# Representing Air Pollution in Future Energy Scenarios

Robert Thurston Arnold

Centre for Environmental Policy
Imperial College London

Thesis submitted for the degree of
Doctor of Philosophy and Diploma of Imperial College

February 2019
Supervised by Prof. Helen ApSimon and Prof. Nilay Shah

# Acknowledgements

Many people have been shown their kindness and patience through my studies for this thesis. I would like to thank all of them, but I would particularly like to express my gratitude to the following.

Firstly, I would like to thank my supervisors, Professor Helen ApSimon and Professor Nilay Shah for their ongoing support in helping me to complete this PhD thesis. It has been a privilege to work with such renowned experts in their fields and to draw in their depth of knowledge in my studies.

I am very grateful to my colleagues at Imperial College: to Dr Tim Oxley for the use of and instruction in the UKIAM and iMOVE models and for his humour throughout this project; to Huw Woodward, for his help in writing the Python script used to plot some of the charts on vehicles behaviour; to Dr Jeremy Woods for his advice; to Dr Rosalind O'Driscoll for her insights into vehicle emissions data, during her own studies, and to Shane Murphy for his help in navigating Imperial College's bureaucracy.

This project would also not have been possible without the help of Nick Molden of Emissions Analytics, who gave me generous access to data on the real-world drive cycles of cars that underpin a chapter of this thesis, and to my colleagues in the UK Civil Service – particularly Dr Ian Llewellyn of the Department for Business, Energy and Industrial Strategy – who have facilitated my completion of this research whilst working.

Ultimately, it would have been impossible to complete this thesis without the love and patience of my family: of my wife, Marta, who has been of unfailing support throughout my studies and who has carefully moderated our children's relentless encouragement to me with choruses of “Daddy, have you finished yet?” and of my parents, for the inspiration to persevere with my studies.

# Declaration of originality

As the author of this thesis, Robert Arnold, confirms that this manuscript is fully his own work. Except where otherwise stated, this thesis is the result of the author's own research. The analysis described and presented in the thesis was carried out independently to fulfil the requirements of a thesis for the degree of Doctor of Philosophy. All potential errors are the responsibility of the thesis author.

# Copyright declaration

# Abstract

Decarbonisation of a country’s energy system requires a change in energy supply chains, infrastructure and the introduction of new technologies. These lead to changes in the scale and type of combustion processes, the fuels used, as well as the activities required to supply fuels and operate energy infrastructure. They lead to changes in emission budgets of greenhouse gases and air pollutants that will have environmental and public health impacts. Such impacts can be highly dependent on the location and on the implementation of emerging energy technologies. This study compares the capabilities of tools for describing atmospheric emissions of air pollutants and greenhouse gases in future energy scenarios, for costing them and for cost-optimising deployment strategy. Case studies of technology choices for deploying decentralised CHP and for the uptake of hybrid vehicles are used to illustrate the challenges of representing emerging technologies in these models. The effectiveness of these technologies of reducing emissions budgets, together with synergies and antagonisms between delivering reductions in greenhouse gas emissions and air pollutant budgets are also explored. Recommendations are made on the using of incumbent models to assess air pollution, on the inclusion of novel technologies in energy scenarios and on how modelling systems might be better adapted to represent these. Spatial and temporal resolution are identified as key influences on models’ capabilities. In the hybrid vehicles case study, the precise technology options for vehicles – particularly hybrid powertrain architectures – is a key influence on optimising the benefits of atmospheric emissions reduction from future road transport. In the case of decentralised CHP, the surface morphology close to emission sources or in high population density areas will play a major role in impacts and costs of atmospheric emissions.

# Contents

# List of Figures

# List of Tables

# 1. Introduction

## 1.1 Problem statement

UK energy markets and infrastructure are expected to undergo significant transformation in the coming decades. This is due to a variety of environmental, political and economic influences, including energy security, fossil fuel prices and climate change, which drive energy supply chains away from those of the twentieth century. This affects how society consumes energy, its patterns of usage and the technologies underpinning supply. The sequence of technology change, referred to as a *technology trajectory* has environmental impacts, of which atmospheric emissions are a key contributor.

The way atmospheric emissions change with energy technology is a high profile, global issue. The potential impact of greenhouse gas emissions from the use of fossil fuels and the desire to reduce these is a major incentive for change. National legislation aimed at this has been introduced in many states. Supranational agreements, such as the Kyoto and Paris agreements (UN, 1998; UN, 2015) under the UN Framework Convention for Climate Change, aim to form unified approaches and targets for greenhouse gas emissions reduction, whilst accountancy mechanisms, such as the EU Emissions Trading System, aim to monitor and assess the success of measures to deliver these.

In addition to climate change, changes in energy technology bring further health and environmental impacts from other air pollutants, such as particulate matter, acid gases and nitrogen compounds. These can arise from combustion processes, fuel supply (e.g. for biofuels) and emission remediation processes (e.g. post-combustion $CO_2$ capture). International agreements to limit and reduce these also exist, as the impacts of such pollutants can include major human, environmental and economic costs that include many of the following:

- Individuals’ health degradation.
- Reduced ability to work because of poor health.
- Costs of addressing poor health.
- Curtailing of lifespan.
- Habitat degradation, eutrophication of land and water systems and reduced resilience of ecosystems.
- Impacts on agriculture.

Many tools used for UK energy analysis tend to consider only the impacts of either greenhouse gases or other air pollutants in isolation or consider both, but apply them to a limited range of technologies. If a fuller assessment of future UK energy scenarios is to be achieved, the impacts of all their atmospheric emissions must be considered collectively.

Surveys of UK energy models (Hall and Buckley, 2016) reveal few cover both sets of emissions. Given this small number, it will be helpful for modellers and policy makers to understand how clearly such models can identify co-benefits and trade-offs between reductions of greenhouse gases and other air pollutants. It is also helpful to understand their comparative capabilities, limitations and risks of inaccuracy in describing emerging technologies, which may play key roles in achieving these reductions in future energy scenarios. This study aims to examine both these aspects, within a UK policy and modelling context.

## 1.2 Research objectives and scope

This thesis aims to compare the properties of models and tools for analysing energy technology trajectories, in current use for policy making and analysis, and which consider greenhouse gases and air pollution. It does this by:

- Identifying models and tools that meet appropriate criteria.
- Comparing their inclusion of key parameters and relationships; their ability to compare these; and their ability to represent current and emergent technologies likely to be present in future energy scenarios.
- Use case studies of two potential shifts in energy technologies to examine the capabilities of these tools, to accommodate the deployment of new energy technologies and to assess risks and shortcomings that potential users should be aware of.
- Use these same examples to assess where synergies and trade-offs between budgets of greenhouse gases and air pollutants exist and whether they can be represented in a way that does not detract from tools' function (e.g. the ability to undertake meaningful least-cost optimisation).

The examples of technology shift to be used are: (i) the air and greenhouse gas impacts of a change from centralised electricity generation to distributed heat and power in a city and; (ii) the impacts of the introduction of hybrid vehicles.

The examples chosen are done so to demonstrate challenges of representing the complexities of new technologies that affect both air pollution and climate change. They are based on technologies that involve fuel combustion and result in complex relationships between air pollutant and greenhouse gas emissions budgets. It should be recognised that other technology shifts can occur which eliminate fuel combustion from certain applications. The sources of greenhouse gas and air pollutant combustion products in such scenarios would also be eliminated from these applications.

Such shifts may arise in scenarios where a policy of zero net carbon emissions are pursued by the UK.

## 1.3 Methods and approach

A hybrid approach is taken to this analysis, as is necessary for a technical analysis of policy making tools. The comparison of energy trajectory models and tools is largely qualitative, as it relates to the structure, methodology and function of these. Examples of shifts to emergent technologies are based on quantitative methods: modelling physical emissions of air quality pollutants in the case of a shift to distributed CHP and analysing field data from portable emissions monitoring systems attached to vehicles in the case of considering a shift to hybrids.

Chapters 1-2 of this thesis propose the approach and describe the general scientific literature and legislative background for the research. Chapters 3-6 present the results, analysis and additional background relevant to the research undertaken. In particular, Chapter 5 outlines the legislative and technical background necessary to frame the research on hybrid vehicles.

Chapter 7 presents a summary, discussion and conclusions of the findings of the earlier chapters.

# 2. Literature Survey

## 2.1 Legislative background

### 2.1.1 UK climate change objectives

In the Climate Change Act of 2008, the UK Government committed itself to achieving a reduction of at least 80% on the UK's 1990 levels of greenhouse gas emissions by the year 2050, measured in terms of carbon dioxide equivalent. This ambition was based on the estimate of the reduction of greenhouse gas emissions that the Intergovernmental Panel on Climate Change considered to be necessary to limit the chance of exceeding a 2°C rise in global temperature by 2100 to 50% (IPPC, 2007) and the recommendation from the UK's Committee on Climate Change as to what an equitable share of this would be for the UK to make (CCC, 2008). Achieving this target will require considerable changes to both the UK's energy infrastructure and its use of primary energy resources.

### 2.1.2 UK emission of greenhouse gases

In 2017, 80.1% of the UK's energy resources was of fossil origin (BEIS, 2018f). The combustion of this fuel generated 367 million tonnes of carbon dioxide, representing over 80% of the total UK emissions of greenhouse gases that year, measured as carbon dioxide equivalent (BEIS, 2018c). Most of this was used either for electricity generation, heating or transport.

The remainder of the greenhouse gas emissions arose from direct emissions from:

- Industrial chemical processes, such as cement production, that emit significant amounts of $CO_2$ from non-energy activity.
- Agricultural activity and changes in land use, which can emit sizeable amounts of $N_2O$ and methane.

- Numerous small releases of climate impacting compounds such as halogenated organic compounds or sulphur hexafluoride, such as might occur from semiconductor or refrigeration plant.

### 2.1.3 Decarbonising the UK economy.

Decarbonising energy is the process of reducing the greenhouse gas emissions associated with its delivery and use. The principle methods of decarbonisation are by technology shift in one of two ways:

- Decarbonising the supply chain, replacing primary energy resources and processing technology to produce a functionally identical end-use energy product with lower life cycle greenhouse gas emissions. This includes a shift from using unabated fossil fuel fired power generation to a greater share of electricity generation technologies with lower CO2 emissions, such as renewable, nuclear and carbon capture and storage equipped plant, or the introduction of vehicle fuels or heating fuels with a greater renewable component.
- Decarbonising end-use technology in order to fulfil the same service demand, by increased energy efficiency or replacing equipment with an alternative that uses lower carbon resources. Typical examples include lower energy lighting, the use of heat pumps for space and water heating and the electrification of transport.

Similarly, decarbonising an economy involves also reducing the greenhouse gas emissions from non-energy processes, such as agriculture or industrial manufacturing processes.

The process of decarbonising the UK economy to its target levels of an 80% reduction on 1990 levels is ongoing and, by 2017, greenhouse gas emissions stood at 57% of 1990 levels (BEIS, 2018c). Of the fossil fuelled part of the UK energy economy, the electricity generation sector has long been identified as the easiest to decarbonise (BERR, 2007; UKERC, 2009) This has fallen from 203 Mt $CO_2e$ in 1990 to 71.8 Mt $CO_2e$ in 2017, with the sharpest continual fall occurring from 157.8 Mt $CO_2e$ in

2013 to the 2017 level (BEIS, 2018c). This is the result of the rapid growth in renewable generation which, along with gas, replaces coal and reducing electricity demand (Staffell, 2017).

Whilst such shifts of technology can reduce greenhouse gas emissions towards decarbonisation targets, they will also have other environmental impacts associated with them. These include water-stress, biodiversity reduction, habitat degradation and air pollution. In order to fully understand the environmental impacts of technology shift, these impacts need to be considered and suitably represented in decision making tools.

## 2.2 Air pollution and the energy infrastructure

### 2.2.1 Air pollution legislation and the UK

The nineteenth century and the first half of the twentieth century saw increasing emissions of particulates and acid gases emissions in the UK, due to fossil fuel combustion. This was largely from coal for heat and power, supplemented towards the end of this period with road transport emissions. The need for legislation to control this came to public attention in two ways: concern over its public health impacts and political pressure over its transboundary impacts on the environment.

Public health impacts of direct combustion emissions can arise from high concentrations of sulphur oxides ($SO_x$), nitrogen oxides ($NO_x$) and particulate matter (PM). Particulate matter can also be produced from the interaction of combustion emissions with other ambient air pollutants, such as ammonia and ozone. The overall health impacts of air pollution tends to be more severe if it occurs in areas of high population density, as more people are affected. The substances emitted directly can affect the respiratory and pulmonary systems (Kim, Kabir et al., 2015), particularly in vulnerable groups (Guarnieri and Balmes, 2014), and the chemical reactions they undergo in the atmosphere can form secondary pollutants with similar health effects. Furthermore, non-combustion emissions of energy, such as ammonia from anaerobic digestion, can promote secondary pollutant formation.

A defining event for UK legislation was the December 1952 smog in London, which has been estimated to have produced up to 12,000 early deaths in the most medically vulnerable groups of the population (MoH, 1954). This episode persisted over several days and was characterised by simultaneously high levels of $SO_2$ and PM, which has been linked to the high levels of formation of sulphate aerosols as secondary pollutants (Wang, Zhang et al., 2016). Concern over this level of air pollution led to the introduction of the Clean Air Acts of 1956 and 1968. Respectively, these introduced zones in which the burning of smoky fuels was prohibited and minimum limits on the height of emission stacks of combustion plant.

