Greenpeace East Asia Tokyo Office

The macroeconomic and environmental impacts of decarbonising Japan's passenger car fleet

cambridge econometrics
clarity from complexity

Final Report

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Acronyms and Abbreviations

Table 0.1 sets out the acronyms and abbreviations commonly used in the report.

Table 0.1: Acronyms and abbreviations

	Abbreviation	Definition
Powertrain types		
Internal combustion engine	Petrol or diesel ICE vehicle	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 petrol or diesel ICE vehicles. Efficiency improvements cover engine options, transmission options, driving resistance reduction, tyres and hybridisation. Under our definition of a petrol or diesel ICE vehicle, hybridisation is limited to micro-hybrids with start-stop technology and regenerative braking.
Hybrid electric vehicle	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 petrol or diesel ICE vehicles).
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 internal combustion engine.
Fuel cell electric vehicle	FCEV	Fuel cell electric vehicles are mostly hydrogen fuelled vehicles, which include a fuel cell and a battery-powered electric motor.
Zero-carbon 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.
Other acronyms		
Carbon Capture and Storage	CCS	CCS is the technology that allows to capture CO_2 generated from large point sources before it enters the atmosphere. The CO_2 is then stored, for example in an underground geological formation.
Combined Heat and Power	CHP	CHP is a technology that generates electricity and captures the heat that would otherwise be wasted to provide thermal energy.
New European Driving Cycle	NEDC	Test cycle used for the certification of cars in Europe until September 2017.

Original equipment manufacturers	OEM	Equipment manufacturers of motor vehicles.
Million barrels of oil equivalent	MBOE	A unit of measuring oil volumes.
Worldwide harmonized Light vehicles Test Procedure	WLTP	Test cycle used for the certification of cars in Europe since September 2017.
Hydrogen refuelling station	HRS	Infrastructure for the dispensing of hydrogen for motor vehicles.
State of Charge	SOC	The level of charge of an electric battery relative to its capacity.

Executive Summary

This study assesses the macroeconomic and environmental impact of decarbonising passenger cars in Japan in the medium term (to 2030) and in the long term (to 2050). A scenario approach has been developed to envisage various possible vehicle technology futures, and then economic modelling has been applied to assess the impacts. The analytical work was carried out by Cambridge Econometrics, who worked in coordination with the Greenpeace East Asia Tokyo Office to assess the likely economic impacts and the transitional challenges associated with decarbonising the Japanese car fleet.

This technical report sets out the findings from the analysis. It provides details about the charging infrastructure requirements, technology costs and economic impacts of the transition to low-carbon mobility.

The study shows that a rapid transition to phase out internal combustion engine and hybrid vehicles by 2030, and replacing them with a fleet dominated by battery electric vehicles, will;

- Deliver rapid reductions in fossil fuel use, as well as reducing oil imports by up to around 4.8 billion barrels of oil equivalent by 2050.
- Achieve major emissions reductions compared to a ‘business as usual’ case, even taking into account the indirect emissions that are related to the generation of electricity. Tailpipe emissions are reduced by almost 99% in 2050 if ICE and hybrid vehicles are phased out by 2030, compared to baseline. Once emissions embedded in electricity generation are included, cumulative emissions from the vehicle fleet can be almost halved over the period to 2050 through the phase-out, if the electricity sector is decarbonised at the same time.
- Lead to beneficial economic outcomes in the medium- and long-term, with GDP over 1.2% higher than the baseline by 2050. The modelling shows that the price of electric vehicles falls to be lower than combustion engine and hybrid vehicles, and the costs of recharging via electricity are substantially lower than refuelling with fossil fuels, resulting in consumers spending less money on buying and running an electric car compared to an internal combustion engine vehicle. This reduces spending on imported fossil fuels and allows consumers to increase spending on other goods and domestic services.
- Create jobs across the economy, most notably in the services and manufacturing sectors. These jobs, in the manufacturing sectors as part of the supply chain for electric vehicles but also linked to higher consumer spending across the economy, will more than outweigh the jobs lost in the conventional motor vehicle industry and fossil fuels, with up to 300,000 additional jobs, mostly in the services sector, in the Japanese economy in 2050.
- Decarbonising the power sector at the same time as transitioning the vehicle stock leads to greater environmental benefits (as the emissions embedded in electricity generation are reduced), but moderates somewhat the socioeconomic impacts. GDP impacts are more strongly positive in early years, as a result of the greater investment required in low-carbon

electricity generation sources, although in the longer term GDP impacts, while substantially above baseline, are depressed slightly due to higher electricity prices than in the modelling which doesn’t assume the same transition in the power sector.

1 Introduction

1.1 Background

Japan’s standards for controlling emission levels of new passenger cars are among the most stringent in the world. Japan has a long history of applying fiscal incentives to reward vehicle fuel efficiency and that, combined with the innovative work of Japanese OEMs, means that Japan has one of the world’s most efficient passenger vehicle fleets.[1] Nevertheless, the transport sector was responsible for the 18% of total CO_2 emissions in Japan in 2017.[2]

Furthermore, Japan is lagging behind much of the rest of the developed world in terms of the take-up of low carbon vehicles. In the first half of 2020, pure battery electric vehicles (BEVs) were less than 1% of total sales in Japan, and it is estimated over the year as a whole that sales of BEVs and plug-in hybrid vehicles (PHEVs) actually fell compared to 2019, in contrast to all other major markets where BEVs increased their market share. Domestic BEV sales are dominated by the Nissan Leaf, but plug-in hybrid vehicles (such as the Toyota Prius Prime and the Mitsubishi Outlander PHEV) continue to play a major role in sales and are backed by the automotive industry and the Japanese government. Japanese vehicle manufacturers also continue to push fuel cell electric vehicles (FCEVs), such as Toyota’s Mirai. As a result, Japan currently has the largest network of hydrogen refuelling stations in the world.

Although the Japanese government has announced plans to ban the sales of conventional internal combustion engine vehicles from the mid-2030s, there is no current date for the phase-out of the sale of new plug-in hybrids, or even conventional hybrids (which do not have a plug). The government expects a drawn-out transition to electric vehicles, with hybrids playing a key role in ‘bridging’ the gap from internal combustion engine vehicles (petrol or diesel ICE vehicles) to zero-carbon vehicles.

The aim of this analysis is to explore the potential macroeconomic and environmental impact of decarbonising passenger cars in Japan; by comparing a rapid phase-out of sales of new non-zero carbon vehicles by 2030 against the ‘business as usual’ trajectory of phase-out of only new conventional petrol or diesel ICE vehicles in 2035. Specifically, the work will provide insight into the impacts on the domestic manufacturing industry (including relevant supply chains) and the Japanese economy more broadly.

1.2 Methodology

For this study, a set of scenarios were defined in which it was assumed that a certain low-carbon vehicle technology mix would be introduced and taken up in response to vehicle CO_2 emissions regulations. The particular factors affecting consumers’ decisions to purchase alternative vehicle technologies were not assessed.

The methodology involved two key stages:

1) Defining the scenarios and agreeing the key modelling assumptions

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[1] ICCT – Japan, accessed on 15/11/2021

[2] Transport and Environment in Japan 2020, accessed on 15/11/2021

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, vehicle prices, technology costs and the total vehicle cost of ownership and (ii) application of the E3ME model to assess the wider socio-economic effects of the low-carbon vehicle transition.

The two models that were applied in our framework are:

- Cambridge Econometrics' Vehicle Stock Model
- Cambridge Econometrics' E3ME model

The 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 new vehicle 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 by increasing uptake of fuel-efficient technologies. The vehicle stock model is highly disaggregated, modelling 5 powertrains, 6 fuels and two different size-bands (mini, ordinary & small)[3].

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 Japan) allows modelling of scenarios specific to Japan, 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 affects household incomes, trade in oil and petroleum, consumption, GDP, employment, CO_2, NO_x and particulates.

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

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

2 Overview of the Scenarios

2.1 Scenario design

The analysis presented in this report is based on a set of scenarios developed by Cambridge Econometrics in conjunction with Greenpeace, each assuming a different new vehicle sales mix. These represent a range of decarbonisation pathways and are designed to assess the impacts of a shift towards low carbon powertrains; they do not necessarily reflect current predictions of the future makeup of the Japanese fleet of passenger cars. Uptake of each kind of vehicle is by assumption: implicitly we assume that this change is brought about by policy, but do not model that policy. The three core scenarios modelled for this study are summarised in Table 2.1.

Table 2.1: Description of the three core modelling scenarios

Scenario	Scenario description
REF (Reference)	• No change in the deployment of efficiency technology or the sales mix from 2021 onwards. • Some improvements in the fuel-efficiency of the vehicle stock, due to stock turnover.
CPI (Current Policy Initiatives)	• Efficiency improvements and deployment of new powertrains. • Phase-out of the sale of new petrol or diesel ICE vehicles by 2035. • No further changes after the year 2035.
TECH 2030 Phase-out (High Technology, phase-out by 2030)	• Efficiency improvements and ambitious deployment of EVs, mostly BEVs. • Phase-out of the sale of new petrol or diesel ICE vehicles, HEVs and PHEVs by 2030.

These scenarios were chosen to explore different speeds of phase-out of non-zero carbon vehicles. The CPI scenario represents the current political discussions in Japan, as there is no target date for the phase-out of the sale of new hybrids and plug-in hybrids, only conventional petrol or diesel ICE vehicles. The ambitious TECH 2030 scenario then provides a comparison outlining what a more rapid, while still manageable, phase-out might look like, and is used to evaluate the socio-economic implications of such a move.

Alongside these core scenarios, the impacts of the scenarios under different future electricity systems were also explored. In the ‘Central’ power sector variant it is assumed that additional electricity demand is met through a mix of generation technologies similar to that used today in Japan, and in the ‘Decarbonised’ variant the impact of the passenger car transition is modelled under an assumption of a steadily decarbonising power sector. Electrifying passenger cars will increase emissions associated with power generation; the impact of this is explored in Chapter 7.

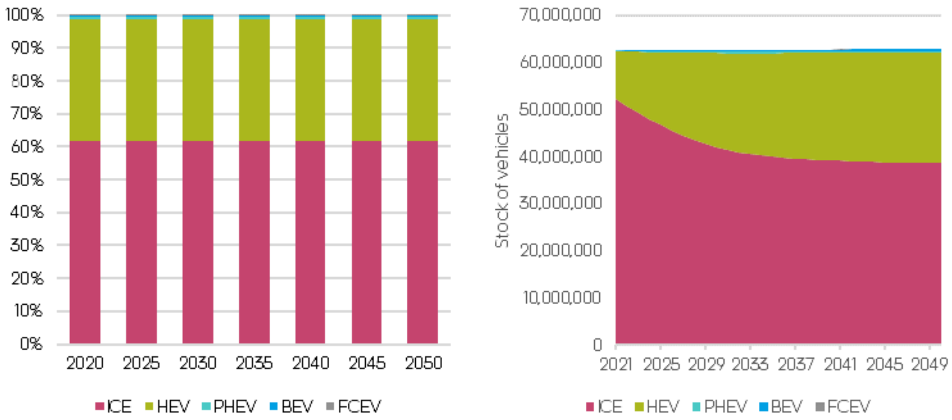
2.2 Vehicle sales and stock

In this section we outline the sales mix by powertrain deployed across each of the scenarios and vehicle size classes.

Reference scenario

In the REF scenario the dominance of petrol or diesel ICE vehicles remains in the whole projected period, however HEVs play a prominent role as they represent 37% of new sales. Although the sales mix does not change over time, the shares of HEVs increase in the Japanese stock due to stock turnover. HEVs share reaches almost 37% by 2040 (up from 14% in 2020) while BEVs remain insignificant in the fleet as they only represent 0.6%. Petrol or diesel ICE vehicles make up 62% of the stock in 2050, while PHEVs' and BEVs' shares stay below 1% as shown in Figure 2.1.

Figure 2.1: Sales mix (left) and stock composition (right) in the REF scenario

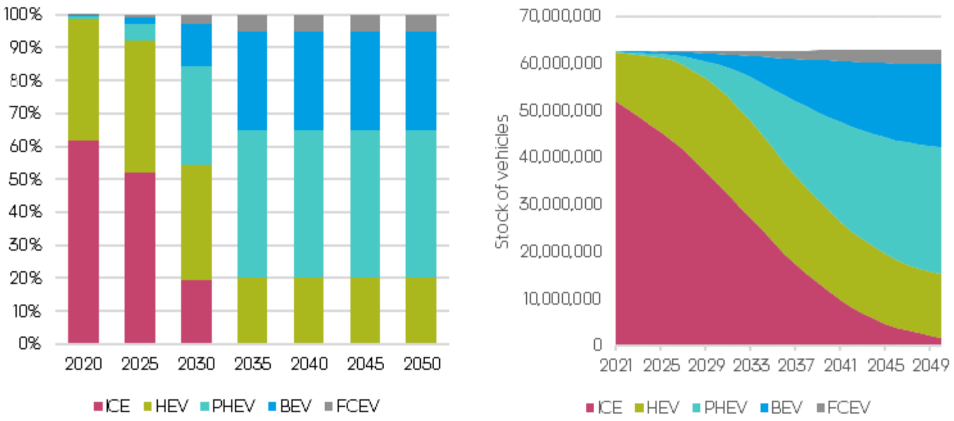


CPI scenario

The CPI scenario reflects the phase-out of the sale of new petrol or diesel ICE vehicles by 2035. To meet this target, a scenario was developed for new vehicle sales that assumes a more important role of PHEVs and BEVs. PHEVs rely less on new charging infrastructure than BEVs, thus, they are capable of 'bridging' the gap from petrol or diesel ICE vehicles to zero-carbon vehicles. The PHEV share of new vehicle sales increases to 30% by 2030, and to 45% by 2035. On the other hand, the penetration of BEVs is relatively slow, their share reaching only 30% by 2035. Since there are no emission targets announced beyond the mid-2030s (interpreted as 2035 in this scenario) in the passenger road transport sector, we assume no change after that point (see Figure 2.2). The penetration of PHEVs and BEVs into new sales translates into an 8% and a 3% share of the stock by 2030 respectively. By 2050 PHEVs represent 43% of the stock, the BEV share does not reach 30%, while FCEVs, used for longer distances, achieve 5%. In 2050 petrol or diesel ICE vehicles still represent a small fraction of the stock (almost 3%), as a small number of petrol or diesel ICE vehicles older than 15 years are still on the road.

