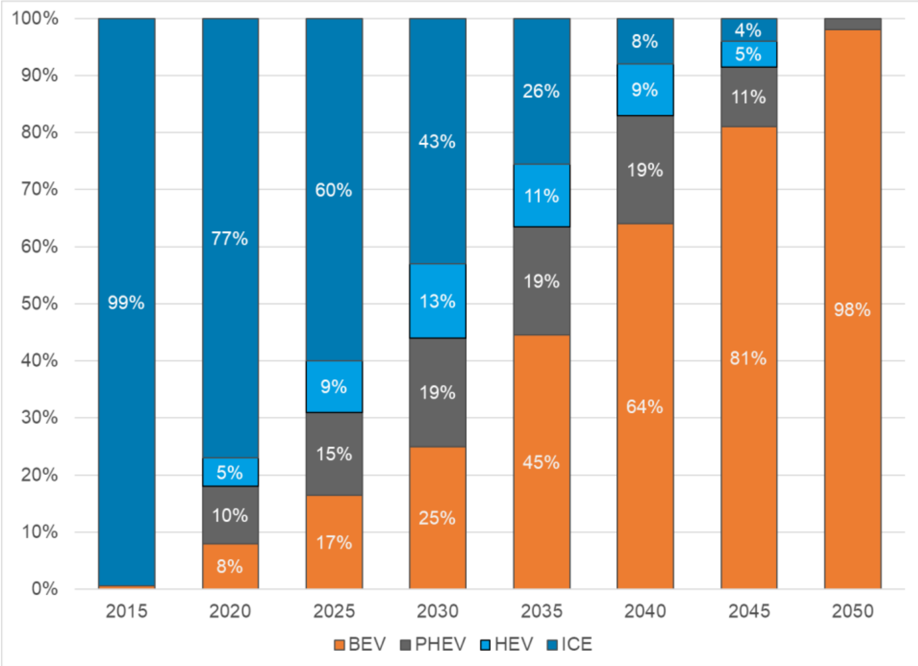
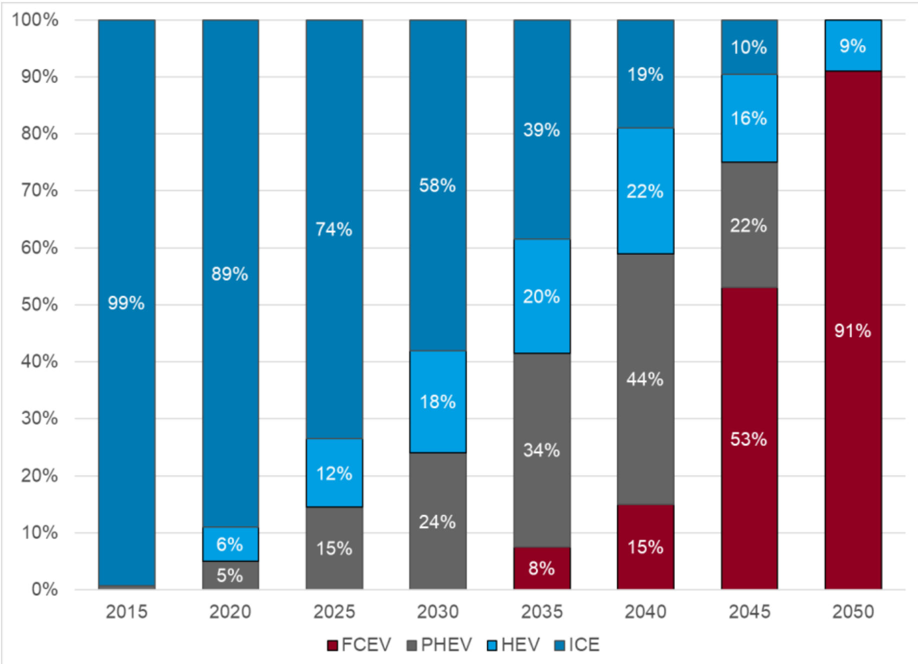
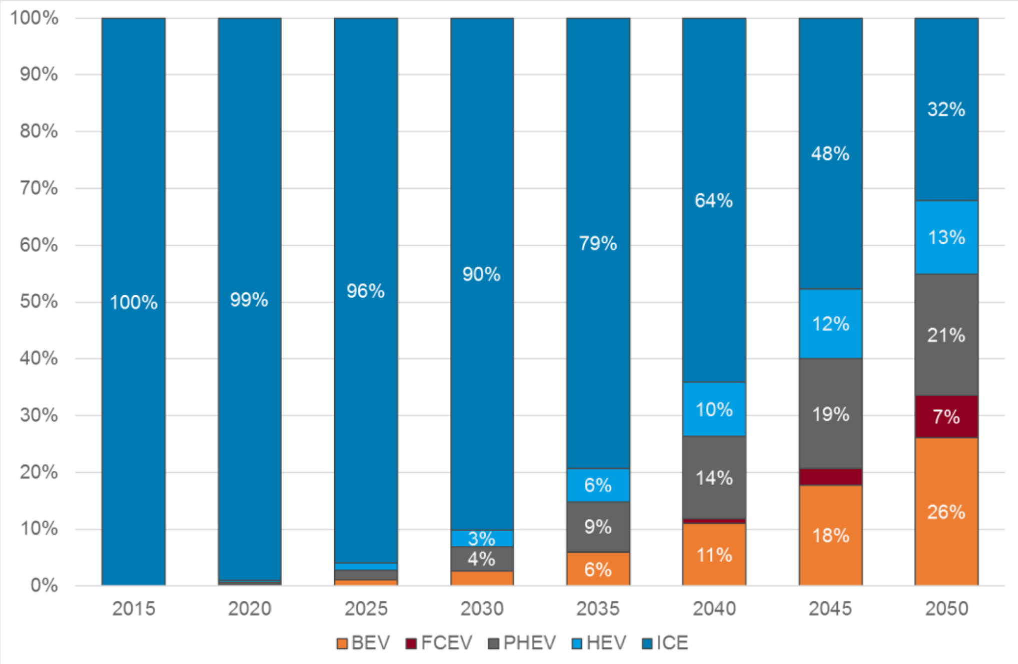