### *Legislation on transboundary pollutants*

Legislation on transboundary air pollution grew out of a need to reduce the acidification and eutrophication of ecosystems caused by sulphate and nitrate compounds being transported over long distances and being deposited in vulnerable areas. Prior to the mid-twentieth century, the geographical range of air pollutants had not been appreciated fully. As the volumes of emissions and the height at which they were emitted increased in the 19th and 20th centuries, so did the geographical reach of air pollutants.

From the 1950s to the 1970s, increasing evidence was found that a significant proportion of the emissions responsible for acid deposition in southern Scandinavia originated from other areas of northern Europe, including the British Isles (Almer, 1974). By the mid-1970s, sufficient scientific and political consensus had been achieved to allow the signing in 1979 of the Convention on Long-Range Transboundary Air Pollution (CLRTAP), which aims to both protect the human environment from long range air pollution and to reduce the level of this pollution over time.

The CLRTAP has been supplemented by eight additional protocols since its signing, placing additional limits on monitoring regimes or agreeing new ones for the most common forms of air pollution.

These include the 1985 Helsinki Protocol on the Reduction of Sulphur Emissions (UNECE, 1985) and the following 1994 Oslo Protocol (UNECE, 1994), which have led to a reduction of more than 30% from 1980 emissions of sulphur oxides ($SO_x$) from signatory states. These agreements played a key role in the migration of UK power generation away from coal in the 1980s and 1990s and the installation of flue gas desulphurisation as a remedial measure on the larger remaining UK coal-fired power stations.

The most recent protocol of the CLRTAP is the 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, which sets emission ceiling limits for the emissions of oxides of sulphur and nitrogen, volatile organic compounds and ammonia. If successful, this should reduce Europe's annual emissions of sulphur by at least 63%, its $NO_x$ emissions by 41%, its VOC emissions by 40% and its ammonia emissions by 17% compared to 1990. In the UK, this has seen emissions from 1970 levels fall by 97% for $SO_2$, 72% for $NO_x$ and 73% for $PM_{10}$ (Defra, 2018).

*European law*

Air pollution emissions in EU member states are also regulated at transnational level via two principle pieces of EU legislation.

The National Emissions Ceiling Directive (2001/81/EC) limits the annual overall emission budgets of specific pollutants from EU Member States. Its main function is to curb growth in transboundary air pollutant emissions from EU Member States and limit damage to public health and ecosystems. However, it also contributes to keeping regional background levels of pollutants within required limits by limiting the transboundary contribution to these.

The Air Quality Directive (2008/50/EC) aims to limit exposure of organisms (especially people) to potentially damaging concentrations of air pollutants. It achieves this by establishing maximum permitted maximum permitted limit values for common air pollutants (CO, $NO_x$, $SO_2$, $O_3$, $PM_{10}$ and $PM_{2.5}$, as well as a range of metals and organic compounds), some of which may be exceeded temporarily on a limited number of occasions within a given period. Compliance is demonstrated via a combination of monitoring via national monitoring networks and by modelling expected concentrations across the territory of the Member State.

### 2.2.2 Primary pollutants under consideration

Air quality pollutants emitted directly to the atmosphere from energy related sources are a subject of this study and the characteristics of key ones related to energy use are outlined below. In addition to their detrimental impacts on ecosystems, many of these pollutants can also damage human health and property. Consequently, the potential costs to society from failure to manage the volumes of pollutants emitted and to implement measures to limit exposure to them can be significant, both in absolute terms and relation to their abatement costs.

*Sulphur oxides (SOx)*

Sulphur oxides arise from the combustion of sulphur present in coal and oil. The dominant component of primary $SO_x$ emissions is sulphur dioxide, which dissolves in water to form sulphurous acid ($H_2SO_3$) and, with time, oxidises to sulphuric acid ($H_2SO_4$) and to secondary particulates. It has been mentioned as one of the first pollutants to be identified as a cause of long range and transboundary air pollution (Wright and Gjessing, 1976; OECD, 1981). The most visible effects of these have been the reduction of ability of certain lakes and water bodies to support populations of fish and mollusc species (Jensen and Snekvik, 1972; Tammi, Appelberg et al., 2003) and the decline of forests in areas of high sulphur oxide deposition (Grodzińska-Jurczak and Szarek-Łukaszewska, 1999).

There is also substantial evidence to link the exposure to $SO_x$ emissions with the exacerbation of pre-existing respiratory ailments, including the production of observable symptoms from sub-clinical conditions (Guarnieri and Balmes, 2014; WHO, 2015). However, the dose–response relationship and the influences on this are difficult to determine epidemiologically, due to the multitude of other confounding factors.

*Oxides of nitrogen (NOx)*

Nitric oxide and nitrogen dioxide are usually emitted as a mixture and referred to collectively as $NO_x$. Around 32% of the UK's 0.87 Mt emission budget of $NO_x$ in 2017 came from road vehicles and a further 15% from off-road vehicles. Energy production was also a significant contributor, delivering a further 21% of $NO_x$ (Defra, 2018). $NO_x$ is produced in three distinct ways:

- Thermal $NO_x$ – the reaction of atmospheric oxygen and nitrogen in high-temperature processes that take place in air, such as combustion or electrical discharge,
- Prompt $NO_x$ – generated by the reaction of organic radicals from the fuel combining with atmospheric nitrogen, which then oxidised to NO.
- Fuel $NO_x$ – produced from the oxidation of nitrogen-containing compounds in many fuels.

The amount of $NO_x$ and the NO to $NO_2$ ratio produced in combustion depends on both the combustion temperature and the nitrogen content of the fuel. In any nitrogen containing fuel, such as biomass or certain oils, fuel $NO_x$ will tend to be the dominant source. Thermal $NO_x$ production also becomes significant above about 1500°C, as long as the fuel to air mixture consists of between one-quarter to one-half excess air, which allows combustion temperature to be maintained without starving the process of oxygen. Prompt $NO_x$ is generally a very minor component of combustion emissions.

The NO component of $NO_x$ oxidises in air to form $NO_2$, and the equilibrium of $NO_x$ in the atmosphere is almost entirely $NO_2$. However, the proportion of $NO_2$ in $NO_x$ can be altered dramatically by exhaust gas aftertreatment technology designed to reduce air pollution from vehicles. These systems tend to be based on oxidative catalysts that accelerate the oxidation of NO to $NO_2$. The result is that, whilst overall $NO_x$ emissions from vehicles have been falling, the proportion of $NO_x$ emitted as $NO_2$ has been on the increase (AQEG, 2007). This is significant, as by far the largest source of the UK's $NO_x$ emissions are vehicle engines.

$NO_x$ contributes to environmental acidification in a more complex manner than $SO_x$ emissions. During the daytime, ·OH radicals are produced photochemically and create nitrous (HONO) and nitric ($HNO_3$) acids from NO and $NO_2$ respectively. Both of these may be deposited dry, whilst the solubility of $HNO_3$ also leads to a high level of wet deposition. $HNO_3$ also reacts with other pollutants to form secondary particulates, such as ammonium nitrate, which may also be deposited dry or breathed in.

Despite acidification effects, the main impact of $NO_x$ upon ecosystems stems from the role of the nitrate ion as a fertiliser, which can encourage the growth of aquatic plant life and lead to the eutrophication of water bodies.

The health effects of $NO_x$ are significant but are largely caused by the $NO_2$ fraction of the mixture. As NO oxidises slowly to $NO_2$ upon exposure to air, this fraction increases with residence time of the $NO_x$. Prolonged exposure to high concentrations of $NO_2$ can cause significant health impact (WHO, 2013; Eum, Kazemiparkouhi et al., 2019). The relationships between of typical ambient $NO_2$ concentrations and specific health impacts are still not fully understood, but evidence points to reduced disease resistance, lung function, damage to the respiratory tract and deterioration of the health of those with pre-existing respiratory ailments (Frampton, Boscia et al., 2002; Samoli, Aga et al., 2006). There are also clear mechanisms through which exposure to the $NO_2$ component of $NO_x$, such as found in diesel vehicle emissions, can cause cancer (Espín-Pérez, Krauskopf et al., 2018). As most $NO_2$ is emitted from transport sources, it is often encountered as part of a wider mixture of pollutants. Identifying those impacts due solely to $NO_2$ in such circumstances is challenging (WHO, 2003; COMEAP, 2018)

If $NO_x$ is converted to $HNO_3$, it can react with other pollutants to form secondary particulates, such as ammonium nitrate, which may also be deposited dry or breathed in.

*Particulate matter (PM)*

Particulate is a mixture of solid and condensed volatile substances suspended in the air. Unlike other types of air pollutant considered here, it is often classified by size (particle diameter) and not composition. This can vary by location, according to emission source. Constituents of particulate matter include black carbon and organic solids from combustion, the products of brake and tyre wear from vehicles, solid condensate from more volatile air pollutants and natural substances such as resuspended dust and soil. Particulates are of concern mainly due to their health impact which, whilst dependent upon the chemical composition, is thought to correspond most with the size fraction (Deng, Deng et al., 2019).

$PM_{10}$, the fraction of particulate with a diameter of 10 µm or less, can penetrate the upper respiratory systems of animals and cause inflammation and irritation, whilst the finer fractions of 2.5 µm diameter or lower ($PM_{2.5}$) pose greater health risks due to their greater ability to reach the entire respiratory system, be absorbed across the lung wall and become embedded in tissue for long periods of time or cross cell membranes. This can cause a variety of health impacts including cardiopulmonary degradation, lung cancer, and the exacerbation of existing respiratory ailments (Pope Iii, Burnett et al., 2002; Bentayeb, Wagner et al., 2015; Espín-Pérez, Krauskopf et al., 2018).

PM can act as a short-term irritant to eyes and sensitive membranes in the nose and throat and can exacerbate respiratory ailments, such as asthma. Longer term exposure is thought to have graver and more subtle effects: placing stress on the cardiovascular system through chronic impairment of lung function, causing organ damage via toxicity from particulates that manage to cross the lung wall, inhibiting lung development in children and increasing the likelihood of lung cancer (Espín-Pérez, Krauskopf et al., 2018).

About 133 kt of $PM_{10}$ particulates are estimated to be emitted directly from anthropogenic sources in the UK each year, with a further 20 kt “resuspended” into the air (as opposed to being emitted directly) as the result of human activities. Neither of these budgets include the suspension and transport of particulates from natural sources, although this, too, will contribute to the measured concentrations of PM in the UK. Nor does it include those “secondary” particulates that form as the result of the chemical reactions of air pollutants already released, which are discussed in section 2.2.3.

*Volatile organic compounds (VOCs)*

Volatile organics are the umbrella term for a range of carbon-based compounds that vaporise at ambient temperatures and include most simple organic molecules, with the exception of methane. The vast majority of VOCs are not anthropogenic in source, with over gigatonnes being emitted annually from plant life – mostly in the form of terpenes and mostly, where there are seasonal climates, in the warmer months of the year (Sindelarova, Granier et al., 2014). Anthropogenic VOC emissions are thought to be an order of magnitude lower, with the UK annual budget of man-made VOC emissions to the atmosphere currently being around one million tonnes, mostly from solvent use, agriculture and industrial processes (NAEI, 2018b).

Whilst VOCs can be toxic indoor at high enough atmospheric concentrations, these effects are hardly ever seen in an outdoor environment and the direct impacts of VOCs on humans remain largely an issue for indoor air quality and health and safety. Nonetheless, they are regarded as a significant indicator of outdoor air quality due to their role as precursor molecules in the formation of tropospheric ozone and photochemical smog.

*Ammonia (NH3)*

The majority of ammonia emission arises from the decomposition of, urea, uric acid and undigested proteins in animal excrement and soils, so it is linked strongly to the agricultural sector. Additional sources of ammonia include direct emission from artificial fertilisers that contain the ammonium ($NH_4^+$) ion, from selective catalytic reduction of $NO_x$ in vehicle exhaust aftertreatment systems and from certain industrial processes. UK emissions are approximately 280 kilotonnes, mostly from the agricultural sector (NAEI, 2018a).

One particular anticipated source of ammonia under some 2050 energy scenarios, which is not present today, is that from large-scale post-combustion carbon dioxide capture systems on power stations. It is possible that the atmospheric decomposition products of the amine based solvents used in this process might increase ammonia emissions per unit of electricity produced, with consequent environment and health impacts (Tzanidakis, Oxley et al., 2013). In context, this would represent a large proportional increase on what is a relatively small contributor to ammonia emissions and would be unlikely to overshadow agricultural sources. Furthermore, alternative solvents to the current amines proposed for use may mean that the anticipated increases in electricity-related ammonia emission never occur (EC, 2006).

Ammonia poses a risk to ecosystems by increasing the nutrient load, leading to eutrophication of water bodies and overwhelming of vegetation in nutrient-poor ecosystems (such as heathland and upland forests) by fast-growing species. It can also increase soil acidity though oxidation to nitrate, increasing stress on vegetation and mobilising toxic substances (such as heavy metal ions) that would otherwise have been unable to enter environmental chemical cycles (Thornton, Farago et al., 1998; AQEG, 2018).