It should be noted that this is our own interpretation of the existing government targets, which are lacking in detail, and may be more optimistic than the current policy ultimately delivers.

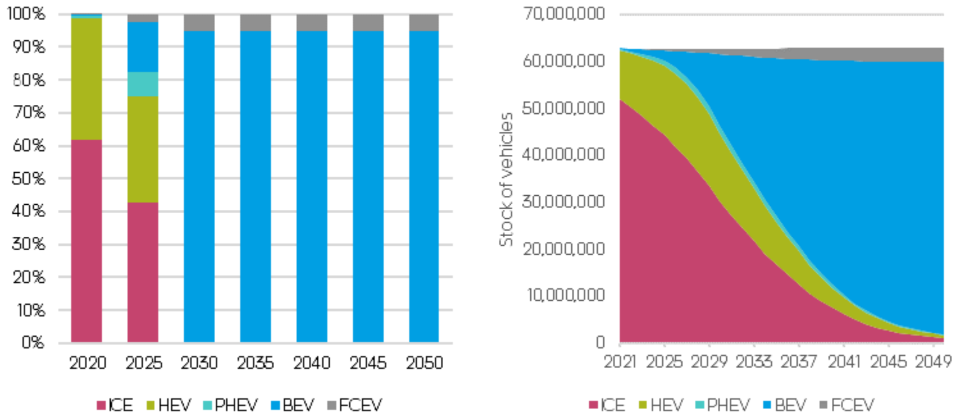
Figure 2.2: Sales mix (left) and stock composition (right) in the CPI scenario



TECH 2030 Phase-out scenario

Sales and stock in the TECH 2030 Phase-out scenario are shown in Figure 2.3 below. We assume a rapid increase in the share of advanced powertrains up to 2030 when petrol or diesel ICE vehicles are phased out of new sales. BEVs make up 95% of new sales from this date and FCEVs, mostly used to cover longer ranges, are the remaining 5%. After 2030, the sales mix remains constant, but the BEV share of the stock grows rapidly, reaching 93% by 2050 (up from 34% in 2030). Thanks to the early phase out of non-zero carbon vehicles, the share of petrol or diesel ICE vehicles falls to 1.4% by 2050.

Figure 2.3: Sales mix (left) and stock composition (right) in the TECH 2030 Phase-out scenario



2.3 Energy demand

The fuel demand stemming from use of the Japanese passenger car stock depends on its composition. Zero-carbon powertrains are more energy efficient, based on their test cycle performance reported by the Ministry of Land, Infrastructure, Transport and Tourism[4] of Japan and the Korea Energy Agency[5], while the CPI and TECH 2030 Phase-out scenarios also deploy additional energy efficiency technologies into new vehicles, and therefore these cars consume less energy (and ultimately, fuel including electricity and hydrogen). Figure 2.4 shows the combined effects of efficiency improvements and the deployment of zero-carbon powertrains on fuel consumption by the Japanese vehicle stock in each scenario. Annual fuel demand substantially

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[4] List of automobile fuel consumption, accessed on 16/11/2021

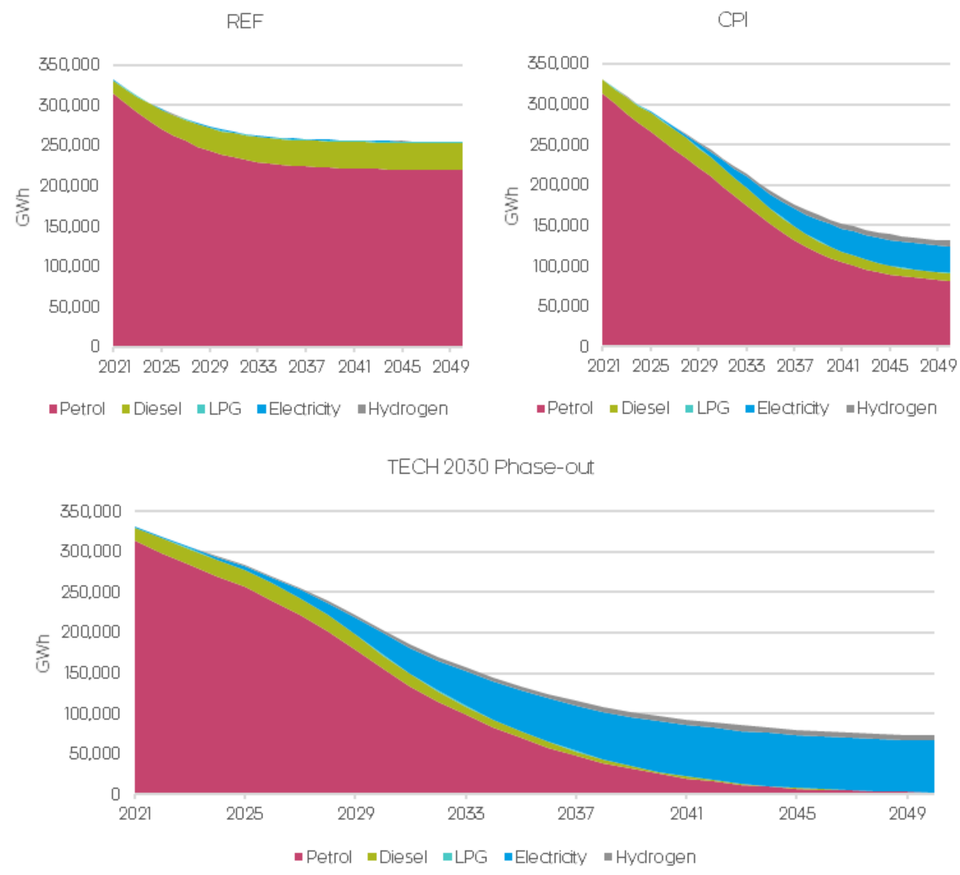
[5] Automotive energy consumption efficiency analysis books, accessed on 16/11/2021

decreases compared to the 2021 levels even in the baseline scenario (24% by 2035) due to the wider penetration of new HEVs into the stock and to the stock turnover as more efficient new vehicles replace the older ones. Nevertheless, after 2035 fuel demand stagnates as no further efficiency improvements are considered.

In the CPI and TECH 2030 Phase-out scenarios we see a substantial reduction in the total demand for fuel even after 2035. The reduction is mostly due to the fall in demand for petrol and diesel, with smaller increases in electricity consumption. By 2040 petrol and diesel demand decreases by 51% and 89% in the CPI and TECH 2030 Phase-out scenarios respectively, relative to the Reference scenario in 2040. The reductions further widen until 2050 when demand for petrol and diesel will have fallen by more than 99% compared to 2021 levels in the TECH 2030 Phase-out scenario and by 72% in the CPI scenario. Moreover, the more rapid phase-out of new petrol or diesel ICE vehicles, HEVs and PHEVs in the TECH 2030 Phase-out scenario translates to an almost 40% (3.2 million GWh) reduction in cumulative fuel demand throughout the projection period compared to the baseline scenario and to a 21% (1.3 million GWh) reduction compared to the CPI scenario.

Electricity and hydrogen demand grows in line with the rollout of BEVs and FCEVs. Due to the higher energy efficiency of these vehicles, their share of total energy demand is consistently lower than their share of the vehicle stock.

Figure 2.4 Demand of petrol, diesel, gas, hydrogen and electricity (GWh) by scenario



3 Modelling Assumptions

This section sets out the modelling assumptions underpinning the analysis.

The scenarios are defined by (i) the new sales mix by vehicle powertrain type, (ii) the uptake of fuel efficiency technologies, and (iii) the assumed policy targets. Key assumptions that are common to all scenarios are set out in Table 3.1. The subsequent sections provide information about our technology costs and deployment, battery costs, fuel cell vehicle and power sector assumptions.

3.1 Common modelling assumptions

Table 3.1: Key assumptions used in the vehicle stock model

	Details of assumptions used
Vehicle sales	• Historical sales data is taken from the statistics provided by the Japan Automobile Dealers Association and by Japan Light Motor Vehicle and Motorcycle Association. • Total new registrations are kept constant at 4.4 million vehicles sold per year, corresponding to the number of new cars sold in the year 2019, assuming that in 2021 new registrations reach the pre-COVID levels after the significant fallback in 2020.
Efficiency of new vehicles	• We used Japan-specific data on new petrol and diesel ICE vehicle efficiency from the Ministry of Land, Infrastructure, Transport and Tourism for 2006 to 2019. • We used data on new BEV and FCEV efficiency from the Korea Energy Agency for 2006 to 2019. • Future efficiency of new vehicles is endogenous to the vehicle stock model, based on assumptions about the vehicle powertrain and the energy efficient technologies that are installed in the vehicle, calculated using Ricardo-AEA's cost curve study for the European Commission.[6]
Mileage by age cohort	• Historical data on mileage by size of the car is taken from Nikkoken. • We assume that the average annual mileage falls gradually over the lifetime of a vehicle and varies depending on size and powertrain. To estimate how the annual mileage varies by fuel-type and as the vehicle ages, we relied on data from the TRACCS database.
Vehicle survival rates	• The survival rate curve is the key assumption for converting annual sales into a vehicle stock. This curve is defined as the % of vehicles from a given sales cohort that survive to a certain age. • The survival rate was derived from the number of registrations and deregistrations of cars by age in 2020 provided by the Automobile Inspection & Registration Information Association. The average age of passenger cars in the Japanese fleet in 2020 was 8.4. • The same survival rate is used for all powertrains and segments. We assume an average survival rate curve for all vehicle types and assume one survival rate curve across the whole-time period.
Fuel prices	• Historical data for fuel prices is taken from the Agency for Natural Resources and Energy. In their survey, fuel prices are broken down into prices for petrol and prices for diesel.

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[6] Ricardo -AEA (2016), Improving understanding of technology and costs for CO_2 reductions from cars and LCVs in the period to 2030 and development of cost curves

Hydrogen prices	• Hydrogen price projections are taken from the Hydrogen Council (2020) forecasts up to the year 2030, and thereafter we assume that the price remains constant, due to extensive uncertainty over the evolution of the hydrogen prices in this timeframe.
Value chains	• In all scenarios, we assume that Japan captures a consistent share of the vehicle value chain for conventional petrol or diesel ICE vehicles. • We assume that the assembly of battery modules and battery packs are part of the electrical equipment value chain. In the central scenarios, we assume that battery modules and battery packs for EVs are assembled in Japan proportionally to the share of electrical equipment demand that is currently met by domestic production.
Trade in motor vehicles	• We assume that the decarbonisation of transport is taking place at a similar pace across the rest of the world. • Therefore, there is no change in demand for Japanese motor vehicle exports.
Air quality	• Standards for NO_x and PM emissions of newly registered passenger cars by year of registration are taken from the Ministry of Land, Infrastructure, Transport and Tourism.

3.2 ICE efficiency gains

There remains a large number of measures that can be introduced to improve the efficiency of the internal combustion engine and transmission system, and many of the technologies that are already available can make a significant impact on fuel consumption in the 2021-2025 timeframe.

Table 3.2 and Table 3.3 below show the assumptions used on the uptake of fuel-efficient technologies for petrol or diesel ICE vehicles in the TECH scenario. This rollout builds on the deployments schedules that Ricardo AEA developed for the UK Committee on Climate Change. These deployments were used to create technology packages to represent a central deployment of technologies over time; technologies were grouped so that complementary changes are introduced side-by-side into new vehicles. The deployments then ensure that these technology packages are deployed into new sales over time in a way which improves the overall efficiency of new vehicles. We then tweaked the deployment of these packages to meet the specific ambitions of our scenarios. For example, complementary technologies which improve the efficiency of combustion in internal combustion engines are grouped into three categories (the first three rows of Table 3.2) – Level 1, Level 2 and Level 3. The level 1 package is deployed in around 80% of new vehicles in 2020, and we assume that this quickly increases to all new sales by 2030. However, Level 2 and Level 3 improvements cannot *both* be deployed into new vehicles, since they involve the same components of the engine being improved (but with Level 3 improvements being more expensive, and leading to greater energy efficiency gains, than Level 2). As such, only Level 2 *or* Level 3 improvements can be deployed in a given vehicle. We assume that Level 2 improvements are initially deployed in most vehicles (e.g. 82% of new vehicles by 2030), although as new vehicles are further improved in later years, Level 2 improvements are foregone in favour of Level 3 improvements – by 2050 78% of vehicles have Level 3 improvements, and only the remaining 22% have the Level 2 improvements.

Where applicable (e.g. for technologies and measures that affect the body of the car rather than the powertrain efficiency), the fuel-efficient technologies are also assumed to be installed in the same proportion of alternative powertrain vehicles.