Figure 8.1 Sales shares of coaches in the TECH scenario



In terms of the evolution of the bus and coach stock, ICEs continue to dominate until the mid 2040s, and even in 2050 represent around one-third of the stock; just over one-quarter of vehicles are BEVs, with the remainder a mix of FCEVs, PHEVs and HEVs (see Figure 8.3).

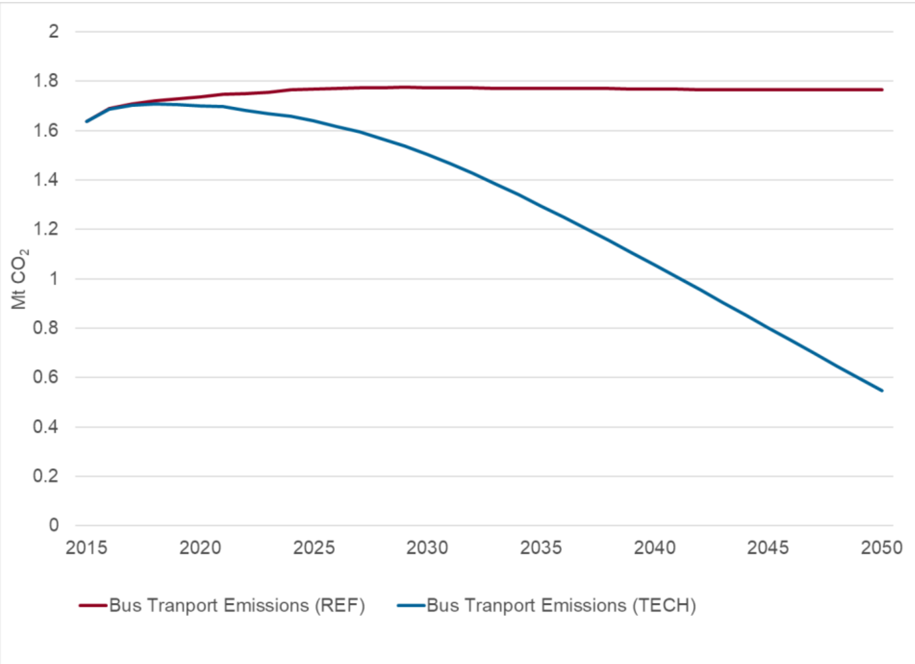
Figure 8.3 The combined bus and coach fleet in the TECH scenario



8.3 The impact of decarbonising buses and coaches on emissions

Under the TECH scenario, CO_2 emissions from the bus and coach fleet would fall substantially; from 1.7 Mt in 2017 to less than 0.6 Mt in 2050 (see Figure 8.4).