As ammonia does not have a long residence time in the atmosphere, most of the gas is deposited near to its point of origin. However, it still causes long range environmental and health impacts through secondary products, which take the form of very fine particulates that result from reaction with acid gases such as $SO_2$ and $NO_2$. Due to the ratio of their mass to their aerodynamic cross section, their transport is dominated by air movement, rather than gravity, and they can travel easily across long distances by air currents.

### 2.2.3 Secondary air pollutants

Air pollutants that are emitted directly to the atmosphere as the result of combustion or industrial processes, such as $NO_x$ and $SO_2$, are classified as primary emissions. Those that are not emitted directly but are generated by reactions between ambient precursors are considered to be secondary emissions. They include ozone, a large fraction of particulates and the portion of $NO_2$ that forms from NO.

The speed at which secondary pollutants form and the concentrations they are found in depends on ambient meteorology and often on illumination, as some of the more common reactions are photochemical. As they are not formed instantaneously, modelling their concentrations and location is complicated. A single pollution event can have multiple points of origin, as different individual precursor compounds can be emitted by different sources. Furthermore, the air containing their precursors can travel some distance before the secondary pollutants are produced, breaking the relationship between concentration and distance from source, which tends to hold for primary pollutants.

The two most relevant types of secondary pollution related to energy production are:

### *Tropospheric Ozone (O3)*

Ozone is one of the most significant photochemical oxidants in the troposphere. It has a sufficiently long atmospheric lifetime to allow long-range transport and is therefore considered to be a transboundary air pollutant. It is produced via a number of chemical pathways, but for ozone episodes caused by anthropogenic pollutants, the photochemical driven reaction of $NO_x$ in the presence of VOCs below provides the mechanism:

When $NO_2$ alone is present, ozone is limited by both the concentration of the $NO_2$ and an equilibrium being established by the NO being oxidised by ozone back to NO and $O_2$.

$$NO_2 \overset{h\nu}{\rightleftharpoons} NO + \cdot O(^1D) \overset{O^2}{\rightleftharpoons} O_3 + NO$$

In areas with high levels of additional NO emission, such as those with intense road traffic activity, the excess NO will react with ozone. This alters the balance of the equilibrium and leads to lower levels of ozone in urban centres than might otherwise be expected, given the level of VOC and hydrocarbons emitted. This effect may decrease in the near future, due to the observed increase in the primary $NO_2$ fraction of vehicle $NO_x$ emissions from (Jenkin, Utembe et al., 2008).

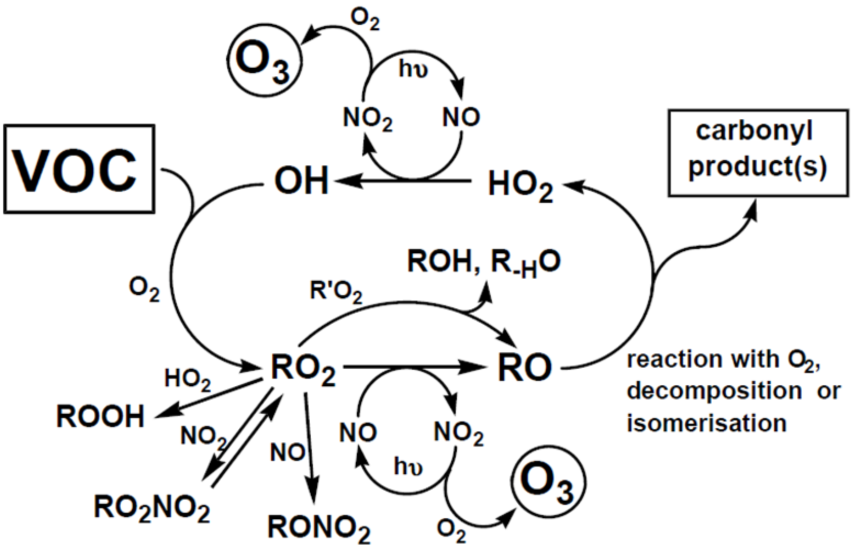


Figure 2.1: Reaction scheme for the photochemical formation of tropospheric ozone (AEA, 2002)

Ozone is a highly oxidising substance and, being gaseous, can enter airways in plants and animals efficiently. In plants it can cause oxidative stress, reduce gas intake and slow photosynthesis. It can cause lung inflammation in humans and there is evidence that can exacerbate the response of asthma suffers to other lung irritants. Long-term exposure is thought to inhibit lung function development in children and there is some epidemiological evidence to link it with lung cancer (WHO, 2003). However, the secondary nature of ozone as a pollutant and the fact that it is usually found in conjunction with other pollutants, has made it harder to draw detailed conclusions on aspects such as long-term dose-response relationships than for primary pollutants.

*Secondary particulates*

Secondary particulates tend to be the condensate of primary air pollutants or the products of gaseous reactions between pollutants. Consequently, they tend to be both more volatile and to have a smaller aerodynamic size than the overall average for $PM_{10}$. Typically, these are condensed nitrate, sulphate or ammonium compounds, or the heavier oxides of nitrogen that fall well within the $PM_{2.5}$ range and often have "ultrafine" diameters of less than 100 nm (i.e. they lie within the $PM_{0.1}$ size spectrum).

## 2.3 Modelling climate change and air quality

### 2.3.1 Modelling climate impact

Long term assessment of the climate effects of greenhouse gases requires models that can calculate how the atmosphere absorbs and retains solar radiation, how it is transferred around the planet, the effect this can have on land and sea and how these feedback on the atmosphere. Known as general (or "global") circulation models (GCMs) these model these physical processes on the range of decades to centuries. Most GCMs are built from a several coupled models, each describing physical processes of energy absorption, transfer and transport for a specific element of the planet's energy system - typically, the atmosphere, oceans, land and cryosphere (IPCC, 2018). They tend to treat the chemical and biological components of these systems as either fixed, such as vegetation distribution, or express them exogenously as time-varying boundary conditions unaffected by model output.

GCMs normally assume that greenhouse gases are well mixed across the entire atmosphere, making their impact independent of the location of their emission. Spatial resolution is coarse, with grid cells measuring about 250 - 600 km in the horizontal dimensions, each containing 10-20 layer of atmosphere. The HadCM3 model used by the UK Met Office's Hadley Centre is typical of an advanced GCM and exhibits many of these characteristics (Murphy, Sexton et al., 2009).

The large grid size means that local variation in concentrations of these gases play no significant role and emission budgets are the most significant metric of anthropogenic contribution to radiative forcing. Localised changes in the radiation budget of GCM simulations do still occur by other means, such as reflection and absorption of surfaces or atmospheric aerosol, but the size of the grid cells determine the maximum level of detail achievable without nesting regional climate models.

Natural emissions budgets of greenhouse gases are usually integrated into GCMs, including emissions from sources that are changed by climate impacts, such as the release of carbon from boreal wetlands. Anthropogenic greenhouse gas emission budgets are an exogenous input to climate models and must be generated separately. These are provided by models of the energy system and of land use. This study focuses on the development of energy system models and the challenges of realistic descriptions of energy scenarios, which are a prerequisite for developing realistic climate forecasting.

### 2.3.2 Modelling air quality impact

The impacts of air quality pollutants are much more localised than for greenhouse gases and depend strongly on concentration. Modelling these requires both accurate descriptions of their spatial distribution, transport processes and chemistry. The applicability of different types of model varies with scale. Pure diffusion modelling, which assumes that pollutants disperse to adjacent air masses in a Gaussian manner, is adequate for describing local pollution events. It underlies modelling packages such as Cambridge Environmental Research Consultants' ADMS product, which are used for assessment of the local impacts of proposed changes in energy, transport and industrial infrastructure, (Blair, Johnson et al., 2003).

Longer-range impacts need to describe the trajectories of the air masses that carry the pollutants in addition to their diffusion throughout these air masses. One of the most used models for assessing air pollution distribution across the British Isles is FRAME (Fine Resolution Atmospheric Multi-pollutant Exchange), which describes the movement of an air column along straight line trajectories within a 5km x 5km horizontal grid with 33 vertical layers of increasing depth with altitude (Fournier, Dore et al., 2004). FRAME takes emissions data of $NH_3$, $SO_2$ and $NO_x$ and considers how reactions involving $NH_3$, NO, $NO_2$, $HNO_3$, peroxyacetyl nitrate, $SO_2$ and $H_2SO_4$, as well as ammonium, sulphate and nitrate based secondary pollutants, proceed in the moving air (Dore, Kryza et al., 2009). Deposition is calculated by estimating precipitation in the case of wet deposition and dry deposition is estimated by assigning one of five different land use types to each grid square with the rate of deposition for each of these land types depending on its typical aerodynamic resistance properties.

Another major model used is EMEP/MSC-W, which is developed by the European Monitoring and Evaluation Programme (EMEP) for the Convention on Long Range Transboundary Air Pollution. This is a multiple air quality pollutant chemical transport model, based on the emission inventories as reported by the parties to the LRTAP convention (NMI, 2018). It calculates atmospheric concentrations, deposition fields and long-range transport for particulate air pollutants and pollutants that cause acidification and eutrophication. EMEP is one of the inputs for the UKIAM – one of the key models used for predicting air pollutant concentrations and impacts in the UK to demonstrate policy compliance (Oxley, Dore et al., 2010).

Time horizons for air quality modelling have been much shorter term than for climate impacts, focusing largely on:

- Demonstration of regulatory compliance and modelling expected air quality based on a limited number of measurements. This is how the UK demonstrates compliance with EU air quality legislation.
- Assessment of counterfactual scenarios of air quality in the immediate environment. This is usually used in planning impact assessments for proposed construction and land development projects, such as the building of a new road.
- Prediction of future compliance with air quality legislation, commonly used in assessing the risk of exceeding regulatory air quality limit values during the negotiation of new

legislation, or for the demonstration of expected near term compliance with air quality legislation.

Rarely do any of these uses require modelling of more than a few years ahead and few detailed models consider impacts beyond the 2030s. Despite this, there is no reason in principle why such modelling cannot consider scenarios beyond 2030 if justifiable assumptions can be made about the nature of pollutant sources.

# 3. Energy trajectory scenario modelling tools and their capabilities

## 3.1 Introduction

Energy trajectory modelling is an underpinning tool of energy policy analysis. Models are developed at all scales and for many purposes, from technical capability assessment to economic analysis. Some are confined to individual sectors of activity, such as domestic energy use (e.g. the BREDEM model (Henderson and Hart, 2015)), or the operation of the electricity market (e.g. the Dynamic Despatch Model (DECC, 2012a)); some cover entire supranational regional economies (e.g. PROMETHEUS (E3MLab/ICCS)).

Over 100 energy models are in common use in the UK and are referred to in research literature (Hall and Buckley, 2016). Most are designed for a specific purpose and this defines their structure, usually through the technologies and sectors included and the parameters available to define these. A small fraction of these meet four key criteria:

- They assess energy decarbonisation trajectories (descriptions of the evolution of the energy system in a manner that reduces $CO_2$ production) on a national scale.
- Can accept data on multi-decade time scales.
- Have a history of use in national policy formulation.
- Are capable of some form of assessment of air quality impacts.

These are considered in this study as suitable tools for assessing atmospheric emissions from future energy scenarios. They include two technoeconomic cost optimisations tools (GAINS and the UK versions of TIMES / MARKAL) and a scenario-building calculator (the 2050 Carbon Calculator).

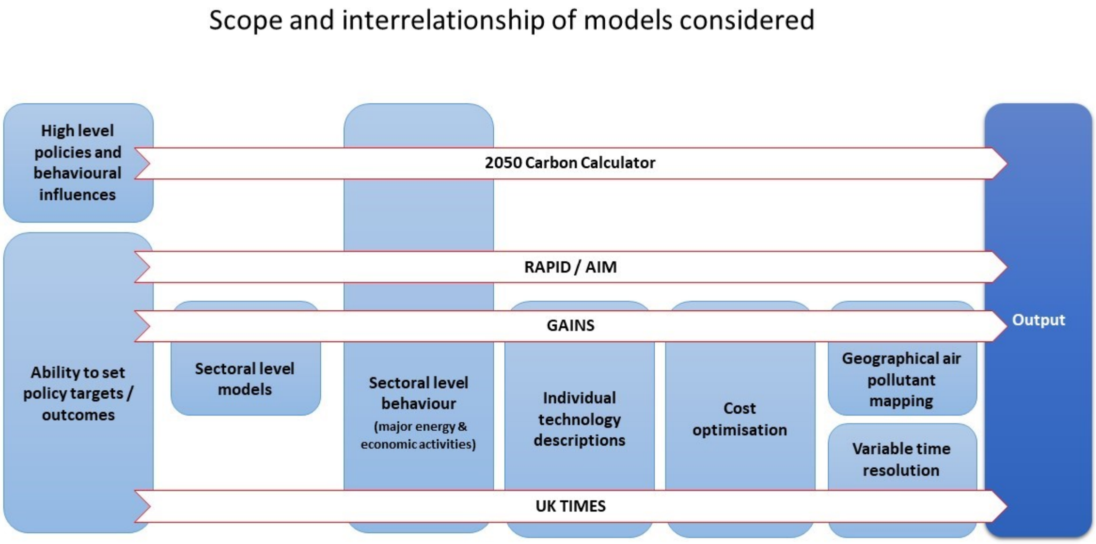


**Figure 3.1: Scope and interrelationships between considered energy models**

The interrelationship and scope of these models is shown in Figure 3.1. This chapter aims to compare the capabilities of these tools in describing air pollutant emissions and impacts, the detail in which they can describe emission sources and their ability to incorporate emerging energy technologies.