Table 3.2 Deployment of fuel-efficient technologies in petrol ICE vehicles over the period to 2050 (as a share of all new vehicles)

Efficiency Technology	2020	2030	2050
Combustion improvements for engines: Level 1	80%	100%	100%
Combustion improvements for engines: Level 2	33%	82%	22%
Combustion improvements for engines: Level 3	0%	7%	78%
Direct injection - homogeneous	40%	36%	1%
Direct injection - stratified charge & lean burn	20%	54%	51%
Thermodynamic cycle improvements	1%	4%	47%
Cylinder deactivation	1%	2%	1%
Mild downsizing (15% cylinder content reduction) + boost	51%	27%	0%
Medium downsizing (30% cylinder content reduction) + boost	29%	60%	22%
Strong downsizing (>=45% cylinder content reduction) + boost	4%	13%	78%
Cooled low-pressure EGR	20%	60%	99%
Cam-phasing	60%	27%	0%
Variable valve actuation and lift	33%	73%	54%
Engine friction reduction: Level 1	65%	34%	0%
Engine friction reduction: Level 2	20%	66%	100%
Start-stop system	36%	17%	0%
Automated manual transmission (AMT)	25%	47%	2%
Dual clutch transmission (DCT)	6%	27%	20%
Continuously variable transmission (CVT)	3%	12%	78%
Optimising gearbox ratios / downspeeding	4%	2%	0%
Further optimisation of gearbox, increase gears from 6 to 8+	30%	64%	99%
Mild weight reduction (10% from the whole vehicle)	2%	1%	0%
Medium weight reduction (20% from the whole vehicle)	48%	34%	1%
Strong weight reduction (30% from the whole vehicle)	21%	66%	100%
Aerodynamics improvement 1 (Cd reduced by 10%)	20%	40%	2%
Aerodynamics improvement 2 (Cd reduced by 20%)	10%	36%	18%
Low rolling resistance tyres 1	2%	10%	81%
Low rolling resistance tyres 2	45%	36%	2%
Reduced driveline friction 1	37%	64%	99%
Reduced driveline friction 2	23%	20%	0%
Low drag brakes	28%	80%	100%
Thermal management	36%	47%	0%
Thermo-electric waste heat recovery	12%	53%	100%
Auxiliary (thermal) systems improvement	8%	27%	83%
Auxiliary (other) systems improvement	29%	60%	99%

Table 3.3 Deployment of fuel efficient technologies in diesel ICE vehicles over the period to 2050 (as a share of all new vehicles)

Efficiency Technology	2020	2030	2050
Combustion improvements for engines: Level 1	80%	100%	100%
Combustion improvements for engines: Level 2	33%	82%	22%
Combustion improvements for engines: Level 3	0%	7%	78%
Mild downsizing (15% cylinder content reduction) + boost	51%	27%	0%
Medium downsizing (30% cylinder content reduction) + boost	29%	60%	22%

Strong downsizing (>=45% cylinder content reduction) + boost	4%	13%	78%
Cooled low-pressure EGR	20%	60%	99%
Variable valve actuation and lift	33%	73%	54%
Engine friction reduction: Level 1	65%	34%	0%
Engine friction reduction: Level 2	20%	66%	100%
Start-stop system	36%	17%	0%
Automated manual transmission (AMT)	4%	2%	0%
Dual clutch transmission (DCT)	30%	64%	99%
Continuously variable transmission (CVT)	2%	1%	0%
Optimising gearbox ratios / downspeeding	48%	34%	1%
Further optimisation of gearbox, increase gears from 6 to 8+	21%	66%	100%
Mild weight reduction (10% from the whole vehicle)	20%	40%	2%
Medium weight reduction (20% from the whole vehicle)	10%	36%	18%
Strong weight reduction (30% from the whole vehicle)	2%	10%	81%
Aerodynamics improvement 1 (Cd reduced by 10%)	45%	36%	2%
Aerodynamics improvement 2 (Cd reduced by 20%)	37%	64%	99%
Low rolling resistance tyres 1	23%	20%	0%
Low rolling resistance tyres 2	28%	80%	100%
Reduced driveline friction 1	36%	47%	0%
Reduced driveline friction 2	12%	53%	100%
Low drag brakes	8%	27%	83%
Thermal management	29%	60%	99%
Thermo-electric waste heat recovery	0%	4%	25%
Auxiliary (thermal) systems improvement	32%	87%	100%
Auxiliary (other) systems improvement	20%	53%	91%

3.3 Vehicle costs

Our cost assumptions for the improvements mentioned above are based on Ricardo-AEA (2015).

The costs in Table 3.4 are taken from the latest Ricardo-AEA (2015) datasets developed for the European Commission. Table 3.4 summarises the main technologies included and the associated energy savings and cost increase.

Table 3.4 Technology Energy Savings and Cost

Efficiency Technologies	Energy saving	Production Cost ($2021)	
		Mini car	Ordinary & Small car
Combustion improvements for engines: Level 1	2-3%	77	77
Combustion improvements for engines: Level 2	2-3%	16	17
Combustion improvements for engines: Level 3	2-7%	611	611
Direct injection - homogeneous	5%	277	277
Direct injection - stratified charge & lean burn	7-11%	570	750
Thermodynamic cycle improvements	13-25%	689	698
Cylinder deactivation	2-3%	303	303
Mild downsizing (15% cylinder content reduction) + boost	2-3%	126	166
Medium downsizing (30% cylinder content reduction) + boost	2-7%	214	315

Strong downsizing (>=45% cylinder content reduction) + boost	8-10%	505	582
Cooled low-pressure EGR	2-3%	133	143
Cam-phasing	4%	95	100
Variable valve actuation and lift	1-7%	266	280
Engine friction reduction: Level 1	1-2%	68	68
Engine friction reduction: Level 2	3-3%	128	128
Start-stop system	1-2%	152	174
Automated manual transmission (AMT)	1-2%	498	498
Dual clutch transmission (DCT)	1-2%	527	562
Continuously variable transmission (CVT)	2-3%	1,027	1,027
Optimising gearbox ratios / downspeeding	1-5%	93	93
Further optimisation of gearbox, increase gears from 6 to 8+	3-9%	176	176
Mild weight reduction (10% from the whole vehicle)	5-7%	46	60
Medium weight reduction (20% from the whole vehicle)	11-12%	279	361
Strong weight reduction (30% from the whole vehicle)	17-19%	1,176	1,528
Aerodynamics improvement 1 (Cd reduced by 10%)	3-4%	62	64
Aerodynamics improvement 2 (Cd reduced by 20%)	5-7%	195	202
Low rolling resistance tyres 1	2-4%	44	51
Low rolling resistance tyres 2	5-8%	123	130
Reduced driveline friction 1	1%	33	33
Reduced driveline friction 2	2%	147	147
Low drag brakes	1%	84	84
Thermal management	2%	257	257
Thermo-electric waste heat recovery	2-3%	743	743
Auxiliary (thermal) systems improvement	2-3%	155	164
Auxiliary (other) systems improvement	2-3%	234	252

Note(s): Costs are mass manufacturing cost

3.4 Battery costs and range

Definitions

A key input to the modelling of EV cost is the battery pack size (kWh). Future battery pack sizes will depend both on future reductions in battery costs and Original Equipment Manufacturer (OEM) design choices to balance vehicle driving ranges against cost based on customer preferences. Currently, the smallest batteries for BEV cars are around 30 kWh, whereas the largest range up to 100 kWh. OEM statements suggest that ordinary & small size BEVs will target driving ranges of 300km or more. Taking these trends into consideration, Table 3.5 shows the assumed battery pack sizes for PHEV and BEV passenger cars between 2021 and 2050.

Table 3.5: Battery pack size assumptions

Battery sizes (kWh)					
Powertrain	**Market segment**	**2021**	**2030**	**2040**	**2050**
PHEV	Mini	7.0	6.3	5.6	4.9
PHEV	Ordinary & Small	10.0	9.0	8.0	7.0
BEV	Mini	45.0	45.0	45.0	45.0
BEV	Ordinary & Small	60.0	60.0	60.0	60.0

We have used different assumptions for PHEVs and BEVs on changes in battery capacity. For PHEVs, it is assumed that OEMs maintain an electric driving range of approximately 50km (ordinary & small sized vehicle), and decrease pack sizes over time as vehicle 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 and vehicle 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.

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. There are four key areas of battery technology where breakthroughs could happen:

- 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 150 kW+ with no impact on battery state of health

According to estimates by Bloomberg New Energy Finance (BNEF), the price of lithium-ion batteries in 2020 was $137/kWh – a drop of 89% since 2010 (BNEF, 2021)[7]. Price decreases between 2010 and 2020 are in part due to technology improvements and economies of scale. Battery pack prices are predicted to continue to drop in the future, but at a slower pace than in previous years.

All of the considered scenarios use a single battery cost projection based on BNEF (2021), according to which battery prices will fall further to about $58/kWh by 2030. Given the absence of projections up to 2050, we do not assume further price changes after the year 2030; this likely leads to a pessimistic view of future battery prices post-2030. Table 3.6 shows the projected battery system costs for PHEVs and BEVs.

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[7] BNEF (2021), Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh.

Table 3.6: Assumed battery system costs

Battery system costs ($2021/kWh)					
Powertrain	Market segment	2020	2030	2040	2050
HEVs, PHEVs, BEVs	All	126	54	54	54

The costs presented in Table 3.6 refer to both the battery and the battery system (pack), but not to the electric drive powertrain; costs for the latter are shown in Table 3.7. The costs are lower per kWh for a larger battery than a small battery.

Table 3.7: Electric powertrain costs (motor, inverter, booster) ($2021)

Powertrain	Market segment	2020	2030	2040	2050
PHEV	Mini	1,034	932	842	762
PHEV	Ordinary & Small	1,164	1,050	948	858
BEV	Mini	1,034	932	842	762
BEV	Ordinary & Small	1,164	1,050	948	858

Overall, the total battery system and powertrain costs are shown in Table 3.8 for each of the different market segments based on the derived battery size.

Table 3.8: Total cost of electric powertrain and battery ($2021)

Powertrain	Market segment	2020	2030	2040	2050
PHEV	Mini	1,922	1,271	1,143	1,026
PHEV	Ordinary & Small	2,434	1,534	1,378	1,234
BEV	Mini	6,748	3,351	3,261	3,181
BEV	Ordinary & Small	8,782	4,275	4,173	4,083

Battery range

State of Charge (SOC) assumptions (Table 3.9) are applied to derive the usable 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, under the Worldwide Harmonised Light Vehicles Test Procedure)[8].

Table 3.9: Battery usable State of Charge (SOC)

Battery usable SOC for electric range (%)					
Powertrain	Market segment	2020	2030	2040	2050
PHEV	Mini	70%	72%	74%	75%
PHEV	Ordinary & Small	70%	72%	74%	75%

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[8] The projected efficiency under the NEDC are converted to WLTP equivalent as per the conversion of each efficiency measure given in Ricardo-AEA (2015). Starting conversion factors for 2015 were sourced from ADAC EcoTest laboratory results. The difference in kWh/km between NEDC and WLTP is typically around 5%.

BEV	Mini	85%	90%	90%	90%
BEV	Ordinary & Small	85%	90%	90%	90%

Table 3.10: Vehicle range in full electric mode

All electric range (km – WLTP)					
Powertrain	Market segment	2020	2030	2040	2050
PHEV	Mini	47	47	45	46
PHEV	Ordinary & Small	52	52	50	51
BEV	Mini	300	342	361	412
BEV	Ordinary & Small	308	350	371	424

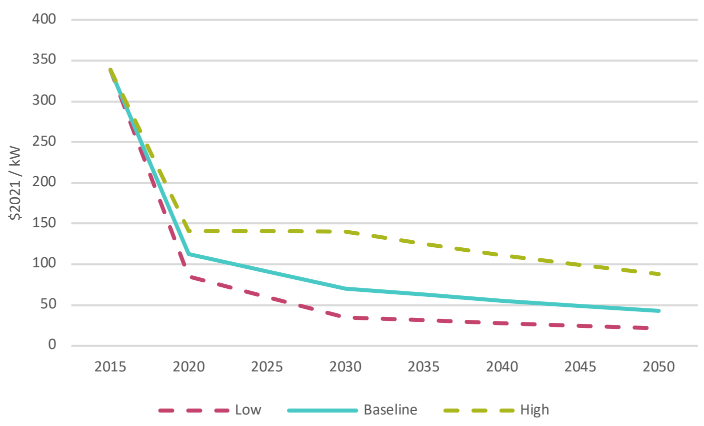
3.5 Fuel cell vehicle assumptions

The assumptions regarding FCEVs (e.g. fuel cell system costs, hydrogen tank costs, driving range, system power outputs and hydrogen production costs) build on work carried out by Element Energy for several national hydrogen mobility initiatives, as well as the cross-cutting Hydrogen Mobility Europe (H2ME) demonstration project funded by the Fuel Cells and Hydrogen Joint Undertaking. They are based on aggregated and anonymised data provided by technology suppliers and vehicle manufacturers, data from real-world deployments and published data from the national hydrogen mobility initiatives and academic research.

Fuel cell system and hydrogen tank costs

The two largest components influencing the costs of FCEVs are the fuel cell system and the high-pressure hydrogen tank. Future values for these costs are subject to significant uncertainty, since they depend greatly on improvements at a technology level (for example reducing the precious metal content in the stack) and substantial increases in manufacturing volumes. In our analysis we adopt conservative price projections for these; however, recent news from the industry suggests that market for fuel cell system may develop more rapidly due to the improvements to the lifetime of fuel cells. For current costs, representing very low production volumes, fuel cell costs of $113/kW are assumed as a central estimate.

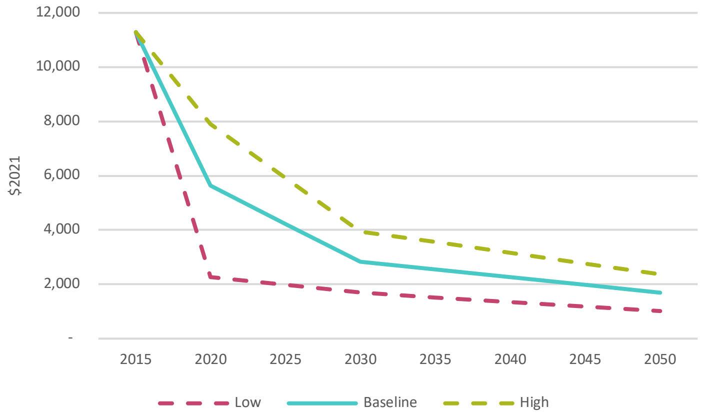
Figure 3.1: Current and projected costs of fuel cell systems ($2021)



In 2021 and beyond, significant cost reductions in fuel cell systems are expected due to technology improvements and increasing production volumes. Future assumptions are based on the EU Powertrains Study and the UK's Hydrogen Technology Innovation Needs Assessment (TINA) carried out by Element Energy and the Carbon Trust. These costs would result in a 100kW fuel cell system costing $5,000-6,000 by 2030.