Figure 8.4 CO2 emissions from buses and coaches



However, the impact on total emissions from road transport are very small; these summed to 45 Mt in 2017, so a reduction of around 1 Mt is of the order of 2-3% reduction in total emissions. While buses spend the vast majority of their time in urban areas, their impact in terms of NOx and PM10s is not any more substantial, due to the large volume of car miles that are also driven in urban centres.

8.4 The role of buses in the transition

Despite the relatively small overall impact of the transition of buses in terms of emissions or socioeconomic impact (due to the small proportion of total road transport miles that they represent), there are a number of reasons that pursuing the decarbonisation of bus transport is a worthwhile endeavour.

Firstly, electric vehicles already make economic sense; our own analysis shows that the lifetime total cost of ownership of BEVs, PHEVs and FCEVs is already well below that of an ICE, and analysis by others, such as BNEF, has shown similar. This is due to the high usage rates, and therefore high number of miles covered by these vehicles; this means that the lower running costs quickly outweigh the higher purchase price of advanced powertrains.

Secondly, buses and coaches have an important role as a demonstration technology. Electric vehicles in these segments can “normalise” the technology, in that it exposes consumers to electric powertrains and their benefits. It is also relatively straightforward to do; given the lower cost of these options, and the fact that the vast majority of buses and coaches operate on contracts that are either directly or indirectly controlled by the public sector; so public procurement regulations can easily encourage (or mandate) the use of advanced powertrains.

Finally, and perhaps most relevant in the case of Poland; transitioning to electric buses and coaches provides an avenue to develop domestic expertise in both the manufacture and installation of motor vehicle batteries and the electric vehicles themselves. This can help to secure investment and create jobs in the Polish economy, as well as secure or improve the position of Polish companies in the new value chains associated with electric vehicles.

9 Conclusions

This study focused on the potential benefits and the transitional challenges of decarbonising cars in Poland.

We find that different levels of ambitious transitions all yield net economic benefits in the short, medium and long term. This comes about because of the economic benefits of reducing oil imports, and all scenarios lead to reductions in oil consumption and emissions. The economic benefit increases over the period to 2050 as oil imports are reduced. The implication of this finding is that a transition towards low carbon cars can deliver economic and environmental benefits to Poland.

Lowering Poland's dependence on imported oil also contributes to its energy security. Moreover, in all scenarios CO_2 emissions are reduced, and local air quality improved.

A number of challenges to the transition were observed and require management:

- In Poland, the turnover of the vehicle fleet is slow, and vehicles have long life spans by European standards. This slows the potential speed at which new powertrains, and more fuel-efficient vehicles, can penetrate the stock.
- Around two-thirds of newly registered vehicles in Poland are second-hand vehicles imported from other EU states (primarily Germany). This slows the impact of the transition (which happens in new sales), and also presents a policy challenge; more advanced transport decarbonisation policy in Germany (such as a city centre diesel ban) could cut the resale value of ICEs, and lead to them flooding into the Polish market (and further slowing the transition).
- Employment in the motor vehicles sector would likely fall post 2030 (or post 2025 in a more ambitious scenario) as advanced powertrains dominate the market, since they require fewer people to manufacture and assemble the components.
- The implementation of a rapid charging infrastructure in Poland will require annual investments reaching hundreds of millions of euros by 2050.
- Fuel duty revenues would decline, but at a manageable rate, and these revenues are a small portion of the overall Polish tax take.

However, Poland is well-positioned to take advantage of the transition to low-carbon mobility. In addition, a simultaneous transition in buses and coaches would have small environmental benefits, but could also serve to strength Poland's strengths in the development and manufacture of vehicle batteries and associated low-carbon technologies, building upon the success of domestic companies such as Solaris.

Appendix A E3ME model description

Introduction

Overview

E3ME is a computer-based model of the world's economic and energy systems and the environment. It was originally developed through the European Commission's research framework programmes and is now widely used in Europe and beyond for policy assessment, for forecasting and for research purposes.