## 3.2 The 2050 Carbon Calculator

### 3.2.1 Purpose

In 2010, the UK's Department of Energy and Climate Change (DECC) developed a tool to allow illustrative exploration of potential pathways between current UK energy supply, demand and associated carbon emissions and scenarios that we might see by 2050. The 2050 Carbon Calculator (sometimes referred to as the 2050 Pathways Analysis Tool) can produce self-consistent scenarios that describe the energy production, demand and greenhouse gas output of major UK economic sectors. Its aim is to provide an accessible way of conceptualising the challenge and implications that these changes may have for society.

The tool is currently maintained by DECC’s successor, the Department of Business, Energy and Industrial Strategy, and is available in two versions:

- A standalone spreadsheet version, which allows users a high level of granularity in setting all parameters and offers a complete view of the calculations. As the model is open source, the spreadsheet version can be modified at will and updated, if necessary, by the user.
- A website, which acts as simplified a front end for the tool and allows users to set key parameters in a more accessible manner, with a focus on graphical presentation.

Scenarios are able to be saved, copied and pasted in the form of a string of parameter settings and the web tool has a facility to share users’ own scenarios via social media.

The initial versions of the calculator released covered only energy usage and greenhouse gas emissions. Subsequently, additional functionality has included assessment of air pollutant emissions, estimation of comparative costs of scenarios, generation of Sankey energy flow diagrams of scenarios and a narrative engine that produces descriptions of elements of the energy systems postulated in easily understood terms.

The approach taken by the Calculator in communicating to the public the challenges of decarbonising energy has proved popular in other countries and regions. The same design of calculator has been taken up by the governments of Wallonia, China, South Korea, Taiwan, India, South Africa and Japan to publish versions for the energy systems of these countries.

More recently, the UK Government and the EU’s Climate-KIC funded the development of a similar tool to explore future energy scenarios for the global energy system out to the year 2050 (HMG, IEA et al., 2013). EUCalc, a calculator covering the EU’s economy is also under development, funded by the EU’s Horizon 2020 research framework programme (EC, 2017).

### 3.2.2 Structure

The 2050 Carbon Calculator breaks down the UK economy into high level supply and demand sectors, corresponding to energy production capacity for various technologies, demand for energy consumption and the amount of greenhouse gases produced or abated by non-energy producing activities (BEIS, 2018d). These are:

**Energy supply:**

- Indigenous bioenergy supply
- Nuclear
- Thermal combustion power stations (coal, gas, oil and biomass fired), with and without CCS
- Onshore wind
- Offshore wind
- Tidal range (e.g. tidal barrages)
- Wave and tidal stream
- Distributed renewable micro-generation
- Hydrogen production for transport
- Geothermal
- Hydroelectric power

**Energy Demand:**

- Lighting and appliances
- Transport energy demand
- Industrial processes
- Heating and cooling

**Non- energy GHG factors**

- Emissions from the waste management sector (disposal and handling of waste)
- Agricultural and land-use related emissions and energy demand
- Industrial process emissions
- Emissions from land use, land use change and forestry

**Non-GHG factors influencing overall GHG emissions**

- Fuel and electricity distribution infrastructure losses
- Electricity demand shifting and storage capacity
- Electricity interconnection and import / export capacity
- Petroleum and biofuel imports and exports
- Carbon storage facilities for storing CCS plant $CO_2$

Source: (BEIS, 2018e)

The tool runs as linked Excel spread sheets, using 2007 as a baseline year. The level of ambition that the user sets for each sector then defines growth assumptions of the size of the installed generating capacity or the amount of demand for the technologies represented.

The Calculator uses historical data up to 2012, primarily from the UK Greenhouse Gas Inventory (GHGI), which underlies the UK Government's reports on greenhouse gas emissions to the UNFCC. The GHGI, in turn, takes much of its data of fuel use and generation from the Digest of UK Energy Statistics (DUKES), which catalogues UK energy consumption on an annual basis, covering energy production and imports a breakdown of end-user energy consumption. DUKES brings together data from a wide variety of sources, some of which are very high level. Vehicle fuel consumption, for example is derived from tax information sales, on the assumption that most of the fuel sold to end-users each year is burned in vehicles. This offers a more accurate way of assessing transport greenhouse gas emissions than the alternative of estimating vehicle kilometres travelled and fuel efficiency of the vehicle fleet, but limits identification of the proportion of emissions that different classes of vehicle are responsible for by vehicle powertrains: it is possible to say that diesel road vehicles emitted a given amount of $CO_2$ in 2012, but not how much were emitted by freight, public transport or cars.

The Calculator's near-term forecasting for fuel consumption and the capacity and range of energy technologies deployed is based on the UK Government's Unified Energy Projections for the 2010s and early 2020s. Beyond 2020, it uses linear rates of change for technology deployment, decommissioning and fuel consumption to meet the end point in 2050 that the user sets through their scenario choices. Unlike the optimisation models considered in this study, the 2050 Calculator has no integrated ability to generate technology growth curves from scratch and the values of the curves used for each level for a parameter are set exogenously. However, their construction aims to incorporate the expected operating limitations, the efficiency of energy conversion processes, the known or estimated capacity factors for electrical generation types, lifetimes of plant and equipment and the energy content of various fuels. This provides the output of energy supply capacity, demand and other greenhouse gas factors required to describe energy scenarios out to 2050.

The technologies comprising each of these sectors are covered at a fairly high level, but with some unique granularities not seen in the other models considered in this study, particularly in relation to low carbon energy supply. The approach to micro generation as a separate energy sector is one such aspect. Large centralised renewable generation plant, such as wind farms, tidal ranges and geothermal plant that may be of a capacity of a similar order of magnitude to today's power stations are classified as "national renewables". Solar photovoltaic (PV), solar thermal and small wind plant are assumed to consist of large numbers of small units distributed across the country and are treated separately. This is on the basis that their deployment may be via addition to residential or commercial buildings, as well as the construction of dedicated power generation facilities. The levels and rates of deployment are thus linked to different factors than those affecting large centralised electrical generation plant, such as the number of households and available area of roof or wall space. Furthermore, in the case of small wind, the capital and operational cost of generation capacity is very different to large wind farms, due the different types of turbines used, the greater importance of wind resource assessment (Drew, Barlow et al., 2015; REH, 2018) and the greater opportunities for system optimisation of large wind turbine arrays (Wang, Li et al., 2018).

The approach to solar photovoltaics does not account for the growth of large, aggregated PV arrays, where very large numbers of PV panels are installed in an integrated manner on a dedicated site. Such "solar farms" have started to appear in the UK and other northern European countries, driven partly by financial incentives such as attractive mandatory tariffs for feeding renewable energy into electricity grids. Since these types of installations do not require buildings, they both add to the potential amount of PV that might be deployed and improve the cost and the ease with which this might be increased.

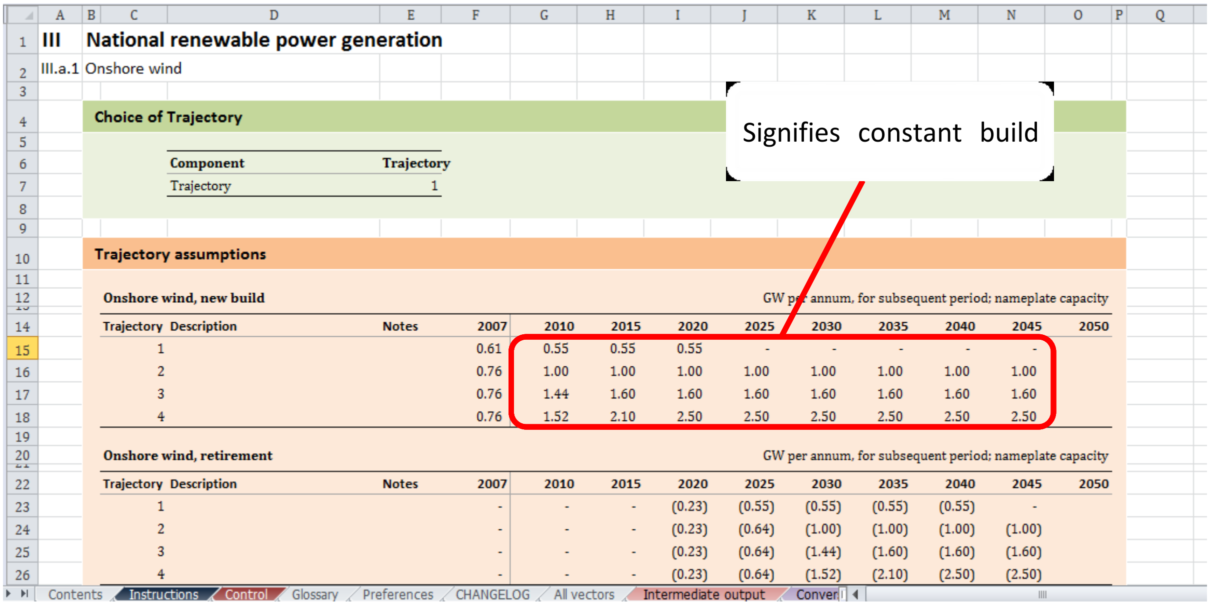
The Calculator also accounts for carbon capture and storage (CCS) and negative emissions technologies in a fine-grained manner. CCS power generation is represented as a separate suite of generation technologies to conventional combustion power stations and is used to substitute this plant. Pre-combustion and post-combustion CCS plant are represented in the calculator separately for solid fuelled generation. Gas fired CCS is represented as a third type of CCS plant. This is due to the different processes required to remove combustion products from the flue gas, prior to capture.

Negative emissions technology is represented in the tool as two separate “geosequestration” technologies to capture $CO_2$: via chemical processes that react the carbon in $CO_2$ into compounds that lock it away from the atmosphere and via mechanical capture systems that absorb $CO_2$ temporarily and then release it again for storage. Both processes feed into estimated data on storage costs of captured $CO_2$. Whilst this does not influence the levels of CCS deployment or the greenhouse gas emission budgets of a scenario, as would be the case in an optimisation model, this does still feed into the overall cost estimates of energy trajectories.

Bioenergy is treated as a primary energy source and its production and fuel supply chain is treated in a similar manner to petrochemical fuels: there are cost and emissions associated with production of the initial feedstock and further costs, emissions and efficiencies of conversion associated with the product supply chain. The final bioenergy products are considered equivalent to their non-biological counterparts: the section of the calculator describing power plant, for instance, does not discriminate between coal or solid biofuels. Instead, emission credits (which are effectively negative emissions in the Calculator’s methodology) are attributed to bioenergy feedstock at its point of growth.

### 3.2.3 Operation

Being spreadsheet-based, most of the Calculator’s interim data and assumptions can be inspected, altered and ported to other models (Figure 3.22). These include descriptions of power sector activity in terms of generating capacity, type and consumption of fuel, air quality emission factors– similar parameters that can feed into the UKIAM atmospheric pollution model or, potentially, some of the other energy modelling systems in this study. Furthermore, the tool's assumptions about plant efficiency and output allow one to describe the volume of fuel consumed, thereby allowing supply chain emissions of fuel production to be calculated.



Signifies constant build

**III National renewable power generation**

III.a.1 Onshore wind

**Choice of Trajectory**

| Component | Trajectory |
|---|---|
| Trajectory | 1 |

**Trajectory assumptions**

**Onshore wind, new build** — GW per annum, for subsequent period; nameplate capacity

| Trajectory | Description | Notes | 2007 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | 0.61 | 0.55 | 0.55 | 0.55 | - | - | - | - | - | |
| 2 | | | 0.76 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | |
| 3 | | | 0.76 | 1.44 | 1.60 | 1.60 | 1.60 | 1.60 | 1.60 | 1.60 | 1.60 | |
| 4 | | | 0.76 | 1.52 | 2.10 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | 2.50 | |

**Onshore wind, retirement** — GW per annum, for subsequent period; nameplate capacity

| Trajectory | Description | Notes | 2007 | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | - | - | - | (0.23) | (0.55) | (0.55) | (0.55) | (0.55) | - | |
| 2 | | | - | - | - | (0.23) | (0.64) | (1.00) | (1.00) | (1.00) | (1.00) | |
| 3 | | | - | - | - | (0.23) | (0.64) | (1.44) | (1.60) | (1.60) | (1.60) | |
| 4 | | | - | - | - | (0.23) | (0.64) | (1.52) | (2.10) | (2.50) | (2.50) | |

**Figure 3.2: Example of technology trajectory in the DECC 2050 Pathways Analysis Tool, showing spread sheet format**

The Calculator works by the user setting deployment and development levels for each of the sectors. These usually represent increasing ambition in development and deployment of low carbon energy technology, regulatory and behavioural change in society. However, a few parameters represent different options for deployment, such as splits between fuel types. Source data and assumptions about the ambition levels are based on views of experts and key movers in the sectors involved, with the intention that that the resulting levels of ambition do not relate solely to government proposals.