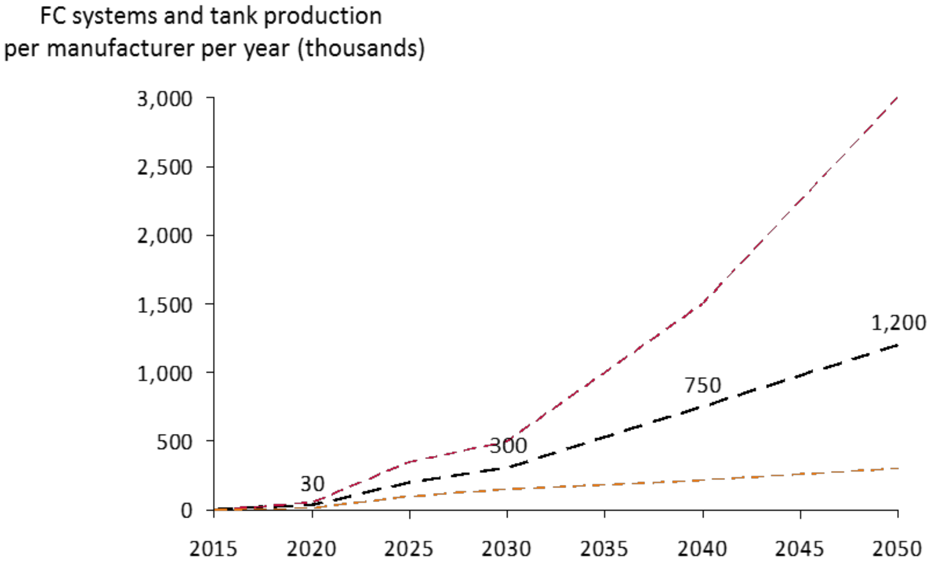
Figure 3.2 shows the expected cost progression of hydrogen tanks. These are based on the UK TINA and bilateral discussions with vehicle manufacturers. Like fuel cell costs, significant cost reductions are expected as manufacturing volumes increase, with a reduction of at least 50% relative to today's prices by 2030.

Figure 3.2: Hydrogen tank cost projections for full power fuel cell electric passenger cars ($2021)



Low and high estimates of fuel cell and hydrogen tank trends (from the TINA) are also provided for use in sensitivity analysis, reflecting higher and lower sales volume assumptions from system manufacturers as shown in Figure 3.3.

Figure 3.3 Assumed growth in global automotive fuel cell systems (units per manufacturer per year)



Driving range and system power outputs

The average FCEV driving range between refuelling events is currently around 500 km, which is higher than current generation battery electric vehicles. Range assumptions and the assumed motor and fuel cell powers are shown below in Table 3.11. As fuel cell costs decrease and fuel efficiency improves, vehicle manufacturers may choose to increase vehicle range, or reduce hydrogen tank sizes while keeping the range constant. This also applies to fuel cell and motor powers, where manufacturers can trade off increased power (and hence increased performance) with cost reduction for a given performance. These decisions will depend on perceived customer needs as well as technology progression. A similar trade-off exists for range-extended fuel cell vans, where the relative sizes of the battery and fuel cell stack can be optimised, based on the future rates of cost reduction in each technology.

As a simplifying assumption, motor/fuel cell powers are assumed to remain constant throughout the study timeframe. This is consistent with manufacturers favouring cost reduction to improve total cost of ownership relative to conventional vehicles, rather than 'spending' technology improvements on better performance. Fuel tank sizes are assumed to remain constant and therefore any fuel efficiency improvements result in an increased driving range. This increase in range is similar to a recent Hyundai prototype (Nexo, 609 km range), and also reflects the need to provide similar operating range to diesel cars and maintain an operational advantage compared with battery electric vehicles for long range duty cycles (with charging time less than 5 minutes for a FCEV).

Table 3.11 Modelling assumptions for hydrogen vehicle range and power outputs of drive motors and fuel cell systems

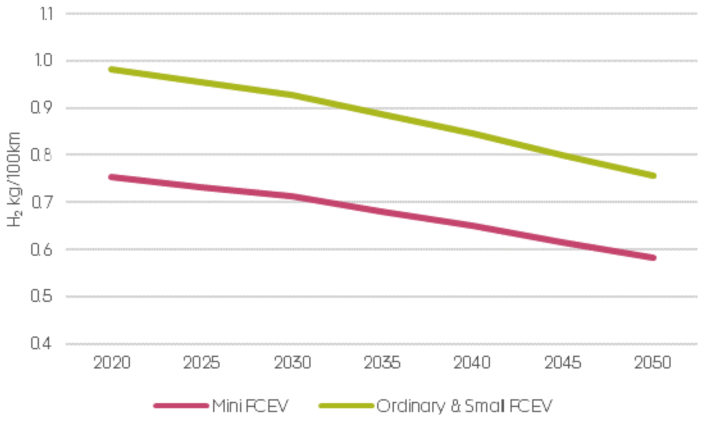
Market segment	Year	Driving range (km)	Electric motor power (kWh)	Fuel cell system power (kWh)
Mini	2020	399	70	70
Mini	2050	515	70	70
Ordinary & Small	2020	509	100	100
Ordinary & Small	2050	662	100	100

Hydrogen fuel consumption

Fuel consumption assumptions for FCEV were sourced from historical estimates provided by the Korea Energy Agency (using Korea as the closest proxy to Japan for which data was available) for the year 2019. The future evolution of fuel consumption values is endogenously calculated in the vehicle stock model. Fuel consumption is expected to decrease in future model generations, partly due to increasing fuel cell efficiency but also through efficiency savings at a vehicle level such as weight reduction or improved aerodynamics.

Figure 3.4 presents the assumed evolution of fuel consumption for mini, and ordinary & small FCEVs used in this study. Fuel consumption levels fall steadily over time, reflecting increased efficiency.

Figure 3.4 Fuel consumption assumptions for mini, and ordinary & small FCEVs (H_2 kg/100km)



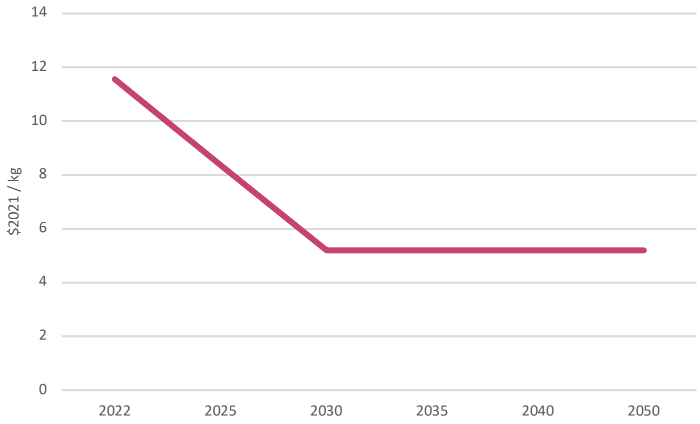
The price of hydrogen

The production of hydrogen is expected to increase substantially, driving down the price globally. Currently there are two major technologies to produce hydrogen: Steam Methane Reforming (SMR) and electrolysis. While SMR has significantly lower costs, the related carbon dioxide emissions are substantial. However, emissions can be reduced by around 90% through carbon capture and storage (CCS) technologies. Hydrogen generated by steam methane reforming with CCS is labelled as blue hydrogen. Hydrogen production through electrolysis using renewable electricity on the other hand has no CO_2 emissions.

Figure 3.5 shows the projected average retail price of hydrogen of the Hydrogen Council (2020). These hydrogen prices include all the production ($2.2/kg cost in 2030), preparation, distribution, and fuelling station costs of the hydrogen supply chain. Forecasts are only up to the year 2030, thus, thereafter we assume that the price remains constant, due to extensive uncertainty over the evolution of the hydrogen prices in this timeframe. In fact, hydrogen prices are likely to further decrease beyond 2030 – but without firm quantitative published estimates we have adopted a conservative assumption. Since FCEVs represent only a small fraction of the passenger car fleet, the socioeconomic analysis is not substantially affected by this conservative view.

Although the price projections are not specific to Japan, in this study we base our hydrogen price assumptions on the analysis of the Hydrogen Council (2020) as we consider their short term price projection of $13.15 feasible.

Figure 3.5 Hydrogen price projections of the Hydrogen Council (2020) ($2021 / kg)



3.6 Power sector assumptions

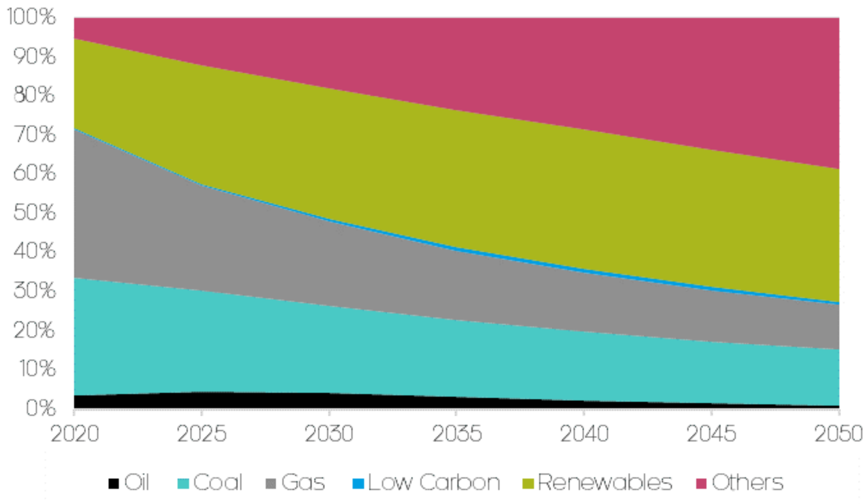
The structure of the power sector, and the renewable content of electricity generation in particular, has important implications for the results of the study:

- It determines the net environmental impact of the electrification of the vehicle fleet;
- It affects the economic and employment impacts of the transition.

Power sector structure

In this study, we consider two scenarios for the evolution of the power sector in Japan up to the year 2050. These scenarios are developed in our power sector model, FTT:Power. The model generates projections for the future power system based on diffusion dynamics and relative prices of the different technologies; in order to model the different scenarios, varying input assumptions are introduced to alter the path of technological deployments in the sector. This also has socio-economic implications, as set out in Chapter 7; different generation mixes can lead to different end-user prices for electricity. Due to the iterative nature of the model, although our scenarios are informed by existing publications, the power sector modelled in FTT:Power is not a perfect replica of those publications – instead we have introduced assumptions which lead to outcomes which are broadly in line with those published elsewhere.

Figure 3.6: Annual electricity generation by source (as a % of total generation) in the Central scenario



In the ‘Central’ scenario, the power generation mix is based broadly on the Sixth Basic Plan for electricity, published in September 2021, with the result that the generation mix does not substantially vary over the projected period, as represented in Figure 3.6[9]. Therefore, this scenario does not assume explicit decarbonisation of the power sector.

In contrast, in the ‘Decarbonisation’ scenario, we assume a power generation mix that is broadly in line with the Renewable Energy Institute’s 2030 and 2050 decarbonisation plans[10]. In this power sector scenario additional policies will be introduced in Japan to phase-out electricity generation from fossil fuels

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[9] The category ‘Others’ include electricity generated from Nuclear, fuel cells, and CHP plants.

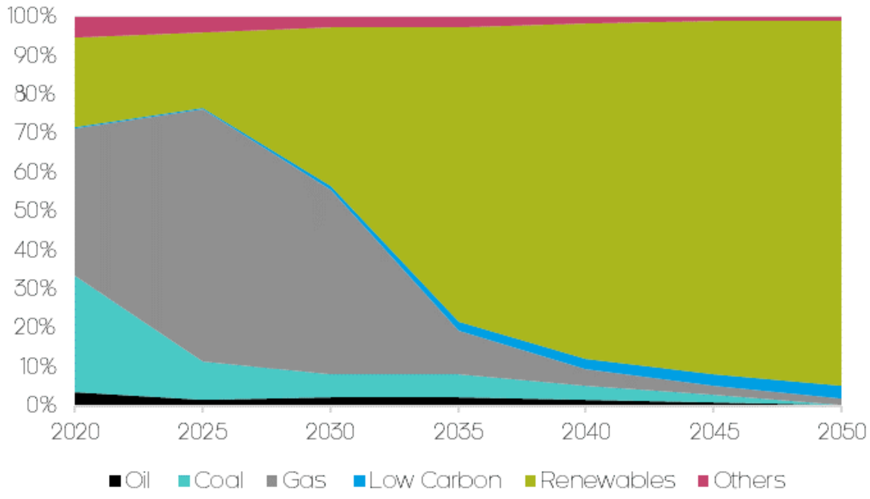
[10] Whilst the figures used for the ‘Decarbonisation’ scenario are based upon proposals by the Renewable Energy Institute, they do vary and include elements such as nuclear and CCUS, unlike the original proposal.

(coal, oil, and natural gas) by 2050. The electricity generation mix therefore radically changes over the period, as showed in Figure 3.7.

Renewables play crucial role in the decarbonisation of electricity generation, while nuclear (classified as part of 'Others') continues to decline throughout the period. However, there is a small fraction of generation that is not met by renewables, but by other dispatchable 'Low Carbon' sources. This could be covered by the importing of electricity via interconnectors, or low carbon fuels (such as hydrogen for use in grid fuel cells) or, probably least desirably, the use of CCS technologies.

As the power sector undertakes a transition to renewable sources in the 'Decarbonisation' scenario, this directly influences the economic and employment impacts of the considered scenarios in the road transport sector. These impacts are presented in more detail in Chapter 7.

Figure 3.7: Annual electricity generation by source (as a % of total generation) in the Decarbonisation scenario



4 Infrastructure Requirements

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

4.1 EV infrastructure

Definition and costs for EV charging points

We adopt the definitions and costs for charging points as presented in this section. These definitions and costs were sourced from recent literature (e.g., Cambridge Econometrics and CE Delft) and agreed upon to reflect the Japanese market.

Table 4.1 represents the range of available charge points to end users and illustrates the characteristics and costs of charging posts. Within each 'archetype', significant variation in price and features would be expected to occur in the real world.