Recent applications

Recent applications of E3ME include:

- a global assessment of the economic impact of renewables for IRENA
- contribution to the EU's Impact Assessment of its 2030 climate and energy package
- evaluations of the economic impact of removing fossil fuel subsidies in India and Indonesia
- analysis of future energy systems, environmental tax reform and trade deals in East Asia
- an assessment of the potential for green jobs in Europe
- an economic evaluation for the EU Impact Assessment of the Energy Efficiency Directive

This model description provides a short summary of the E3ME model. For further details, the reader is referred to the full model manual available online from www.e3me.com.

E3ME's basic structure and data

The structure of E3ME is based on the system of national accounts, with further linkages to energy demand and environmental emissions. The labour market is also covered in detail, including both voluntary and involuntary unemployment. In total there are 33 sets of econometrically estimated equations, also including the components of GDP (consumption, investment, international trade), prices, energy demand and materials demand. Each equation set is disaggregated by country and by sector.

E3ME's historical database covers the period 1970-2014 and the model projects forward annually to 2050. The main data sources for European countries are Eurostat and the IEA, supplemented by the OECD's STAN database and other sources where appropriate. For regions outside Europe, additional sources for data include the UN, OECD, World Bank, IMF, ILO and national statistics. Gaps in the data are estimated using customised software algorithms.

The main dimensions of the model

The main dimensions of E3ME are:

- 59 countries – all major world economies, the EU28 and candidate countries plus other countries' economies grouped

- 43 or 69 (Europe) industry sectors, based on standard international classifications
- 28 or 43 (Europe) categories of household expenditure
- 22 different users of 12 different fuel types
- 14 types of air-borne emission (where data are available) including the six greenhouse gases monitored under the Kyoto protocol

The countries and sectors covered by the model are listed at the end of this document.

Standard outputs from the model

As a general model of the economy, based on the full structure of the national accounts, E3ME is capable of producing a broad range of economic indicators. In addition there is range of energy and environment indicators. The following list provides a summary of the most common model outputs:

- GDP and the aggregate components of GDP (household expenditure, investment, government expenditure and international trade)
- sectoral output and GVA, prices, trade and competitiveness effects
- international trade by sector, origin and destination
- consumer prices and expenditures
- sectoral employment, unemployment, sectoral wage rates and labour supply
- energy demand, by sector and by fuel, energy prices
- CO_2 emissions by sector and by fuel
- other air-borne emissions
- material demands

This list is by no means exhaustive and the delivered outputs often depend on the requirements of the specific application. In addition to the sectoral dimension mentioned in the list, all indicators are produced at the national and regional level and annually over the period up to 2050.