Parameters are not continuously variable in the simplified web-based versions and can only be set by the user at one of four pre-defined levels. In most parameters, the least ambitious Level 1 equates to little or no action being taken to reduce greenhouse gas emissions from the UK economy. Technologies stay as they are at pre-2010 levels and, in many cases, this represents a fall in ambition from both policies and the public trends. Whilst representing a "no change" scenario, this would be a very pessimistic future that effectively represents a hindering of current policy and technology trends. Ambitions rise through the second and third levels, representing respectively ambitious but "achievable innovation and behaviour change" and "significant change from current policy" and the likely technological breakthroughs required delivering this. The highest level (Level 4) is provided as an illustration of what might be the maximum capability possible within physical and technological limits in the time period considered. Most parameters set at Level 4 would be expected to require a considerable fraction of a developed economy's resources being diverted into achieving it and, for realistic scenario building, is best either avoided or limited to one area at most. The standalone spreadsheet version of the model increases the options beyond the web tool version by allowing the energy parameters to be assigned fractional values.

Several sectors have up to four options, defining the type of technology used to achieve the goal. The options for heating, for example, allow one to meet demand via multiple combustion or electrical technologies, which in turn influence the installed capacity requirements for electricity generation, biomass production and gas supply. Options for biomass allow different ratios of gaseous (via anaerobic digestion) liquid and solid biofuel production.

### 3.2.4 Air quality integration

In 2012, the 2050 Carbon Calculator was updated to include an indication of air quality impacts for four common pollutants: particulate matter, $NO_x$, $SO_2$ and non-methane volatile organic compounds.

Air quality is represented by assigning high level emission factors for direct emissions of activities and technologies. Largely, these correspond to the operation of overarching combustion technologies for the heating, transport and power generation sectors and to process emissions for key industrial and agricultural areas. A smaller number of relevant non-combustion activities, such as fugitive emissions from operation of the gas grid are also included. The conversion of directly emitted air pollutants to secondary air pollutants is not accounted for in the calculator.

There is some granularity in these figures. In domestic heating, for example, boilers are differentiated into age groups, but other emission factors are provided on a one-per-technology basis, such as for heat pumps, district heat and fuel cells. Assumptions need to be made for some of these: CHP plant is all deemed to be natural gas fuelled; industry is divided into limited areas (chemicals, metals and minerals); agriculture is divided in to land type and major livestock national level herds. However, this granularity does not account for variation in emission factors and costs due to variation of scale of installations for a particular technology. The Calculator does not, for example, have a way to account for the fact that aftertreatment is often more economical to apply to larger plan than smaller plant. It therefore cannot reflect the different levels of efficacy and cost effectiveness of applying carbon capture and storage or air pollutant abatement measures to a small number of large combustion facilities, rather than a larger number of small ones.

Vehicles are grouped around major current and emerging powertrain types, but with some notable omissions:

- cars include internal combustion, battery-electric, fuel cell and plug-in hybrid vehicles, but no pure hybrid vehicles;
- non-exhaust emissions of vehicles, such as from tyre and brake wear, are not included.
- emissions from off road mobile machinery (e.g. for the construction industry or agriculture) and certain non-road vehicles, such as military vehicles, are not included in the air quality emissions inventory.
- all internal combustion engine fuels are liquid, with no representation of natural gas or biogas;
- rail travel is limited to using diesel and electric powertrains;
- shipping is limited to internal combustion engine ships, running on bunker fuel. There is no explicit representation of alternative fuels such as liquefied natural gas or of proposed hybrid propulsion systems such as sail-assisted ships.

Reduction of air quality pollutants often depends on different technologies to those represented in the levels of ambition in the Calculator's controls, which aim to reduce greenhouse gases. Rather than include additional controls for measures to address air pollution, the Calculator presents two air pollution scenarios for each energy scenario, representing high and low levels of innovation in emissions reduction. These are derived solely from applying emission factors to the energy usage scenarios and do not account for any energy burdens or benefits of emissions reduction measures.

The Calculator also estimates the health effects of the air pollutants. The spreadsheet version of the tool does this by using impact factors derived from Defra's damage impacts model as used at the time of its design. This yields a figure expressed as cumulative years of life lost ("YOLLs") across the UK population. YOLLs are theoretically equivalent to the sum of the marginal reduction of lifetime expectancy for all those individuals exposed to a pollution source. Thus, a YOLL could represent significant damage to a vulnerable individual, it is more likely to represent a very small reduction of statistical life expectancy to a larger group of people. Because of the variable interpretation of YOLLS, whilst they form part of the internal calculations of the model, they are not used as an output metric. Instead, only proportional changes in the health impacts of air pollution form the energy scenarios are presented.

Since estimated air quality impact was introduced into the Calculator, YOLLs tend to have been superseded in UK air quality studies, due to the information they provide being linked only to mortality in the population. Whilst shortened lifespan is a high-impact effect, using aggregated mortality as metric does not account for the practical, personal and economic effects of the preceding periods of exacerbated ill health likely to be suffered from those affected, nor does it account for the similar impacts of periods of ill health from those unlikely to have their lives shortened (Defra, 2011).

### 3.2.5 Spatial Distribution

Whilst the 2050 Calculator has no true capability of representing the spatial distribution of energy infrastructure, there is an element of spatial impact included in its air pollution estimates, as the damage costs used assume current population distributions. So, as long as there is no geographical shift of the emission sources in each sector of the energy economy or major shift in population centres, the air quality impacts should hold true to the results on the impact model they are derived from.

### 3.2.6 Limitations

Being a simplified representation of a future energy system, the 2050 Calculator does not account for a variety of factors that may have a substantial impact on costs, emission budgets or technical feasibility of scenarios. Some of the key points are detailed below:

*Infrastructure*

There is no assumption made about the electricity grid’s capability for energy storage, which can increase the capacity factor for intermittent sources such as wind, which depend on environmental conditions and do not have “despatchable” generation that can be started up at will. Storage can allow energy fed into the grid at times of excess generation and reduced demand to be retained until demand rises, rather than the being discarded. This allows more energy demand to be met by a given installed capacity of intermittent generation. It can also be used to match inflexible baseload, such as nuclear power plant, to demand curves, potentially allowing higher levels of demand to be met by a given capacity of installed plant.

Currently, most of the UK grid’s electricity storage is in the form of 2.8 GW of generating capacity of pumped storage hydroelectric stations in Wales and Scotland (REA, 2016), which function on a national scale and connect to the high voltage electricity transmission network. Whilst this form of storage remains popular and proposals for new capacity have been granted (Southgate, 2017), newer technologies, such as lithium ion battery farms and cryogenic gas systems (Joyeux, 2019) are proposed to complement it. These offer different operating properties that help go beyond the capabilities of pumped hydro alone, from faster response times to lower capacity and greater power output. They also have the potential to sit on the lower voltage, more localised distribution electricity network, which may potentially help reduce network operation costs through lowering the maximum capacity demand for the transmission network.

There also no limits placed on the available supply of fossil fuels and biomass or on cost limitations for evolution of the energy system with time.

*Reciprocating engine generation plant*

The emission factors used for fossil fuel plant in the Calculator are consistent with the technology used in large, centralised generation. In the case of solid and liquid hydrocarbon fired plant this is an open combustion system, such as grate and fluidised bed combustors, in which fuel combustion raises steam in a boiler to drive the generator's turbines; in the case of gas fired stations, this is a closed cycle gas turbine system, where the generation turbines are powered both by fuel combustion and by raising steam from the exhaust gases. Both these systems offer the potential to be run as cogeneration plant, providing both heat, electricity and sometimes cooling to consumers and offering improvements in fuel efficiency of meeting energy demand.

External combustion boiler-based heat plant is highly scalable and can theoretically reduce to scale down to the kilowatt range, but in cogeneration it is limited by the efficiency and cost of small steam turbines. Gas turbine plant also has limitations on scalability, down to tens of megawatts. However, many CHP installations are smaller than this and tend to use gas or dual (gas and gasoil) fired internal combustion reciprocating engines, which operate on the same mechanical principles as natural gas and diesel vehicle engines. These have very different emissions characteristics and fuel efficiency than either gas turbine or boiler based plant and the impacts of any partial shift to these will not be represented in the Calculator's scenarios.

### *Plant size*

Electricity and heat generation are only defined in terms of capacity, with no information of the numbers or size distribution of plant. Smaller average plant size for any given capacity of generation type in a scenario, implies a greater number of units being deployed. However, it is also likely to represent a smaller geographical footprint per plant and thus a greater number of locations in which a plant might be deployed. This increase in flexibility of location and plant numbers is likely to affect the geographical distribution and the degree of diffusion of air pollutant sources.

Assumptions about plant size that hold true today may prove to be less valid in future. Large heat plant, for example, often depends on large "anchor load" customers that use heat for processes that provide a long term, stable, seasonally independent demand for the majority of a plant's output. Whilst such plant can include smaller commercial and domestic customers in its portfolio, most of the heat demand of these smaller consumers tends to be for highly seasonally, weekly or diurnally variable purposes, such as space heating. Too high a proportion of small consumers would therefore likely lead to underutilisation of a large heat plant's capacity and thus reduce its economic feasibility.

Scenarios with heat supplied through a high proportion of large, centralised plant (such as very large CHP power station heat and power) may therefore be expected to have a relatively small number of plants located in areas close to their largest customers. This would result in a small number of potentially high-output sources of $CO_2$ and air pollutants. Their anchor loads are less likely to be near residential areas and more likely to be near large consumers on industrial sites, reducing the likelihood of long-term exposure to pollution for a large proportion of the local population. Furthermore, the cost effectiveness and efficacy of deploying air pollution abatement measures is likely to be better for large plant (USEPA, 2018).

Smaller heat plant would be likely to be much more flexibly deployable and thus geographically widespread, due to the greater incidence of customers for it. Not only should smaller average plant size lead to more potential sources of air pollution, but it is also likely to lead to these sources being located closer to populated areas. Although the energy demand may be similar in both cases, the latter case is likely to expose more people to pollutants than the former.

*Lack of environmental damage costs from air pollution and of net cost representation*

Whilst the calculator has an estimate of human health impacts and costs built into it, this does not extend to non-human health and environmental impacts. In the UK, key impacts include (Defra, 2019b):

- Acid deposition from air pollution, causing damage to habitats and biodiversity through acidification of water and soils, direct damage to plants;
- Damage to buildings and landforms through acid pollutants increased erosion and corrosion of materials such as stone and metals;
- Oxidative stress on plants, impacting on crop growth and land use, which can occur from acid pollutants and from secondary ozone;
- Eutrophication of water bodies through deposition of nitrogen compounds.

Non-health environmental damage costs are arguably one of the dominating drivers of an international approach to addressing transboundary air pollution, since it was as a result of the identification environmental damage from acid deposition in Scandinavia that the Gothenburg Protocol was originally proposed. Their omission from the Calculator leaves the user in the position of being unable to compare some of the air quality benefits and cost savings of the energy scenarios to the capital costs of the scenarios and this may lead to perception of the net cost of the scenarios as being higher than they are. In a similar manner, the fact that the health costs are not monetised in any way prevents any integration of them into a net cost estimate, further increasing the potential for such misinterpretation.

### *Absence of ammonia modelling*

Ammonia is a pollutant that has significant environmental damage costs in terms of potential for acidification, eutrophication and secondary particulate formation. The 2050 Calculator is unique in the air quality assessment tools considered here in that it does not include ammonia as one of the air pollutants that it covers.  This is likely to be because it is not associated with fuel combustion, with its main source being the agricultural sector and most emissions associated with energy production arising from anaerobic digestion. Secondary pollutant formation mechanisms suggest that ambient ammonia can exacerbate the impact of air pollutant emissions from energy. The agricultural origin of much ammonia also suggests that increases in the growth of biomass feedstock could result in ammonia emissions associated with emerging energy technologies, although it is uncertain how much of this would be additional if it displaced other crops. In either case, the absence of ammonia from the 2050 Calculator is likely to result in an underestimation of impact of the overall energy scenarios generated by the model.

### *Lack of account interaction of costs between GHG and AQ*

The way the model handles innovation in reducing air quality pollutants does not account for some of the costs and impacts of greenhouse gas emissions of abatement technology. Those that are included tend to be calculated from the energy use data in the spreadsheets. These are air pollution abatement measures that rely on reducing the amount of fuel burned or on reducing the use of products that are energy intensive to produce, such as fertilisers. Both of these deliver reduction in air pollution as a co-benefit of greenhouse gas emissions reduction. They are derived by applying air pollutant emissions factors to the combustion and industrial processes.

In contrast, many active processes for removing air pollutants from combustion systems, such as SCR systems on vehicle engines and generators, can reduce the overall energy conversion efficiency of the system using it. Furthermore, methods of reducing $NO_x$ emissions that rely on the reduction of combustion temperature, such as fluidised bed combustors for boilers and power stations can lead to an increase in the production of $N_2O$ (Mann, Collings et al., 1992; Wójtowicz, Pels et al., 1993; Armesto, Boerrigter et al., 2003). Unless removed, $N_2O$ can increase the radiative forcing effect of the flue gases substantially. Such interactions are not included in the 2050 Carbon Calculator.