Table 4.1: Charging post definitions and costs

Main application	Charging point features	Power (kW)	Charge time - 45kWh battery (approx.)	Cost ($2021)
				Production & Installation
Residential	Wall box One plug	3 kW	15 hours	1,501
Workplace	Ground mounted Two plugs	7 kW	6.4 hours	3,725
Parking (on-street and shopping centres)	Ground mounted DC fast charger	50 kW (25 Kw for 2 chargers)	54 minutes (1.8h for 25 kW)	35,557
Rapid chargers on motorways site	DC super-fast charger	150 kW (75kW for 2 chargers)	18 minutes (36 minutes for 75kW)	75,207

Residential charging posts

For the residential sector, we consider a wall box with a power of 3 kW as standard option, allowing slow recharge of the vehicles overnight. This solution is sometimes offered through OEM dealerships either with an OEM branded charging point or through a partnership with an independent provider. In some instances, consumers will choose not to install a wall box and simply charge their EVs from a standard socket to avoid paying capacity charges.

For residential sites with no access to a private driveway or garage, solutions are similar to a private domestic charging point with the addition of options for metering electricity and controlling access to authorised users. In the workplace, we consider a ground mounted charging post at company parking lots with a power of 7 kW, allowing a slow recharge over working hours.

Public charging posts

For public stations in public places such as on street parking spaces, dedicated car parks, and retail car parks, a ground mounted DC fast charger with a power of 50 kW (or 25 kW for two chargers) is assumed. The choice of the installed power will depend on parameters such as parking time (the longer the customers typically spend in a retail market, the lower the kW can be while still able to provide valuable range) and connection costs.

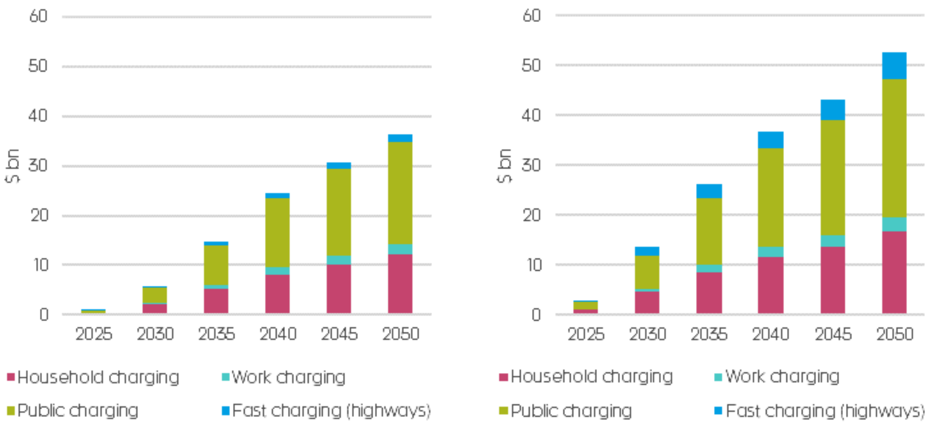
Rapid charging sites

For stations on motorways, a DC super-fast charger of 150 kW (alternatively, 75 kW for two chargers) is assumed, allowing for a full recharge between 18 and 36 minutes for a BEV with a 45 kWh battery pack. High power rates are necessary to maintain acceptable charging times for vehicles with large batteries.

Financing of EV charging posts deployment

The additional charging requirements in each year are 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 per doubling of cumulative charging capacity, meaning that as the total capacity of installed chargers doubles, the cost of additional chargers comes down by 10%. We expect production costs to decrease due to advancements in manufacturing techniques and economies of scale. The actual cost is therefore dependent on the uptake scenario modelled. Figure 4.1 shows the estimated cumulative investment requirements to support the EV fleet in the CPI and TECH 2030 Phase-out scenarios.

Figure 4.1 Cumulative investment requirements to support the EV fleet in the CPI (left) and TECH 2030 Phase-out (right) scenarios ($2021)



We assume that all private infrastructure (household and work charging points) are paid for upfront by the consumer when the vehicle is purchased. This is either explicit (e.g., consumers paying for chargers installed on their private property) or implicit (OEMs installing chargers as part of vehicle purchase and adding an appropriate premium to the purchase price of the vehicle to cover this cost). Investment in public infrastructure and rapid charging points is assumed to be paid for by owners of shopping centres, car parks and motorway service stations. We assume that these costs are fully passed on to customers: the cost of infrastructure in shopping centres and motorway services is ultimately paid for by an increase in prices for consumers in wholesale and retail markets.

Finally, we make the simplifying assumption that site owners or private businesses install the chargers without the financial aid offered by public subsidies. This does not have a large bearing on the economic results. Instead, if we had assumed that the public charging posts are publicly financed, then to balance the government budget in the scenario, tax rates would have to be raised elsewhere, and the cost would still ultimately be borne by businesses and consumers.

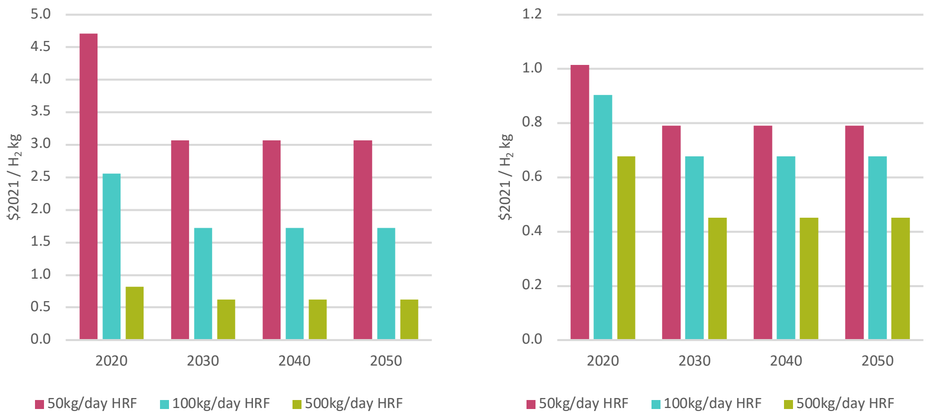
4.2 Hydrogen infrastructure

Refuelling station costs

Fuel cell vehicles are refuelled by hydrogen refuelling stations, dispensing high pressure gaseous hydrogen into the vehicles’ on-board storage tanks. The main elements of a hydrogen refuelling station (HRS) are a compressor, hydrogen storage, pre-cooling/refrigeration equipment and dispensers. The exact configuration of an HRS, in terms of its size, the pressure of primary and buffer storage and dispensing rate per hour, varies according to the station supplier and the intended use.

HRS costs in this study are based on three different station sizes (50, 100 and 500 kg per day), dispensing 700 bar hydrogen and meeting the performance specifications set out in the SAE J2601 international standard. Cost assumptions for the stations are drawn from the ‘Fuelling Italy’s Future’ study and are presented below. Figure 4.2 shows the assumed capital and fixed operating costs for each HRS dispensing 700 bar hydrogen.

Figure 4.2 Capital (left) and fixed operating costs of hydrogen refuelling stations ($2021 / H_2 kg dispensed)



Costs are also shown per kilogram of capacity, assuming a 20-year lifetime, 7% cost of capital and a utilisation factor increasing over time to 75%. These costs are appropriate for hydrogen stations receiving hydrogen deliveries by truck, or from an on-site electrolyser. The costs for the electrolyser itself are included in the production cost section.

Both capital and fixed operating costs are expected to decrease over the period to 2030 due to design improvements, increased manufacturing volumes and more efficient supply chains. However, we assume that the technology reaches maturity at this point, and costs are kept constant afterwards. By 2030, capital costs represent a relatively small proportion of the expected hydrogen selling price, particularly for the larger station sizes. Hence, possible breakthroughs in HRS design that lead to much lower costs than predicted here -while beneficial particularly in terms of reducing capital investment for the early network - do not strongly affect the overall economics of hydrogen refuelling.

Fixed operating costs for HRS are shown in Figure 4.2. Significant cost reductions are expected in future, due to more efficient supply chains, use of local labour for maintenance rather than engineering teams from the equipment supplier, and increased component lifetimes. Again, costs beyond 2020 are a relatively small proportion of the overall hydrogen cost structure, which is dominated by the cost of the hydrogen itself. This is similar to the cost structure for conventional petrol stations, and unlike that of electric charging points, whose capital costs are high in proportion to the value of the electricity supplied.

Deployment of hydrogen infrastructure

The future rate of deployment of HRS in the Japanese market for hydrogen is strongly linked to the roll-out of FCEVs, particularly the step change in sales driven by lower cost, second generation vehicles beyond 2020. In this study, the number of stations in Japan (and implied capital and operating costs) is directly linked to the projected uptake of fuel cell vehicles across scenarios and to the expected volume of vehicles that can be supported per refuelling station. To model the uptake of HRS, we have assumed an initial deployment based only on refuelling stations of reduced size (between 50 and 100 kg / day) which will be gradually phased-out after 2030 to the advantage of stations with larger capacity (500 kg / day).

Besides defining the relative roll-out of each type of HRS, we estimated the total number of HRS that can support the fleet of FCEV consistently with a series of density assumptions. Specifically, we assumed a ratio of 100 FCEVs per 50 kg / day HRS in 2030 increasing to 150 by 2050, a ratio of 250 FCEVs per 100 kg /day HRS in 2030 increasing to 300 by 2050, and a ratio of 1,250 FCEVs per 500 kg / day HRS in 2030 increasing to 2,000 by 2050.

Table 4.2 provides an overview of the hydrogen infrastructure deployment in the TECH 2030 Phase-out scenario resulting from our assumptions, including the densities covering the projected period.

Table 4.2: Number of HRS calculation breakdown in the TECH 2030 Phase-out scenario

Variable	Type	2020	2030	2040	2050
Vehicle stock (000s)	All	62,816	62,557	62,757	62,806
Vehicle stock (000s)	FCEVs	4	1,143	2,663	3,076
Share of vehicle stock	FCEVs	0.0%	1.8%	4.2%	4.9%
Infrastructure density (FCEVs per HRS)	50 kg / day	100	100	150	150
	100 kg / day	200	250	300	300
	500 kg / day	1,000	1,250	1,500	2,000
Total number of HRS	50 kg / day	42	142	19	-
	100 kg / day	-	226	49	-
	500 kg / day	-	495	1,492	1,500
	Total	**42**	**863**	**1,560**	**1,500**

Financing refuelling station deployment

The number of additional hydrogen refuelling stations in each year, in line with the projected deployment of 50 kg /day, 100 kg / day, and 500 kg / day HRS, is multiplied by the projected capital costs per station (see Figure 4.3) in each year to derive the annual investment requirements needed to support the FCEV fleet in the scenarios. Figure 4.3 shows the cumulative investment requirements over the projected periods in the CPI and TECH 2030 Phase-out scenarios.

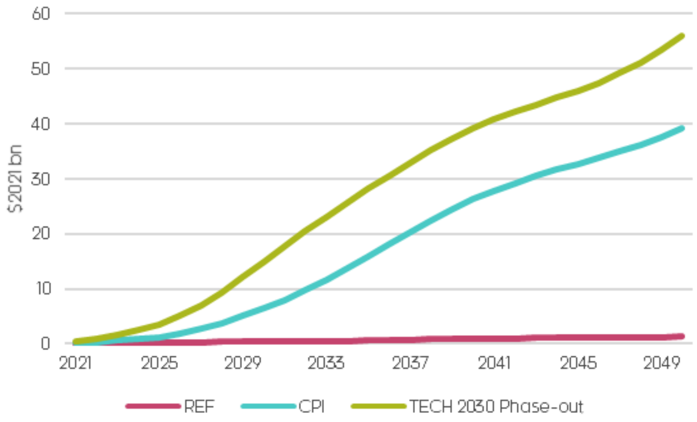
Figure 4.3 Cumulative investment requirements to support the FCEV fleet in the CPI (left) and TECH 2030 Phase-out (right) scenarios

As in the case of public and rapid EV charging infrastructure, we assume that the upfront costs of hydrogen infrastructure, paid by the host site initially, are ultimately fully passed on to customers. The cost of infrastructure in shopping centres and motorway services is ultimately paid for by an increase in prices for consumers in wholesale and retail markets. However, the number of stations deployed in the considered scenarios has minimal effect on the macroeconomic modelling given the small numbers in relation to the overall car stock.

4.3 Total cumulative investment in infrastructure

Figure 4.4 below shows the cumulative infrastructure investment requirements by scenario from 2021 to 2050. In the TECH 2030 Phase-out scenario the rapid deployment of the required infrastructure is essential to enable the penetration of BEVs into the fleet. The cumulative infrastructure investment in the TECH 2030 Phase-out scenario reaches $56 billion by 2050, while in the CPI scenario it is more than $39 billion. Since the deployment of advanced powertrains is much smaller in the CPI and Reference scenarios investment in infrastructure is less substantial (around $1.3 billion in the Reference scenario).

Figure 4.4 Total cumulative investment in infrastructure by scenario ($2021)



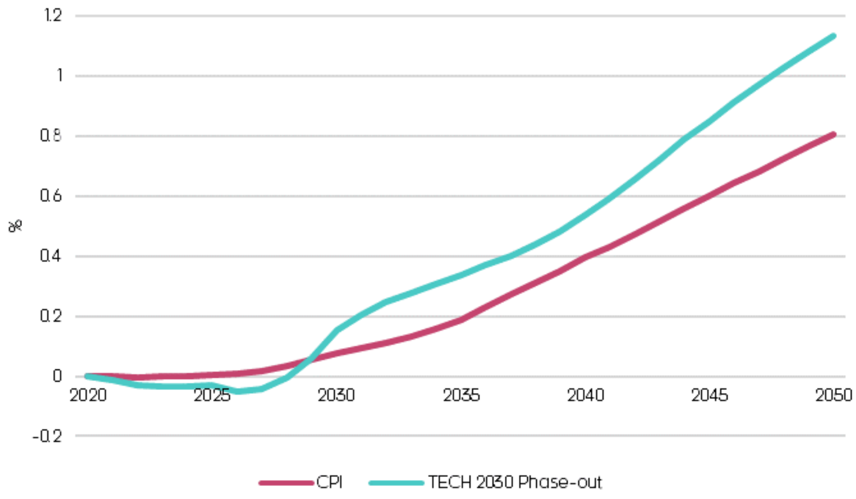
5 Socioeconomic Impacts

The economic impacts of decarbonising Japan's passenger vehicles, compared to a reference scenario (REF) in which cars remain unchanged from today, and a current policy initiatives (CPI) scenario, were modelled using E3ME. The economic outcomes outlined in this section represent the impacts of decarbonising the passenger vehicles on the Japanese economy. This is based on the 'Central' view of the power sector scenario where the power generation mix does not substantially vary over the projected period.