E3ME as an E3 model

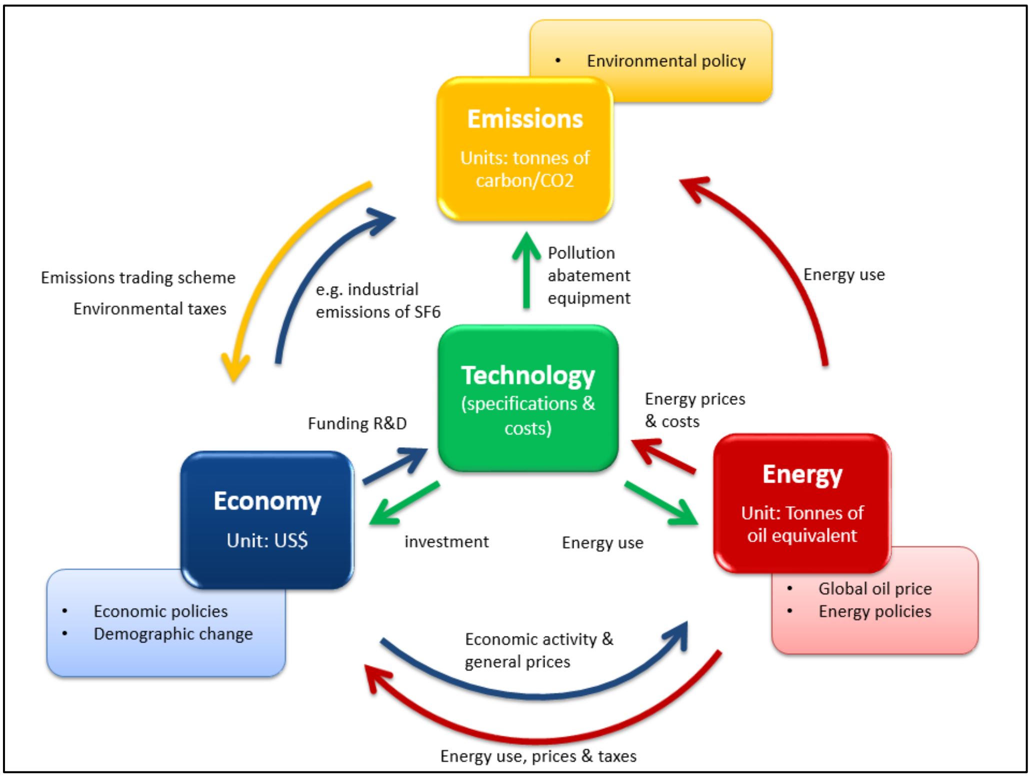
The E3 interactions

The figure below shows how the three components (modules) of the model - energy, environment and economy - fit together. Each component is shown in its own box. Each data set has been constructed by statistical offices to conform with accounting conventions. Exogenous factors coming from outside the modelling framework are shown on the outside edge of the chart as inputs into each component. For each region's economy the exogenous factors are economic policies (including tax rates, growth in government expenditures, interest rates and exchange rates). For the energy system, the outside factors are the world oil prices and energy policy (including regulation of the energy industries). For the environment component, exogenous factors include policies such as reduction in SO_2 emissions by means of end-of-pipe filters from large combustion plants. The linkages between the components of the model are shown explicitly by the arrows that indicate which values are transmitted between components.

The economy module provides measures of economic activity and general price levels to the energy module; the energy module provides measures of emissions of the main air pollutants to the environment module, which in turn can give measures of damage to health and buildings. The energy module provides detailed price levels for energy carriers distinguished in the economy module and the overall price of energy as well as energy use in the economy.

The role of technology

Technological progress plays an important role in the E3ME model, affecting all three Es: economy, energy and environment. The model's endogenous technical progress indicators (TPIs), a function of R&D and gross investment, appear in nine of E3ME's econometric equation sets including trade, the labour market and prices. Investment and R&D in new technologies also appears in the E3ME's energy and material demand equations to capture energy/resource savings technologies as well as pollution abatement equipment. In addition, E3ME also captures low carbon technologies in the power sector through the FTT power sector model[18].



Treatment of international trade

An important part of the modelling concerns international trade. E3ME solves for detailed bilateral trade between regions (similar to a two-tier Armington model). Trade is modelled in three stages:

- econometric estimation of regions' sectoral import demand

[18] See Mercure (2012).

- econometric estimation of regions' bilateral imports from each partner
- forming exports from other regions' import demands

Trade volumes are determined by a combination of economic activity indicators, relative prices and technology.

The labour market

Treatment of the labour market is an area that distinguishes E3ME from other macroeconomic models. E3ME includes econometric equation sets for employment, average working hours, wage rates and participation rates. The first three of these are disaggregated by economic sector while participation rates are disaggregated by gender and five-year age band.

The labour force is determined by multiplying labour market participation rates by population. Unemployment (including both voluntary and involuntary unemployment) is determined by taking the difference between the labour force and employment. This is typically a key variable of interest for policy makers.

Comparison with CGE models and econometric specification

E3ME is often compared to Computable General Equilibrium (CGE) models. In many ways the modelling approaches are similar; they are used to answer similar questions and use similar inputs and outputs. However, underlying this there are important theoretical differences between the modelling approaches.

In a typical CGE framework, optimal behaviour is assumed, output is determined by supply-side constraints and prices adjust fully so that all the available capacity is used. In E3ME the determination of output comes from a post-Keynesian framework and it is possible to have spare capacity. The model is more demand-driven and it is not assumed that prices always adjust to market clearing levels.

The differences have important practical implications, as they mean that in E3ME regulation and other policy may lead to increases in output if they are able to draw upon spare economic capacity. This is described in more detail in the model manual.

The econometric specification of E3ME gives the model a strong empirical grounding. E3ME uses a system of error correction, allowing short-term dynamic (or transition) outcomes, moving towards a long-term trend. The dynamic specification is important when considering short and medium-term analysis (e.g. up to 2020) and rebound effects[19], which are included as standard in the model's results.