*Supply chain limitations*

Some scenarios include very high increases in rates of build of technologies achieved over short periods of time. These are only realistic if the supply chain can be developed sufficiently quickly to support this build and is likely to be influenced for each technology by:

- Growth of worldwide manufacturing capability, to provide sufficient hardware to install in the UK;
- Variation in levels of worldwide demand that is high enough to incentivise the growth in manufacturing, but sufficiently low as to not limit the amount of hardware exported to the UK. This requires long term confidence in global demand to build manufacturing capacity.
- Sufficiently rapid growth in the UK skills base for installing the hardware, including sufficient long-term confidence in the market for the technology to convince the workforce to invest its time into gaining these skills. Thus, a high level of installation of a technology in 2050 is likely to imply ongoing build at similar rate for some time into the future.

If these factors are not accounted for, the model may permit situations to arise that might imply a “cliff-edge” decrease in deployment of a technology after 2050. This is not impossible, but it is unlikely if it is foreseeable, as an expectation of a sudden fall in demand for build of a new technology may provide a disincentive for suppliers to enter this market at a late stage. Incumbent suppliers of the technology would also likely try to manage their workforce and manufacturing capacity away from the technology, in order to avoid labour market disruption and a sudden decline of employment when the technology is fully deployed. Both these would contribute to a slowing of the rate of installation towards the end of the deployment period.

Higher rates of build of some technologies that occur in the calculator in later years of the scenarios in this study (such as the geometric rate of increase in solar PV installations in Scenario 2) may thus be unrealistic. If they occur, the ultimate level of deployment beyond 2050 will likely exceed the 2050 figure; if they do not occur, the target figure for 2050 will likely be reached later. This is also likely to apply to infrastructure supporting technologies, such as that needed for $CO_2$ transport for carbon capture and storage systems. CCS enabled power stations may be hindered in start-up by rates of build of $CO_2$ pipeline.

*Road transport*

Road transport represents technology shift in a simplified fashion. Cars are limited to conventional internal combustion engine (ICE) vehicles, plug in hybrids, battery electric or fuel cell vehicles. There is no variable assumption over the split between petrol and diesel cars, hybrids that lack plug in capability are not considered as a distinct vehicle class and fuel cell vehicles are presumed to only use hydrogen fuel cells, rather than a additional technologies such as solid oxide based natural gas fuel cells.

The fixed assumptions on the fuel type for ICEs and the lack of granularity on hybrid vehicle powertrain architectures are key sources of long-term uncertainty in the calculator for both $CO_2$ and air pollutant emissions, due to the large size of the transport sector and the multitude of approaches to these types of powertrain. Later chapters of this study explore the reasons for this in more detail. The average life of a car in the UK is around 14 years (SMMT, 2018), leaving the market over two cycles of replacement of an average car in which to standardise around novel technology before 2050. This highlights uncertainty over how technologies in future vehicle markets may mature.

*Shipping*

As with all sectors in the Calculator, the international shipping trajectories are based on estimates of improved technical and operational potential. However, unlike the other sectors, these trajectories all have the same changes in shipping activity, with the predictions of goods imported and exported per person and the number of vehicle kilometres undertaken by ships per head of UK population being assumed to remain the same across all scenarios. These assumptions and trajectories are based on a study commissioned by the Department for Transport (DfT) in 2011 (AMEC, 2011). Changes in consumption of overseas goods and influence on energy use for shipping are not accounted for.

### 3.2.7 Illustrative 2050 scenarios

Illustrative scenarios are provided to demonstrate the sensitivities of the Calculator to changes in energy trajectories and the key contributors to these. Detailed information on sectoral energy demand, electricity generation and emissions of air pollutants and greenhouse gases are provided in Annex I. Air pollutant emission trajectories are provided for scenarios of both high and low innovation for air pollutant abatement.

#### *Scenario 1: No ambition*

This scenario demonstrates a future with little change in effort to reduce $CO_2$ emissions from 2015. Few measures are introduced in terms of energy efficiency and some may represent a fall back in progress from the current policies. Some measures do continue, such as continued build of photovoltaic generation, which has seen a significant increase since 2010, as the result of feed-in tariffs.

Thermal electricity plant generation grows, with a high dependence on coal. New nuclear generation fails to appear and the current UK nuclear fleet reaches its end of life around 2030 with no replacement.

Onshore wind in the model reduces towards 2050, as decommissioned sites are not replanted, but offshore wind is maintained. Wind generation increases to a point at which modelled installed capacity in 2015 is roughly similar to actual installed capacity, although the real-world capacity factor for wind generation in the UK at this point in the time series is actually higher than that in the model, resulting in the model underestimating how much wind generation might take place from a given capacity of turbines.

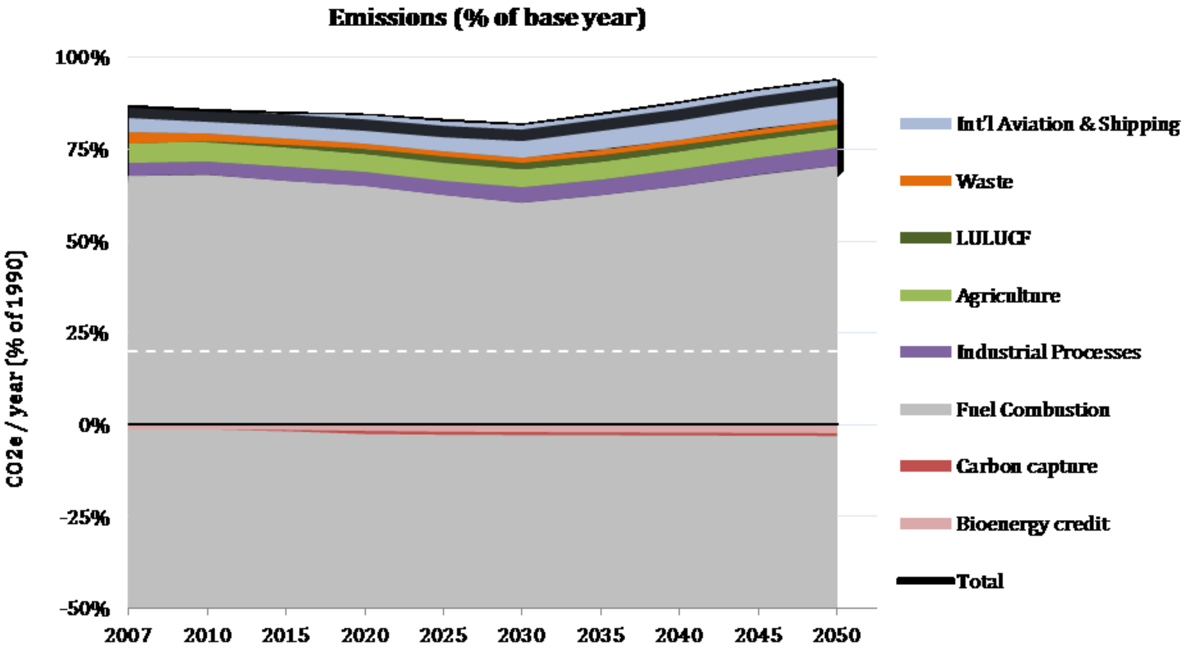


**Figure 3.3: Scenario 1 emissions trajectory**

This is likely due to the increase in size of wind turbines and resulting increase in capacity per turbine. Whilst it is possible to manually update the Calculator's data on changes in wind turbine capacity factors in some versions of the Calculator, this capability is not made clear, it is not available in the web-based interfaces for the Calculator and the default configuration of the Calculator does not account for this. The underestimation of wind generation capacity and consequent overestimation of generation from other sources illustrates one way of how misleading results can arise from poor representation of renewable technology options in the Calculator and the other models (GAINS, UK TIMES) considered in detail in this study.

In transport, rail freight takes up additional demand for goods transport, but this maintains current levels of line electrification and locomotives on the non-electrified part of the network are fuelled by diesel.

Car use increases (from 492 to 668 billion vehicle km), with 77% of the distance that light vehicles travel being undertaken by purely internal combustion engine machines, which are assumed to be twice as fuel efficient as current vehicles. This is a significant leap from current performance although the Calculator offers no detail or options on how this is achieved.  A wide variety of options could deliver this:  technology-led, such as designing lighter vehicles, reducing rolling resistance and powertrain shifts such as electrification or changes in efficiency or size of the engine); operational-led changes, such as curbing maximum speed and acceleration to reduce air resistance and traffic congestion (and thus reduce fuel consumption per vehicle kilometre); consumer-led changes, such as a preference for smaller vehicles, or for increased vehicle occupancy (which reduces emissions per passenger kilometre). However, there is no indication or control of the level of influence each of these factors plays, with the exception of consumer choice of powertrain electrification and vehicle occupancy.

Many of the technology-led and operational-led changes are likely to contribute to reduction in both $CO_2$ and air pollution emissions per unit distance travelled but may also affect the vehicle's ability to deliver service demand. However, the most common methods of improving the thermodynamic efficiency of engines may involve increasing the combustion temperature, with the diesel engine being a prime example.

There is still significant uptake of plug in hybrid cars, with the remaining 20% of light-duty vehicle kilometres being undertaken by them, along with a very small presence of pure battery electric cars.

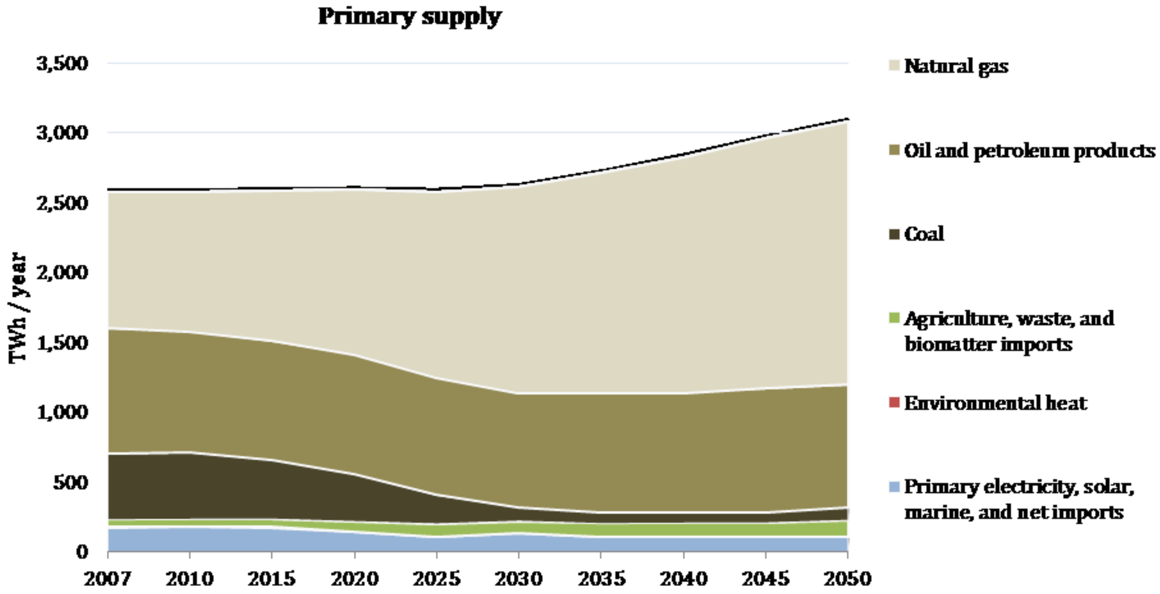


**Figure 3.4: Scenario 1 primary energy supply trajectory.**

Air quality emissions in Scenario 1 differ markedly between high and low innovation scenarios. With high innovation on air quality emission improvements, the level of 2050 PM emissions falls from about 161 kt in 2015 to 30 kt in 2050 and $NO_x$ emissions fall from 1573 kt to 590 kt in the same time. With low innovation, both PM and $NO_x$ emissions see a minimum level reached by 2030 of around half and two thirds of 2010 levels respectively, followed by a gradual increase again that reaches 92 kt of PM and 1279 kt of $NO_x$ by 2050. This is linked to a fall in large and medium combustion plant up to 2030, which drives a decrease in coal fired power stations and larger distributed electricity generation and heating systems with generation capacity above a given threshold and a correspondingly higher level of emissions.

Despite these changes, most of the sectors represented in the Calculator see improvements in most sectors, even in low innovation scenarios and even in this “no ambition” case. The major changes tend to be produced by a minority of sectors. The increases in $NO_x$ are largely driven by international shipping, which sees a 78% increase by 2050 on 2010 levels and accounts for just over half of all the 2050 emissions of $NO_x$ in the low air quality innovation variant of the scenario. For PM, the increases are driven by industry which accounts for about one half of all PM emitted in 2050 in the same variant.

### *Scenario 2: High offshore wind, nuclear as planned at 2009 levels*

This scenario demonstrates a future in which climate objectives are met through high levels of low carbon electricity, but a low reliance on combustion plant for electricity generation. Wind grows rapidly (with installed capacity and generation by 2015 reaching 20% above actual levels). Photovoltaic build proceeds more slowly, with real-world 2015 levels of around 10 GW capacity not achieved until 2035. PV deployment continues to grow markedly after 2035, increasing by a factor of about 1.8 every five years to reach around 70GW by 2050. The success of such a late acceleration of PV deployment hinges on both the ability to grow the supply chain in order to meet this and the ability for the electricity grid to manage a high level of intermittency in generation.