5.1 Real GDP impacts

The evolution of economic impacts (compared to the reference case) shows different paths in the CPI and TECH 2030 Phase-out scenario. In the CPI scenario there is a steady increase in GDP over the projection period due to the gradual shift in spending away from imported oil and towards a higher capital content in vehicles and spending on decarbonised fuels. Although oil imports decrease by more in the TECH 2030 Phase-out scenario, the higher cost of BEVs raises prices for consumers and depresses real incomes and spending in the early years. It diverts spending towards the value chain for manufacturing vehicles and their component parts and away from other sectors of the economy.

Figure 5.1 GDP results relative to the Reference scenario



Nevertheless, by 2030 the TECH 2030 Phase-out scenario outperforms the CPI scenario in terms of GDP (see Figure 5.1). In the TECH 2030 Phase-out scenario, the vehicle fleet is more efficient (due to the higher proportion of more energy efficient BEVs, and the specific fuel-efficiency technologies that are introduced into all different powertrains being sold), and this lowers the amount that consumers have to spend on fuels, and substantially reduces expenditure on fossil fuels. Since fossil fuels are imported, when that spending is instead shifted to domestically produced electricity (for BEVs) and other consumption categories, this reduces leakage from the Japanese economy, improving the balance of trade and increasing domestic economic activity, which leads to further positive multiplier effects within the economy.

A summary of the main economic indicators is presented in Table 5.1.

Table 5.1: Macroeconomic indicators

	CPI	TECH 2030 Phase-out
2030 Impacts		
GDP (%)	0.1%	0.1%
Employment (000s)	18	29
Oil Imports (%)	-4.5%	-12.9%
CO_2 emissions from passenger cars ($mtCO_2$)	-8.3	-23.4
	CPI	**TECH 2030 Phase-out**
2050 Impacts		
GDP (%)	0.8%	1.1%
Employment (000s)	200	281
Oil Imports (%)	-22.8%	-35.4%
CO_2 emissions from passenger cars ($mtCO_2$)	-39.4	-60.9

The scale of the long-term economic impacts is uncertain, depending on a number of factors: the cost of vehicles and low-carbon technologies (including EV batteries); the location of vehicle supply chains, and future oil, hydrogen and electricity prices, to name a few. However, the dominant impact arises from the reduction in oil imports. This is evident in the macroeconomic results in which the GDP impacts tend to follow oil imports in the CPI and TECH 2030 Phase-out scenarios. From 2030 onwards, the ambitious TECH Phase-out scenario yields the greatest economic benefits in terms of the impact on both GDP and employment, which comes mostly from the substantial reduction in oil imports. In other words, the TECH 2030 Phase-out scenario has the largest overall benefits and CO_2 emissions are substantially lower as well.

Note that these scenarios do not consider explicitly the impact of changing demand in the rest of the world; for example, if Japanese vehicle demand was following the REF or CPI trajectory (where domestic vehicle sales continue to be dominated by combustion engine vehicles), but demand in the rest of the world was shifting in favour of battery electric vehicles, it's likely that demand for exports from the Japanese motor vehicle industry would be reduced, lowering GDP, but these effects are not quantified.

5.2 Employment

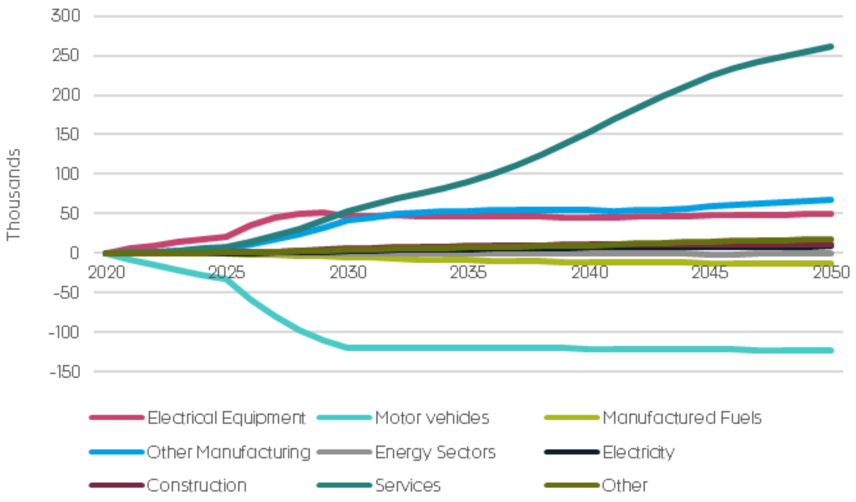
The pattern of impacts on employment, while related to the output impacts, are somewhat different. To assess the impact on employment, we also need to take account of the different employment intensities in the various sectors that are affected, as well as potential wage effects.

The trend towards greater automation in the auto industry is expected to reduce the number of jobs, even ignoring the effects of a low-carbon transition. This trend will be exacerbated by a switch towards BEVs. Building BEVs is less labour intensive than building the gasoline and diesel vehicles they will replace, while building hybrids and plug-in hybrids is expected to be more labour intensive. Previous modelling from Cambridge Econometrics (*Fuelling Europe's Future*) showed that the net employment impact for the auto sector from the transition depends on the market shares of these various technologies, and the degree to which they are imported or produced domestically.

Figure 5.2 shows the evolution of jobs in Japan as a result of the transition to low-carbon cars in the TECH 2030 Phase-out scenario, relative to the reference case. There is a net increase over time in employment in manufacturing sectors, linked the manufacture of more complex vehicles, and a substantial increase in services employment, which arises as a result of lower mobility costs in later years allowing consumers to shift expenditure into the consumption of other goods and services.

By contrast, employment in the motor vehicle sector steadily decreases until 2030 in the TECH 2030 Phase-out scenario. The net impact on motor vehicle sector jobs is negative because petrol or diesel ICE vehicles and hybrids are increasingly replaced by BEVs, which have different supply chains (as seen by increased employment in electrical equipment and other manufacturing), and are simpler to build and therefore generate fewer traditional motor vehicle jobs.

Figure 5.2 The employment impact per sector of the transition to low-carbon cars (TECH 2030 Phase-out compared to REF)



Employment impacts within the motor vehicle sector are an important issue. The benefit of using a macroeconomic modelling approach is that it allows us to assess the economy-wide impacts of this transition. For the low-carbon transition to be successful, care will need to be taken to support those who lose their jobs in technologies that are phased out. Managing the switch in the motor vehicles industry, to ensure a "just transition", should be a key focus of policy, particularly against an overall background of increasing automation.

The largest number of jobs are created in services. These primarily come about as a result of the low cost of mobility. As the purchase price of BEVs falls and their maintenance and fuelling costs are significantly lower, the total cost of ownership of BEVs becomes lower than a petrol or diesel ICE vehicle. Consequently, consumers are spending less on transport, which frees up household income to be spent on other goods and services. We assume that when consumers achieve a cost saving, they spend that money on other goods and services, in line with their existing expenditure. Essentially, we assume that consumers' propensity to spend/save is not changed as a result of lower prices of some goods in the economy. Reflecting existing spending patterns, a large proportion of this reallocated money is then spent on consumer services, such as hotels & restaurants, increasing demand and creating jobs. There are further service jobs created in business services through supply chains to other parts of the economy, but these are secondary in scale compared to addition jobs in consumer services.

5.3 Fossil fuel imports

Japan has negligible fossil-energy resources and relies almost entirely on imported fuels and domestically produced nuclear power. Thus, fossil fuel imports play a crucial role in the Japanese energy mix.

By 2040, in the CPI scenario, annual fossil fuel imports are reduced by around 142 mboe compared to the Reference scenario. Under a more rapid phase-out of petrol or diesel ICE vehicles, by 2030, import reductions are more pronounced, and in the TECH 2030 Phase-out scenario the equivalent reduction is 249 mboe. By 2050, the reduction in annual fossil fuel imports compared to the Reference case increases to 277 mboe in the TECH 2030 Phase-out scenario (Figure 5.3).

Figure 5.3 Annual fossil fuel import savings (mboe difference from REF)

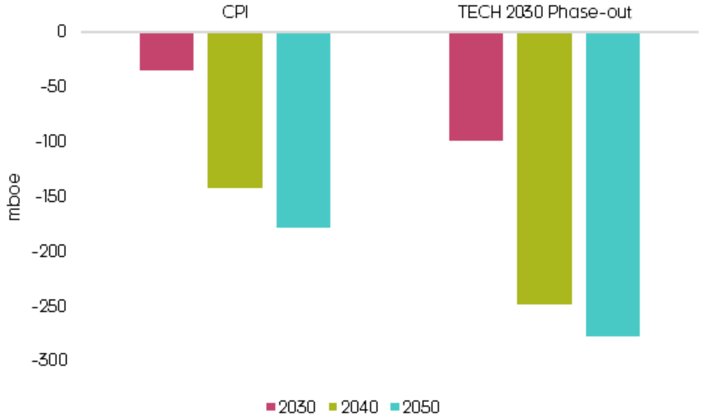
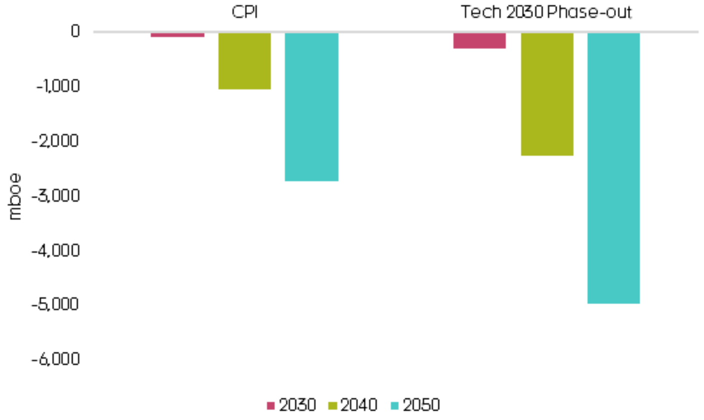


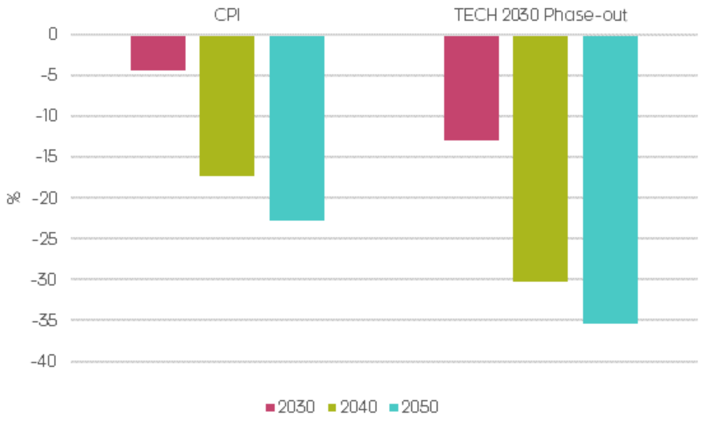
Figure 5.4 Cumulative fossil fuel import savings over time (mboe difference from REF)



This will lead to cumulative fossil fuel import savings of around 2,749 mboe by 2050 in the CPI scenario and 4,974 mboe reduction in the TECH 2030 Phase-out scenario (see Figure 5.4).

Focusing on oil, the import savings are substantial. In the CPI scenario annual oil import savings remain below 23% as HEVs and PHEVs partly fuelled by gasoline are still dominant in 2050. However, the dynamic transition to electricity from gasoline and diesel reduces the demand for oil, thus, in TECH 2030 Phase-out scenario annual oil import decreases by more than 35% by 2050 compared to the baseline scenario. Consequently, the deployment of advanced powertrain cars reduces the dependency on oil of the Japanese economy.

Figure 5.5 Annual oil import savings (% difference from REF)



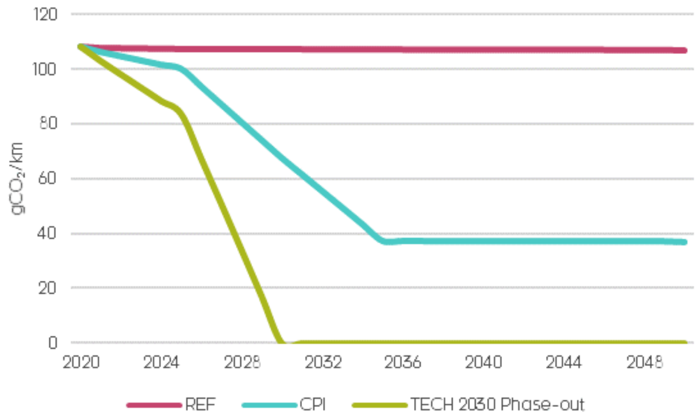
6 Environmental Impacts

6.1 Impact on tailpipe CO_2 emissions

Average emissions

The evolution of average CO_2 emissions for new cars in each scenario are shown in Figure 6.1. In the TECH 2030 Phase-out scenario tailpipe emissions rapidly decrease after 2025 and achieve zero after the phase out of non-zero carbon vehicles in 2030. Nevertheless, average CO_2 emissions of new cars in the CPI scenario only decrease to 37gCO_2/km by 2035 and remain unchanged for the rest of the projection period. The decarbonisation of new vehicles is not achieved in the CPI scenario as HEVs and PHEVs are not emission-free vehicles and currently there is no target date for their phase-out.