Key strengths of E3ME

In summary the key strengths of E3ME are:

[19] Where an initial increase in efficiency reduces demand, but this is negated in the long run as greater efficiency lowers the relative cost and increases consumption. See Barker et al (2009).

- the close integration of the economy, energy systems and the environment, with two-way linkages between each component
- the detailed sectoral disaggregation in the model's classifications, allowing for the analysis of similarly detailed scenarios
- its global coverage, while still allowing for analysis at the national level for large economies
- the econometric approach, which provides a strong empirical basis for the model and means it is not reliant on some of the restrictive assumptions common to CGE models
- the econometric specification of the model, making it suitable for short and medium-term assessment, as well as longer-term trends

Applications of E3ME

Scenario-based analysis

Although E3ME can be used for forecasting, the model is more commonly used for evaluating the impacts of an input shock through a scenario-based analysis. The shock may be either a change in policy, a change in economic assumptions or another change to a model variable. The analysis can be either forward looking (ex-ante) or evaluating previous developments in an ex-post manner. Scenarios may be used either to assess policy, or to assess sensitivities to key inputs (e.g. international energy prices).

For ex-ante analysis a baseline forecast up to 2050 is required; E3ME is usually calibrated to match a set of projections that are published by the European Commission and the IEA but alternative projections may be used. The scenarios represent alternative versions of the future based on a different set of inputs. By comparing the outcomes to the baseline (usually in percentage terms), the effects of the change in inputs can be determined.

It is possible to set up a scenario in which any of the model's inputs or variables are changed. In the case of exogenous inputs, such as population or energy prices, this is straight forward. However, it is also possible to add shocks to other model variables. For example, investment is endogenously determined by E3ME, but additional exogenous investment (e.g. through an increase in public investment expenditure) can also be modelled as part of a scenario input.

Price or tax scenarios

Model-based scenario analyses often focus on changes in price because this is easy to quantify and represent in the model structure. Examples include:

- changes in tax rates including direct, indirect, border, energy and environment taxes
- changes in international energy prices
- emission trading schemes

Regulatory impacts

All of the price changes above can be represented in E3ME's framework reasonably well, given the level of disaggregation available. However, it is also possible to assess the effects of regulation, albeit with an assumption about effectiveness and cost. For example, an increase in vehicle fuel-efficiency standards could be assessed in the model with an assumption about how efficient vehicles become, and the cost of these measures. This would be entered into the model as a higher price for cars and a reduction in fuel consumption (all other things being equal). E3ME could then be used to determine:

- secondary effects, for example on fuel suppliers
- rebound effects[20]
- overall macroeconomic impacts

Table 1: Main dimensions of the E3ME model

	Regions	Industries (Europe)	Industries (non-Europe)
1	Belgium	Crops, animals, etc	Agriculture etc
2	Denmark	Forestry & logging	Coal
3	Germany	Fishing	Oil & Gas etc
4	Greece	Coal	Other Mining
5	Spain	Oil and Gas	Food, Drink & Tobacco
6	France	Other mining	Textiles, Clothing & Leather
7	Ireland	Food, drink & tobacco	Wood & Paper
8	Italy	Textiles & leather	Printing & Publishing
9	Luxembourg	Wood & wood prods	Manufactured Fuels
10	Netherlands	Paper & paper prods	Pharmaceuticals
11	Austria	Printing & reproduction	Other chemicals
12	Portugal	Coke & ref petroleum	Rubber & Plastics
13	Finland	Other chemicals	Non-Metallic Minerals
14	Sweden	Pharmaceuticals	Basic Metals
15	UK	Rubber & plastic products	Metal Goods
16	Czech Rep.	Non-metallic mineral prods	Mechanical Engineering
17	Estonia	Basic metals	Electronics
18	Cyprus	Fabricated metal prods	Electrical Engineering
19	Latvia	Computers etc	Motor Vehicles
20	Lithuania	Electrical equipment	Other Transport Equipment
21	Hungary	Other machinery/equipment	Other Manufacturing
22	Malta	Motor vehicles	Electricity
23	Poland	Other transport equip	Gas Supply
24	Slovenia	Furniture; other manufacture	Water Supply
25	Slovakia	Machinery repair/installation	Construction
26	Bulgaria	Electricity	Distribution
27	Romania	Gas, steam & air cond.	Retailing
28	Norway	Water, treatment & supply	Hotels & Catering
29	Switzerland	Sewerage & waste	Land Transport etc
30	Iceland	Construction	Water Transport
31	Croatia	Wholesale & retail MV	Air Transport
32	Turkey	Wholesale excl MV	Communications
33	Macedonia	Retail excl MV	Banking & Finance
34	USA	Land transport, pipelines	Insurance
35	Japan	Water transport	Computing Services
36	Canada	Air transport	Professional Services
37	Australia	Warehousing	Other Business Services
38	New Zealand	Postal & courier activities	Public Administration
39	Russian Fed.	Accommodation & food serv	Education
40	Rest of Annex I	Publishing activities	Health & Social Work
41	China	Motion pic, video, television	Miscellaneous Services
42	India	Telecommunications	Unallocated
43	Mexico	Computer programming etc.	