About 20% of cars are still pure internal combustion engine, with 32% being plug-in hybrid vehicles, 38% battery electric and 10% fuel cell. Changes in goods transport represent a greater modal shift to rail and water, more efficient HGVs with fuel consumption of around 45% of current consumption per vehicle km and improved efficiency in distribution and logistics.

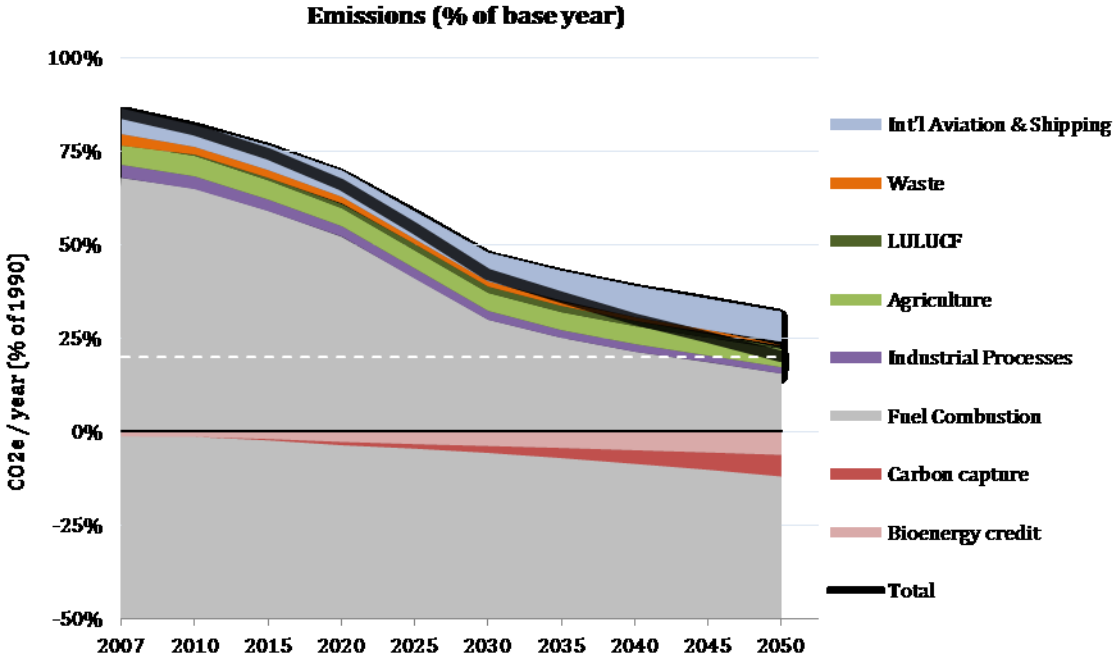


Figure 3.5: Scenario 2 emissions trajectory

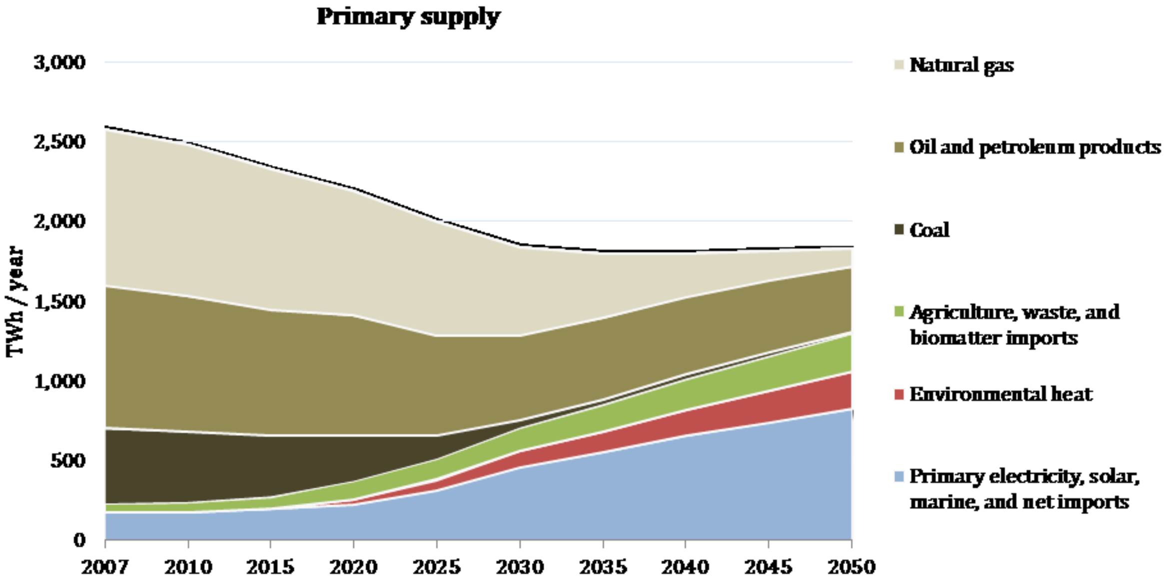


Figure 3.6: Scenario 2 primary energy supply trajectory.

International shipping is presumed to achieve significant improvements in efficiency, which is important, as it is the largest contributor of $NO_x$ emissions in both high and low innovation variations of this scenario. This shows a 14% increase in fuel consumption. If it is assumed that the amount of vehicle km remains constant across scenarios, this describes an approximately 220% increase in international shipping capacity fuelled from the UK. Between low and high innovation scenarios, this makes a difference of 192 kt $NO_x$ emitted, with the overall international shipping contribution being 320 kt $NO_x$ out of a national budget of 586 kt $NO_x$ in low innovation 2050 scenarios. This would be by far the largest contributor to the UK $NO_x$ budget. In 2018, international shipping from all sources was estimated to contribute around 650 kt $NO_x$ emissions to the UK's annual exposure, which may be affected significantly in such a scenario.

*Scenario 3: Low cost, high nuclear, low intermittency*

This scenario demonstrates a future with a low cost of achieving climate targets by 2050 and is based on one of the original ones suggested by the carbon calculator team. It meets 20% emission reduction targets by achieving a high degree of electricity use and by driving electricity towards very large, low carbon baseload, resulting in 70 GW nuclear generation capacity by 2050. This value was chosen as it represents the maximum build in the UK's nuclear R&D roadmap (HMG, 2013) and corresponded to roughly the average annual build rate at which France deployed fission reactors in the 1970s to 1990s – the highest achieved by a western European economy. Realistically, achieving this level of build would be dependent on growing a robust and reliable supply chain for nuclear construction. During the few years after the creation of the Calculator, UK nuclear construction projects fell behind schedule making the high levels of nuclear generation capacity in this scenario still potentially possible in the long run, albeit unlikely by 2050.

By 2050 electricity is almost entirely decarbonised and around 95% nuclear generated, save for a small amount of gas-fired balancing plant and the sector as a whole emits no more than 1 Mt $CO_2$.

Space and water heating in the domestic and commercial sector is highly electrified, with no deployment of district heat networks. All heat for these purposes that is not electric continues to be provided by combustible mineral fuels or biofuels. A future shift to biofuels may result in greenhouse gas reductions, but that which has occurred so far has posed air quality risks in in Europe (Cordell, Mazet et al., 2016).

Passenger transport demand remains roughly the same as current levels, although the distance travelled per person by car falls by around 25% due to an increased shift to using rail transport and buses. Of this, buses are responsible for supporting about three quarters of this shift with around 40% using hybrid powertrains and the remainder using conventional internal combustion engines. Like heating, light-duty vehicles and buses have a high degree of electrification, with around half of all cars being battery electric and around a third being plug-in hybrids. There is no use of hydrogen for transport and no deployment of fuel cell vehicles.

The amount of energy provided by biomass in 2050 doubles on current levels to 71 TWh / 255 PJ with considerably increased land use efficiency than today: this is achieved entirely from domestic production and from the same amount of land currently used, with biomass imports falling to zero. Most of this is in the form of gaseous or solid fuels, with only around 10% of bioenergy available as liquid biofuels for transport use.

The impact this has on air pollution is to maintain overall PM emissions in 2050 at similar levels to Scenario 2 in both high and low innovation scenarios, with the key risk to air quality from PM arising from how effectively industrial emissions are addressed. $NO_x$ emissions in 2050 are around 160% of Scenario 2 levels for both high and low innovation scenarios, mainly attributable to a rise in emissions from international shipping in both cases.

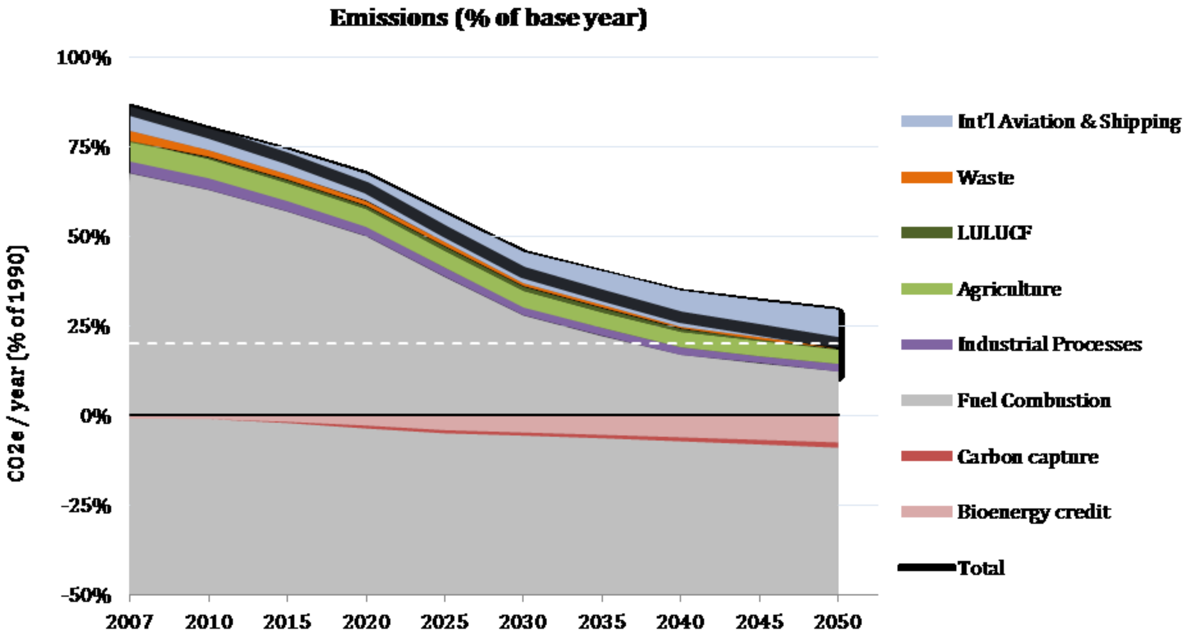


**Figure 3.7: Scenario 3 emissions trajectory.**

The level of nuclear power plant build in Scenario 3 is equivalent to around 23 large power stations of similar capacity to the Hinkley Point C under development in Somerset, or around 30 stations of the type based on the ABWR reactor type that was proposed Hitachi-GE for the Horizon Nuclear Power project. This is equivalent to the build of one 3 GW power station every year between 2020 and 2050, equating to roughly half the rate of growth of nuclear generation in France in its most intense phase in the 1980s, which resulted in around 60GW of net nuclear generation capacity coming online between 1980 and 1992 (Etalab, 2013).

Whilst this rate of build was certainly possible in France at the time, it remains questionable whether it could be achieved in the UK today. Part of this is due to the supply chain: UK (and, indeed, French) heavy engineering facilities in the 2010s are substantially different to those in France in the 1980s and the global manufacturing capacity of key components, such as reactor pressure vessels, are constrained to a few sites worldwide. The ability and affordability of developing current supply chains at national and global level to manufacture sufficient numbers of components to support such a rate of build is thus not certain. Furthermore, the regulatory and planning regimes for nuclear power plant have developed in the meantime and, taking progress of currently proposed nuclear build in the UK, it appears to take longer to meet regulatory requirements.

Additional to the challenge of building nuclear generation facilities, the feasibility of such a future scenario hinges on the capability of the grid to balance a large amount of inflexible baseload generation against patterns of electricity demand.