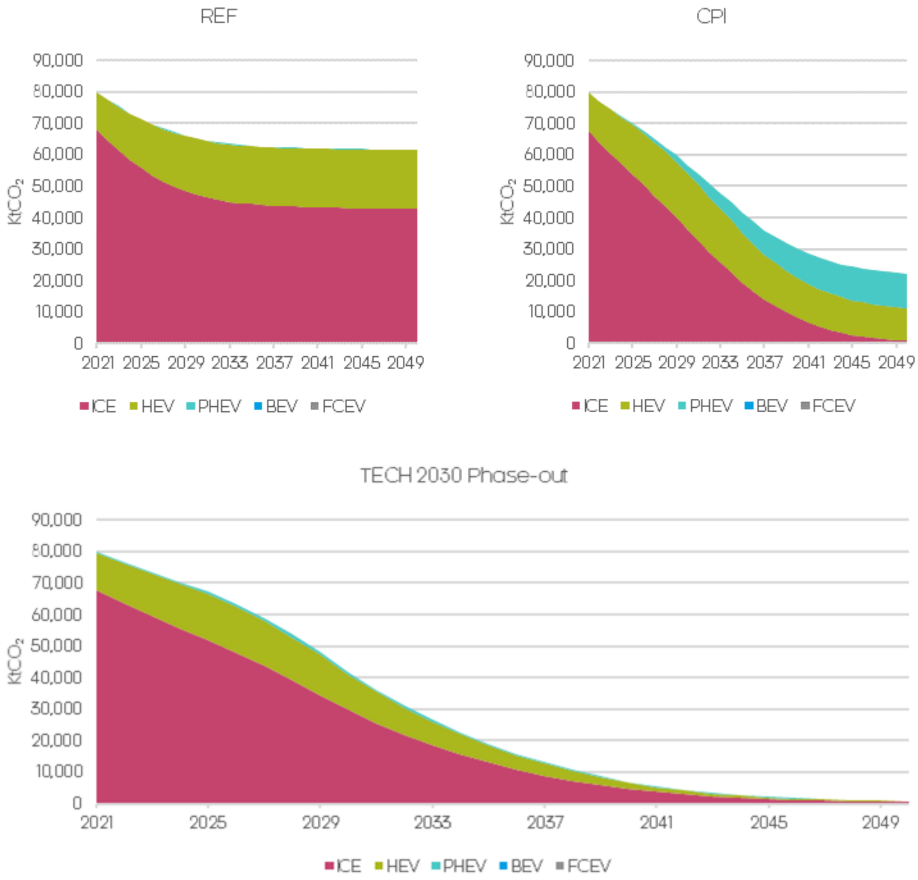
Figure 6.1: Average CO_2 emissions of new cars (gCO_2 / km)



Annual stock CO_2 emissions

Tailpipe emissions of new cars fall to zero after the phase-out in the TECH 2030 Phase-out scenario; however, the tailpipe emissions of the total vehicle stock come down much more slowly, as it takes time for remaining petrol or diesel ICE vehicles to leave the stock. Nevertheless, in the TECH 2030 Phase-out scenario the stock is almost emission-free. Annual CO_2 emissions of the stock are reduced by almost 99% with a phase-out in 2030 compared to the baseline scenario by 2050 (Figure 6.2). This is due to the low number of veteran petrol or diesel ICE vehicles and HEVs remaining in the stock that are not scrapped. In addition, tailpipe emissions in 2050 are significantly lower (by 97%) even compared to the CPI scenario where new petrol or diesel ICE vehicles are phased out by 2035.

Figure 6.2 Average stock tailpipe CO_2 emissions ($KtCO_2$)



6.2 Impacts on emissions of particulate matter and nitrogen oxides

Particulate matter (PM_{10}) and nitrogen oxides (NO_x) emitted from road transport have a substantial impact on local air quality with harmful consequences for human health in many urban centres. The reduction of both pollutants is a substantial co-benefit of decarbonising passenger cars.

In the CPI scenario, particulate matter emissions (PM_{10}) from vehicle exhausts are cut from around 705 t per year in 2020 to around 278 t in 2050 (see Figure 6.4) and NO_x emissions from vehicle exhausts are cut from 32,722 t in 2020 to 8,031 t in 2050 (see Figure 6.3). Nevertheless, in the TECH scenarios both values fall by 99%, almost eliminating all harmful PM_{10} and NO_x emissions. This is mainly achieved by the transition away from petrol and diesel vehicles towards zero-carbon electricity and hydrogen.

It is worth noting that the particulate emissions that we model only refer to *tailpipe* emissions. While substantial, they are only one source of local air pollutants from road transport. The largest source of emissions of particulates from road transport is tyre and brake wear and road abrasion which have been shown to account for over half of total particulate matter emissions.

Figure 6.4 PM_{10} emission reductions from baseline in 2020 by scenario

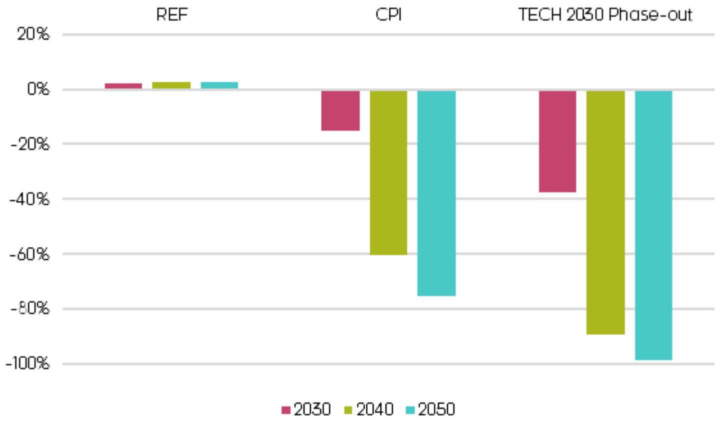
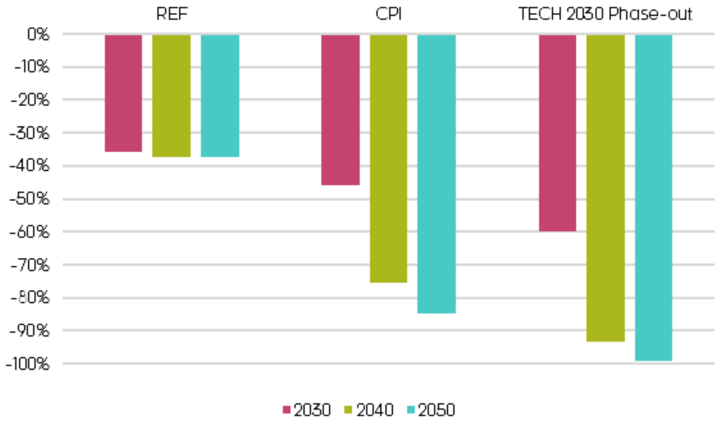


Figure 6.3 NO_x emission reductions from baseline in 2020 by scenario



7 Impacts under a decarbonised power sector

7.1 Emissions associated with the consumption of electricity

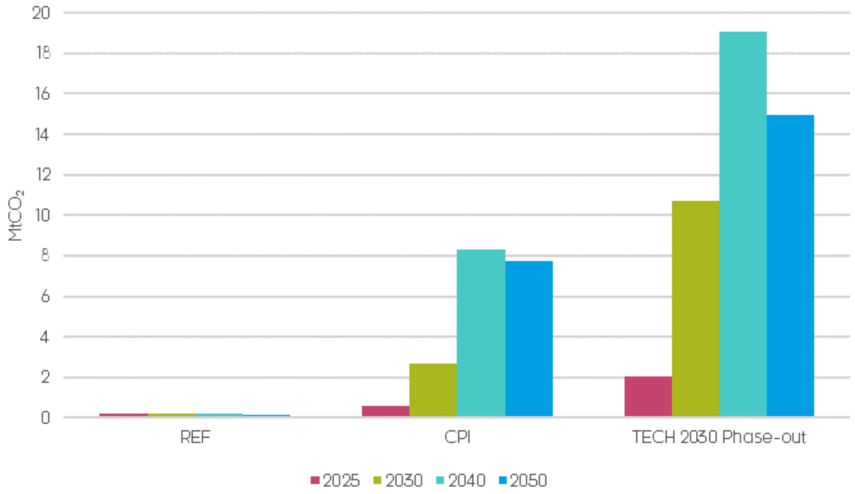
By considering the evolution of the power sector, and the role played by fossil fuel and low-carbon sources of electricity, it is possible to calculate the indirect emissions associated with the use of electricity in electric vehicles, in addition to the tailpipe CO_2 emissions of petrol or diesel ICE vehicles. In this section we estimate the indirect CO_2 emissions associated with the production of the electricity used as fuel by the PHEV and BEV cars in the Japanese stock.

As presented in Section 3.6, two electricity generation mixes are considered. In the first, 'Central' case, the absence of ambitious decarbonisation policies leads to a power mix which relies partially on fossil fuels. The share of coal in electricity generation is still almost 15% while natural gas' is 12% of generation in 2050. In the 'Decarbonised' scenario, electricity is sourced from an increasingly decarbonised grid, with electricity increasingly being produced from renewables. The rapid deployment of renewable energy sources results in almost 94% of electricity coming from renewables in 2050 in this scenario.

The decarbonisation of the power sector has a major impact on the emissions footprint of EVs, since the penetration of EVs substantially increases the electricity consumption of the vehicle fleet. Although the tailpipe emissions of BEVs are zero, if the electricity is not zero-carbon then the well-to-wheel emissions that include the emissions associated with the generation of electricity can still be significant.

Figure 7.1 and Figure 7.2 present the indirect emissions for each passenger car sales mix scenario with the 'Central' and in the 'Decarbonised' power sector mixes. The indirect emissions in the REF scenario are very small due to the low number of EVs in the stock, while in the CPI and TECH 2030 Phase-out scenarios the annual emissions peak in 2040 and then decreases to 7.7 $MtCO_2$ and 14.9 $MtCO_2$ by 2050, respectively, under the less ambitious 'Central' power generation mix. However, in the 'Decarbonised' power sector

Figure 7.1 Annual indirect CO_2 emissions by scenario ('Central' power sector scenario)



scenario emissions are very small, even in the later years of the TECH 2030 Phase-out scenario. By relying on renewables in the power sector, the annual indirect emissions of an EV-dominated fleet of passenger cars peak as early as 2030 and emissions can be reduced by almost 9 $MtCO_2$ by 2050 compared to the 'Central' scenario.

Figure 7.2 Annual indirect CO_2 emissions by scenario ('Decarbonised' power sector scenario)

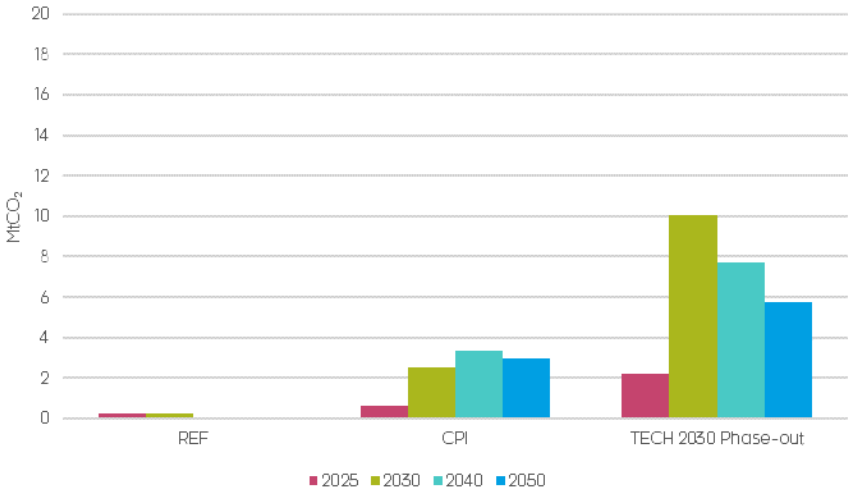
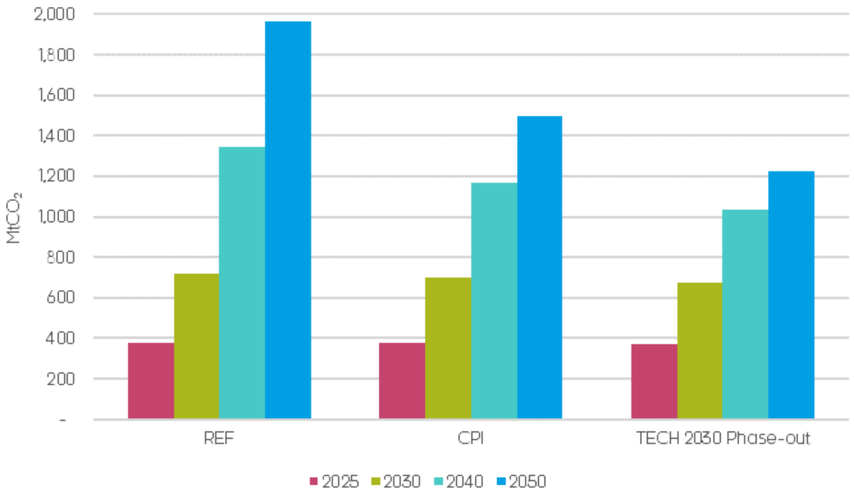


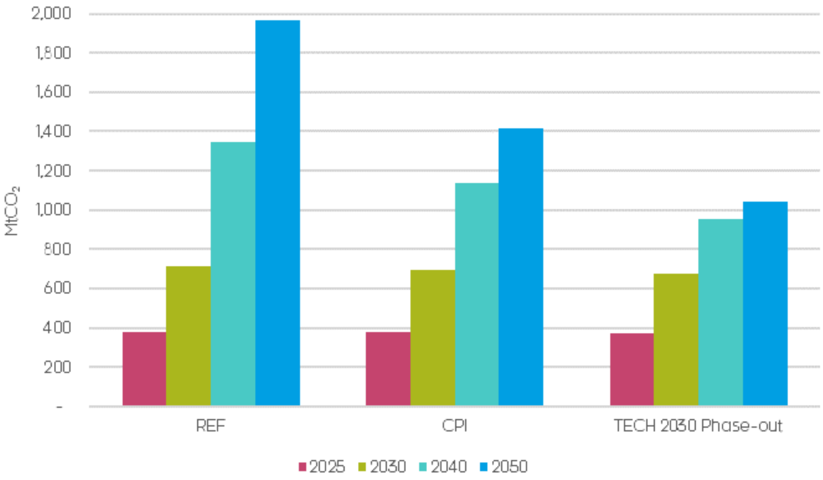
Figure 7.3 shows the cumulative well-to-wheel CO_2 emissions of the vehicle stock under the REF, CPI and TECH 2030 Phase-out scenarios in the 'Central' scenario for the power sector, expressed in $MtCO_2$. It shows that, even when considering emissions associated with power generation for transport fuels from a non-decarbonised power sector CO_2 emissions are significantly lower in TECH 2030 Phase-out scenario than the REF and CPI case over the period to 2050. Since the increase in indirect emissions is small, it is more than compensated by the reductions in direct (tailpipe) emissions.