[20] In the example, the higher fuel efficiency effectively reduces the cost of motoring. In the long-run this is likely to lead to an increase in demand, meaning some of the initial savings are lost. Barker et al (2009) demonstrate that this can be as high as 50% of the original reduction.

44	Brazil	Financial services	
45	Argentina	Insurance	
46	Colombia	Aux to financial services	
47	Rest Latin Am.	Real estate	
48	Korea	Imputed rents	
49	Taiwan	Legal, account, consult	
50	Indonesia	Architectural & engineering	
51	Rest of ASEAN	R&D	
52	Rest of OPEC	Advertising	
53	Rest of world	Other professional	
54	Ukraine	Rental & leasing	
55	Saudi Arabia	Employment activities	
56	Nigeria	Travel agency	
57	South Africa	Security & investigation, etc	
58	Rest of Africa	Public admin & defence	
59	Africa OPEC	Education	
60		Human health activities	
61		Residential care	
62		Creative, arts, recreational	
63		Sports activities	
64		Membership orgs	
65		Repair comp. & pers. goods	
66		Other personal serv.	
67		Hholds as employers	
68		Extraterritorial orgs	
69		Unallocated/Dwellings	

Source(s): Cambridge Econometrics.

Appendix B ICE Vehicle Technology improvements

Table B.1 Engine and transmission options – 2015 cost curve data

Downsizing options	Energy saving	Cost (€)		
		Small car	Medium car	Large car
Mild (15% cylinder content reduction)	4-6%	88	110	115
Medium (30% cylinder content reduction)	10-13%	120	180	180
Strong (45% cylinder content reduction)	15-19%	165	195	195
Combustion improvements (petrol)	5%	224	224	314
Combustion improvements (diesel)	2%	204	204	285
Cylinder deactivation	5%	155	155	155
Other engine options	**Energy saving**	**Cost (€)**		
(petrol only)		**Small car**	**Medium car**	**Large car**
Direct injection (homogenous)	4.5-5.5%	130	130	184
Direct injection (stratified)	10-14%	250	350	435
Thermodynamic cycle improvements	11-13%	280	300	400
Cam phasing	5%	50	50	80
Variable valve actuation and lift (petrol and diesel)	9%	144	150	235
Transmission options	**Energy saving**	**Cost (€)**		
		Small car	**Medium car**	**Large car**
Optimising gearbox ratios / downspeeding	4%	40	40	40

Automated manual transmission	2-5%	220	220	230
Dual clutch transmission	3-6%	233	250	257
Partial hybridisation	**Energy saving**	**Cost (€)**		
		Small car	**Medium car**	**Large car**
Start-stop	2.5-5%	66	80	96
Start-stop with regenerative breaking	6-10%	219	235	300

Appendix C Charging infrastructure assumptions

Table C.1: Number of charging points calculation breakdown for the TECH Rapid scenario

Variable	Type	2015	2020	2025	2030	2035	2040	2045	2050
Vehicle stock (000s)	All	16748	17188	16636	16771	17254	17597	17645	17645
Vehicle stock (000s)	PHEV + BEV	1	115	954	3030	6282	10366	14202	16607
	BEVs	0	40	551	1914	4239	7466	10915	13717
Share of vehicle stock	PHEV + BEV	0%	1%	6%	18%	36%	59%	80%	94%
	BEVs	0%	0%	3%	11%	25%	42%	62%	78%
Infrastructure density (vehicles per charging post)[21]	Household charging	1.25	1.4	1.5	1.7	1.7	1.7	1.7	1.7
	Work charging	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	Public charging	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	Fast charging (highways)	500	500	500	500	500	500	500	500
Total number of charging posts (000s)	Household charging	0	81	617	1,818	3,769	6,220	8,521	9,964
	Work charging	0	23	191	606	1,256	2,073	2,840	3,321
	Public charging	0	23	191	606	1,256	2,073	2,840	3,321
	Fast charging (highways)	0	0	1	4	8	15	22	27
Total number of charging plugs (000s)	Household charging (1 plug per post)	0	81	617	1,818	3,769	6,220	8,521	9,964
	Work charging (2 plug per post)	0	161	1,233	3,635	7,538	12,439	17,042	19,928
	Public charging (2 plugs per post)	0	46	382	1,212	2,513	4,146	5,681	6,643
	Fast charging (3 plugs per post)	0	0	3	11	25	45	65	82
	Total	**1**	**288**	**2,235**	**6,676**	**13,846**	**22,850**	**31,309**	**36,617**

[21] Note that density assumption have been rounded to 1 decimal place.

Table C.2: Calculating the cost of infrastructure investment in the TECH RAPID scenario

Variable	Type	2015	2020	2025	2030	2035	2040	2045	2050
A. Net additional posts required each year (000s)	Household charging	0	32	159	304	440	503	405	208
	Work charging	0	9	51	109	147	168	135	69
	Public charging	0	9	51	109	147	168	135	69
	Fast charging (highways)	0	0	0	1	1	1	1	1
	Total	**0**	**51**	**261**	**522**	**734**	**839**	**677**	**347**
B. Number of charging posts retiring from the stock each year (000s)[22]	Household charging 1 plug per post	-	-	-	-	-	32	159	304
	Work charging 2 plugs per post	-	-	-	-	-	9	51	109
	Public charging 2 plugs per post	-	-	-	-	-	9	51	109
	Fast charging (highways) 3 plugs per post	-	-	-	-	-	0	0	1
	Total	**-**	**-**	**-**	**-**	**0**	**51**	**261**	**522**
C. Gross additional charging posts required each year[23] (000s) = A + B	Household charging 1 plug per post	0	32	159	304	440	535	564	512
	Work charging 2 plugs per post	0	9	51	109	147	177	186	178
	Public charging 2 plugs per post	0	9	51	109	147	177	186	178
	Fast charging (highways) 3 plugs per post	0	0	0	1	1	1	2	2
	Total	**0**	**51**	**261**	**522**	**734**	**890**	**938**	**869**
D. Cost per charging post (€)[24]	Household charging 1 plug per post	1400	613	450	382	342	316	299	287
	Work charging 2 plugs per post	1800	788	572	480	429	397	375	361
	Public charging 2 plugs per post	7500	3285	2382	1998	1789	1655	1565	1504

[22] Assume all charging points are retired after 20 years since construction

[23] Figures in the table represent annual figures required. So, 2020 refers to additional posts required from 2019 to 2020.

[24] Assume a 10% learning rate (Cost of a post fall by 10% for a doubling of the stock of charging posts)

	Fast charging (highways) 3 plugs per post	40000	19800	13270	10983	9733	8923	8367	7982
E. Total annual investment requirements (€m) = (A + B) × D	Household charging 1 plug per post	0	20	71	116	150	169	169	147
	Work charging 2 plugs per post	0	7	29	52	63	70	70	64
	Public charging 2 plugs per post	0	30	122	217	262	293	292	268
	Fast charging (highways) 3 plugs per post	0	1	4	8	11	13	14	14
	Total	**1**	**58**	**227**	**393**	**486**	**545**	**544**	**492**
F. Total cumulative investment requirements (€m)	Household charging 1 plug per point	0	55	316	800	1493	2316	3182	3953
	Work charging 2 plugs per post	0	20	124	335	625	968	1327	1655
	Public charging 2 plugs per post	0	84	518	1395	2605	4034	5528	6896
	Fast charging (highways) 3 plugs per post	0	2	17	48	96	156	224	291
	Total	**1**	**160**	**975**	**2,579**	**4,819**	**7,474**	**10,260**	**12,795**