Figure 7.3 Cumulative CO_2 well-to-wheel emissions by scenario ('Central' power sector scenario)



When considering a progressively decarbonised electricity system, the overall reduction in the well-to-wheel emissions compared to the baseline becomes even more substantial, as depicted in Figure 7.4. By decarbonising the power sector, the emissions associated with passenger cars further decrease by more than 183 $MtCO_2$ compared to the 'Central' power mix, when considering the most rapid deployment of BEVS under the TECH 2030 Phase-out scenario.

Figure 7.4 Cumulative CO_2 well-to-wheel emissions by scenario (‘Decarbonised power sector scenario)



7.2 Economic impacts with a decarbonising power sector

In this section we assess the economic impacts of decarbonising Japan’s passenger vehicles in a scenario where the power sector is decarbonised in both the baseline and the TECH 2030 Phase-out scenario. This way we can assess the overall impact of decarbonisation on the electrification of the passenger car market.

When considering the ‘Decarbonised’ scenario for the power sector, the overall economic impacts are similar to those seen in the ‘Central’ scenario (repeated below, but as also shown in Section 5). Phasing out the sale of petrol or diesel ICE cars by 2030 has positive impacts on both the GDP and employment. In 2030 the impacts on GDP and employment are slightly larger in a decarbonised electricity sector, reflecting higher investment in low-carbon generation technologies; however, by 2050, the economic impacts are more moderate than in the ‘Central’ scenario. This occurs because decarbonised electricity is slightly more expensive, resulting in less money being reallocated away from fuelling (electric) vehicles and towards consumer services – while jobs are created in the electricity sector, this is less labour intensive than the service sector, so the net increase in jobs is smaller (see Table 7.1).

Although it is not included in the current analysis, the decarbonisation of the power sector can have further positive impacts on the Japanese economy. This is due to the benefit stemming from investment in low carbon and renewable technologies in power generation. The increased investment activity and the lower fossil fuel imports boost domestic demand, output and employment leading to positive economic results.

Table 7.1: Macroeconomic indicators with a decarbonising power sector

	TECH 2030 Central power mix	TECH 2030 Decarb power mix
2030 Impacts		
GDP (%)	0.1%	0.2%
Employment (000)	29	42
2050 Impacts		
GDP (%)	1.1%	0.7%
Employment (000)	281	219

8 Conclusions

This study assessed the potential benefits of decarbonising passenger vehicles in Japan.

The analysis showed that the phase-out of non-zero carbon cars is both economically and environmentally desirable, and that the more rapidly this is achieved, the greater the potential benefits. The technology transition of the TECH 2030 Phase-out scenario yields substantial net positive economic outcomes, which is made possible by the reduction in spending on imported oil as well as less overall spending by households on car ownership, and more on other goods and services. Furthermore, lowering Japan’s dependence on imported oil, and replacing it with domestically generated electricity, can improve its energy security.

In addition to the greater GDP impact of the TECH 2030 Phase-out scenario, the earlier phase-out of petrol and diesel cars leads to substantially greater CO_2 emissions reductions. The penetration of EVs also improves local air quality, leading to substantial improvements in human health outcomes.

We also compared the socioeconomic and environmental impacts under different assumptions about the future of Japanese electricity generation. While the environmental benefits are greater under a decarbonised grid, the macroeconomic impacts of the transition are more moderate in the longer run, as a result of slightly higher electricity prices.

This analysis demonstrates that there are substantial benefits, both economic and environmental, that can result from a rapid phase-out of the sale of combustion engine vehicles and their replacement with a fleet of more efficient vehicles dominated by battery electric vehicles; and that the long-term implications of the transition for the economy are small but positive. However, the small net changes in the economy do include larger sectoral changes, and it will be necessary to manage the changes in sectoral employment, e.g. by providing training opportunities so that fossil fuel workers can re-train to find jobs in the low-carbon economy of the future.

9 Appendices

Appendix A E3ME model description

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

A.1 Policy decisions that can be informed by the models

E3ME is often used to assess the impacts of climate mitigation policy on the economy and the labour market. The basic model structure links the economy to the energy system to ensure consistency across each area.

Possible policies to assess include:

- Carbon and energy taxes
- Emission trading systems
- Environmental tax reforms
- Energy efficiency programmes
- Subsidies for particular technologies in the power, transport and residential sectors
- Phase-outs of particular fuels and other direct regulation
- Resource efficiency programmes

Policy changes that have been influenced by the findings/application of the models

Recent E3ME contributions include the EU's Impact Assessment of the 2030 climate and energy package and also the EU's long-term strategy for achieving net-zero emissions. It has also been used in official reviews of the Energy Efficiency Directive and Energy Performance in Buildings Directive (EPBD) that fed into the EU's Clean Energy Package. Increasingly the model has been applied for analysis outside the EU, for example by IRENA and in the 2018 New Climate Economy report.

A.2 A summary appraisal of the range of results the model can offer

As a global E3 (energy-environment-economy) model, E3ME can provide comprehensive analysis of policies;

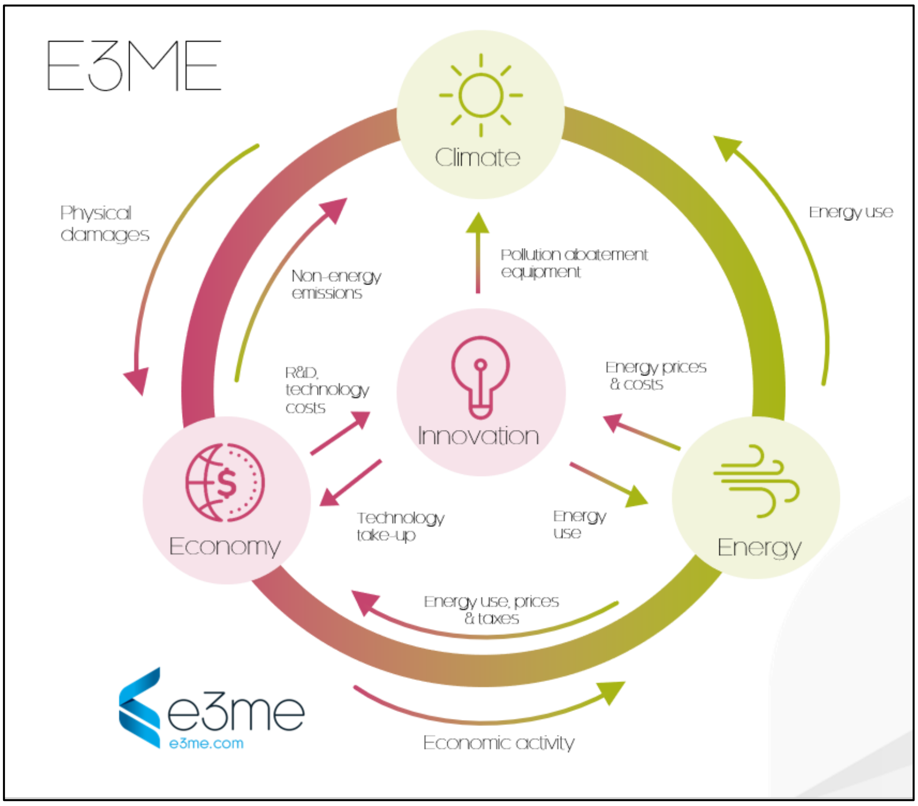
- direct impacts, for example reduction in energy demand and emissions, fuel switching and renewable energy
- secondary effects, for example on fuel suppliers, energy price and competitiveness impacts
- rebound effects of energy and materials consumption from lower price, spending on energy or higher economic activities
- overall macroeconomic impacts; on jobs and economy including income distribution at macro and sectoral level.

A.3 Theoretical underpinnings

Economic activity undertaken by persons, households, firms and other groups in society has effects on other groups (possibly after a time lag), and the effects may persist into future generations. But there are many actors and the effects, both beneficial and damaging, accumulate in economic and physical stocks.

The effects are transmitted through the environment, through the economy and the price and money system (via the markets for labour and commodities), and through global transport and information networks. The markets transmit effects in three main ways: through the level of activity creating demand for inputs of materials, fuels and labour; through wages and prices affecting incomes; and through incomes leading in turn to further demands for goods and services. These interdependencies suggest that an E3 model should be comprehensive and include many linkages between different parts of the economic and energy systems.

The figure below provides a schematic of an idealised model. The current version of the model includes only limited treatment of physical damages (which are often instead calculated off-model) and of pollution-abatement equipment (which is specified exogenously by the model user). These issues remain areas for future development.

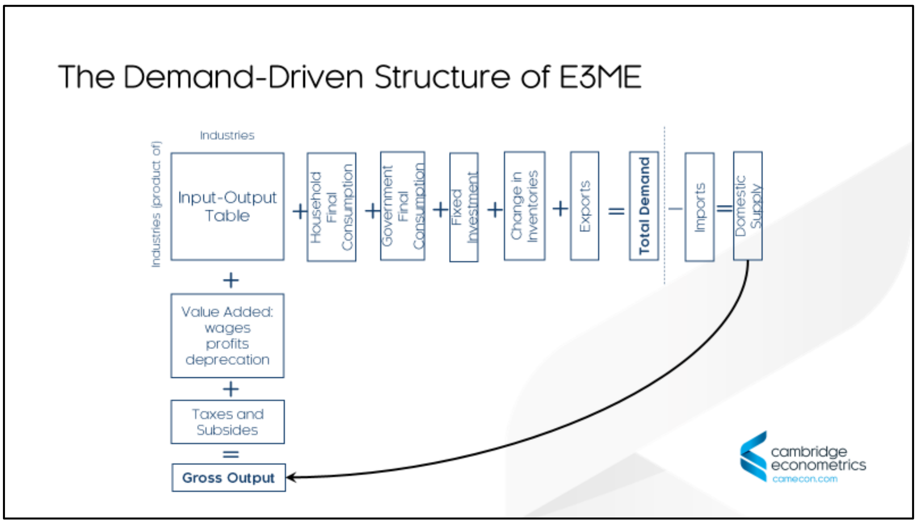


E3ME is often compared to Computable General Equilibrium (CGE) models. In many ways the modelling approaches are similar; they are used to answer similar questions and use similar inputs and outputs. However, underlying this there are important theoretical differences between the modelling approaches.

In a typical CGE framework, optimising 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, demand-driven accounting framework and it is possible to have spare capacity in the economy (see figure below). 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, which are included as standard in the model's results.



A.4 Summary of key strengths

- The close integration of the economy, energy systems and the environment, with two-way linkages between the economy and energy system.
- 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 (70 regions total).
- 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.

A.5 Key limitations

As with all modelling approaches, E3ME is a simplification of reality and is based on a series of assumptions. Compared to other macroeconomic modelling approaches, the assumptions are relatively non-restrictive as most relationships are determined by the historical data in the model database. This does, however, present its own limitations, for which the model user must be aware:

- The quality of the data used in the modelling is very important. Substantial resources are put into maintaining the E3ME database and filling out gaps in the data. However, particularly in developing countries, there is some uncertainty in results due to the data used.
- Econometric approaches are also sometimes criticised for using the past to explain future trends. In cases where there is large-scale policy change, the 'Lucas Critique' that suggests behaviour might change is also applicable. There is no solution to this argument using any modelling approach (as no one can predict the future) but we must always be aware of the uncertainty in the model results.

The other main limitation to the E3ME approach relates to the dimensions of the model. In general, it is very difficult to go into a level of detail beyond that offered by the model classifications. This means that sub-national analysis is difficult and detailed sub-sectoral analysis is also difficult. Similarly, although usually less relevant, attempting to assess impacts on a monthly or quarterly basis would not be possible.

A.6 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 1970-2018 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 statistical agencies. Gaps in the data are estimated using customised software algorithms.

The main dimensions of E3ME are:

- 70 countries – all G20 and major world economies, the EU28 and candidate countries plus other countries' economies grouped
- 44 (or 70 in Europe) industry sectors, based on standard international classifications
- 28 (or 43 in 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 6 GHG's monitored under the Kyoto Protocol

A.7 Key outputs

As a general model of the economy, based on the full structure of the national accounts, E3ME can produce 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
- income distribution
- energy demand, by sector and by fuel, energy prices
- raw material demand by sector and by material types
- power generation mix
- passenger cars and heating technologies
- CO2 emissions by sector and by fuel
- other air-borne emissions

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.

Linking E3ME to bottom up technologies submodules (FTTs)

Since 2012, the power sector in E3ME has been represented using a novel framework for the dynamic selection and diffusion of innovations, initially developed by J.-F. Mercure (Mercure, 2012), called FTT:Power (Future Technology Transformations for the Power sector). This is the first member of the FTT family of technology diffusion models. The current E3ME model version is also linked up to FTT:Transport, FTT: Steel and FTT:Heat.

Drawing on an evolutionary approach, the FTT models use a decision-making core for investors or households facing several options in their purchasing decisions. The model is based on theories of technology diffusion, with rates of diffusion affected by relative market shares and technology prices. The detailed technology representation allows for a range of policy options.

Many of the policies are characterised by long lag times due to the lifetimes of the technologies that are built. However, the model can show rapid transitions as technologies gain market penetration, reinforced by cost reductions that result from learning rates.

The resulting diffusion of competing technologies is constrained by a global database of renewable and non-renewable resources (Mercure & Salas, 2012, 2013).

A.8 Ongoing model developments

The current planned development for E3ME is:

- a new land-allocation module for the agricultural sector, building on the current generation of FTT models

- a bottom-up module for the chemicals sector (FTT:Chemicals)
- expansion of the FTT:Transport sub-model to cover freight as well as passenger road transport
- data updates to reflect the publication of data covering the period of covid-19

A.9 Model manual

A technical model manual of E3ME is available online at www.e3me.com.