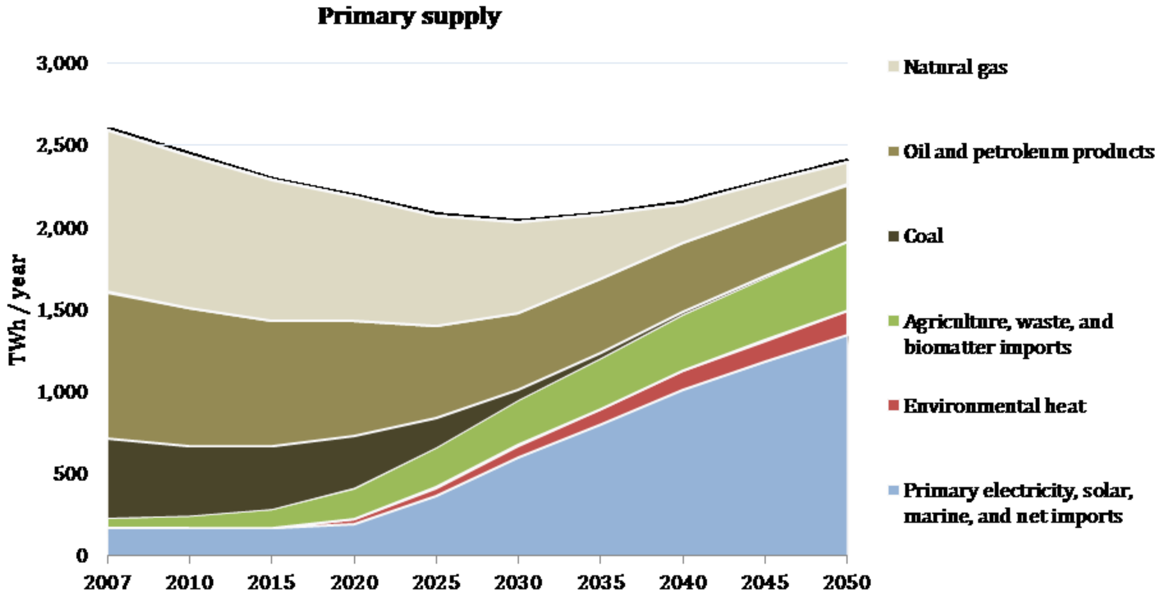


**Figure 3.8: Scenario 3 primary energy supply trajectory.**

*Scenario 4: Well developed CCS*

This scenario demonstrates a future with a high degree of carbon capture and storage. Two thirds of bioenergy resources are producing solid fuel, which is burned or co-fired with coal in CCS equipped power stations. This leads to a significant dependence on negative carbon emissions from bioenergy CCS and thus on the long-term reliability of carbon storage facilities. Other low carbon electricity supplies remain developed to varying degrees. Nuclear energy declines from 2016 levels in the

2020s but recovers to slightly higher than 2016 levels by 2050. Offshore wind grows more slowly in the 2010s than has been observed but maintains growth to a capacity of 18 GW by 2050.

Road transport sees a significant decline in energy demand due to improved efficiency in internal combustion engines and improved efficiency in vehicles.

$NO_x$ and PM emissions in high innovation scenarios compare well to those trajectories in Scenario 3 and International shipping is also a key risk to $NO_x$ emissions in low innovation scenarios. The greatest risk to PM emission levels comes from heating in the domestic sector and arises from domestic heating, which releases 70kt per year of particulates, resulting in the national emissions budget for PM being around twice that of the other scenarios considered here. This would appear to be driven by the abundance of solid biomass for combustion for energy, which is an effective source of particulates and volatile organic compounds. A scenario such as this would deliver a significant increase in health impacts from particulate air pollution, in comparison to those with lower biomass combustion.

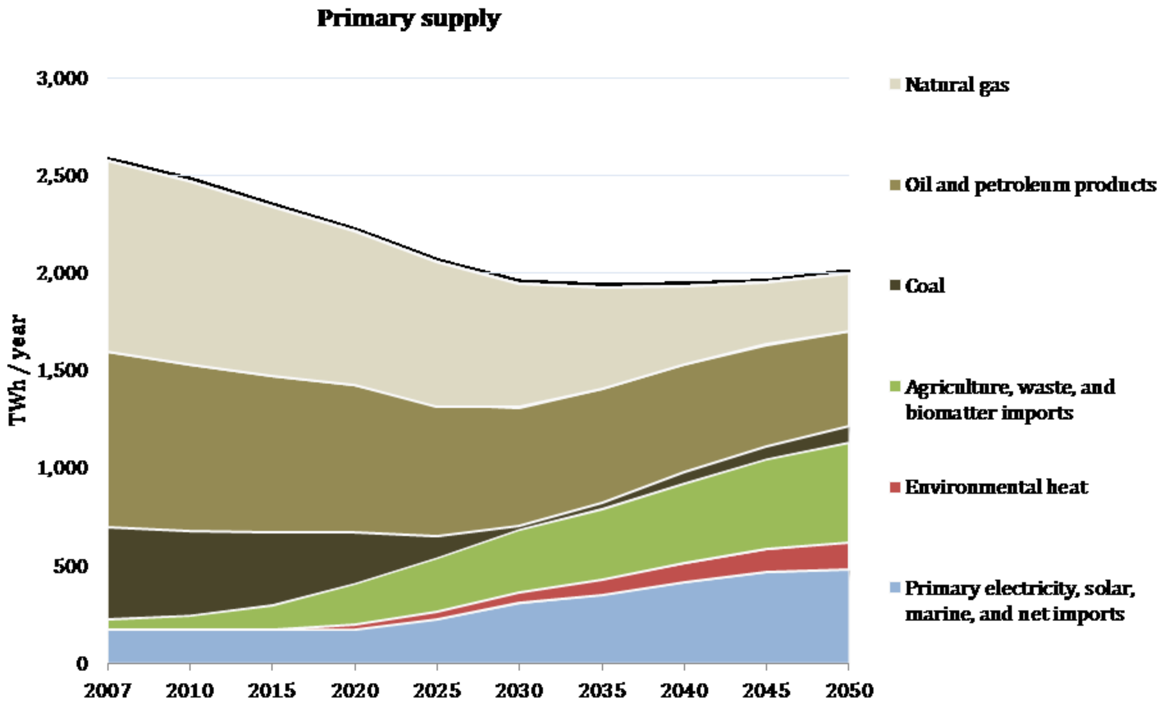


**Figure 3.9 Scenario 4 primary energy supply trajectory.**

Another key difference is seen in the level of $NO_x$ emission from the electricity sector, which ranges from between 43 kt - 87 kt for Scenario 4 in comparison with 14 kt - 30 kt in Scenario 2 and virtually zero in Scenario 3, which relies heavily on nuclear and renewables for electricity. It raises questions about the assumptions about the CCS technology used in the Calculator. Whilst pre-combustion capture systems can reasonably be expected to burn a hydrogen-rich fuel without necessarily using $NO_x$ abatement (Nazir, Bolland et al., 2017), many post-combustion CCS solvents require very low levels of $NO_x$ to be present in the flue gas in order for the CCS system to operate effectively (Wang, Zhao et al., 2017).

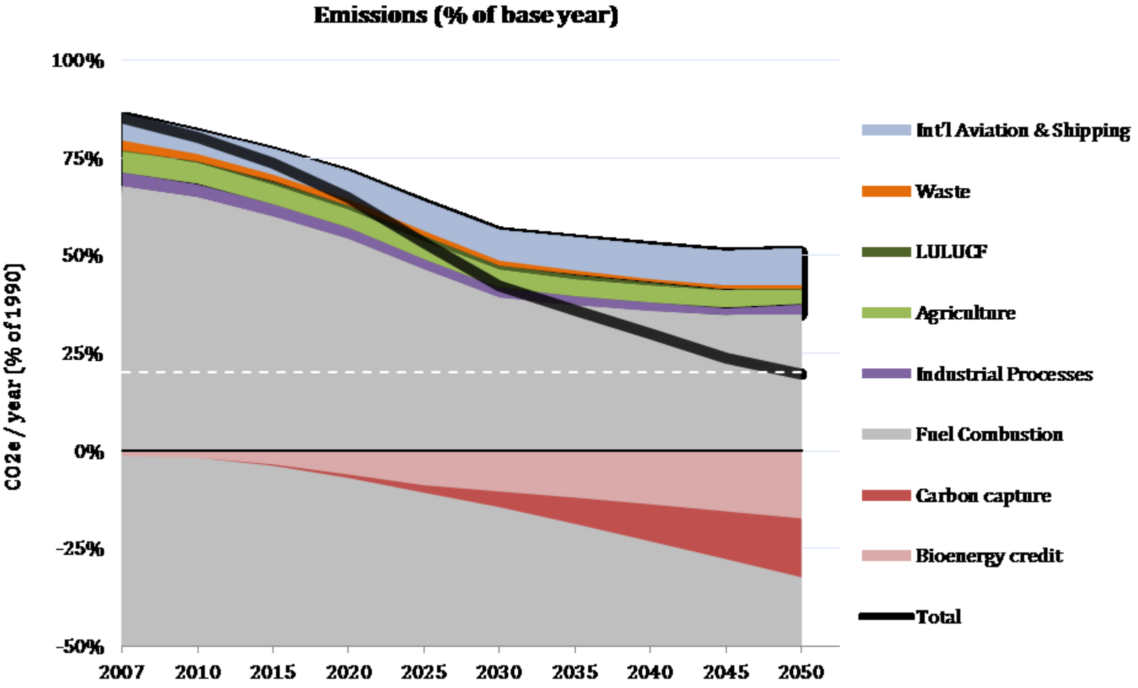


**Figure 3.10: Scenario 4 emissions trajectory.**

In its original build, in which the Calculator only considered greenhouse gas emissions, the type of CCS technology deployed was less critical to the Calculator's output and there was no capability to discriminate between CCS systems and their impact on air pollution. Whilst the updated version introduced an analysis of air quality impact, it retained the limitation in the way that CCS is represented, which hampers the exploration of the benefits and trade-offs of different CCS approaches.

Regardless of this, comparison of scenarios 2 and 4  and scenarios 3 and 4 provide a clear examples of how different energy scenarios with very similar carbon abatement targets can result in very different air quality impacts.

### *Scenario 5: High CCS with power station CHP and improved shipping efficiency*

Scenario 5 is a variation of Scenario 4, and retains the same electricity generation infrastructure. Key differences are that low grade domestic heat is sourced from electricity generation plant operating as cogeneration plant and is distributed to homes via heat networks wherever feasible. Additional technical innovation occurs through further improvements in the efficiency of international shipping, in comparison to Scenario 4.

Of these measures, the CHP and heat network actions deliver a further $CO_2$ reduction of 3% off 1990 levels by 2050 and the shipping measure a further 2% reduction. $NO_x$ emissions in 2050 under high and low innovation scenarios are around 75% of their respective levels in scenario 4 and particulate emissions are similar to Scenario 3, with the domestic component of the PM budget being almost zero.

Scenario 5 is a clear illustration of both how air quality impact can be influenced considerably by the choice of low carbon generation technologies, as well as of how simultaneous benefits can be achieved in terms of air quality and climate emissions by technology choice.

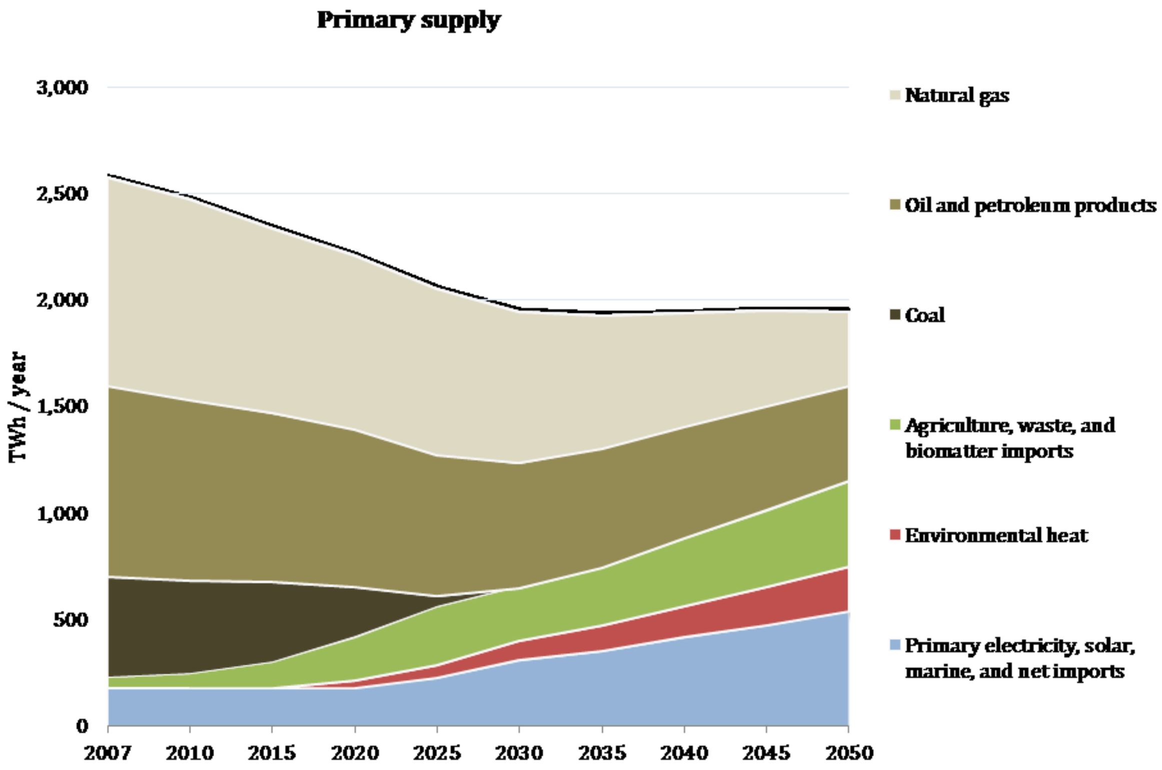


**Figure 3.11 Scenario 5 primary energy supply trajectory.**

Scenario 5 would appear to have a higher dependence on infrastructure than many of the previous scenarios: both CCS power generation and heating networks require significant upfront investment in pipelines in order to distribute heat and transport $CO_2$ to repositories. This is likely to have a significant investment cost, which may be a barrier to deployment and will vary depending on the location in which the infrastructure is deployed, due to the demands of local geography and population density. These are highly spatially dependent factors which the Calculator does not account for, as it lacks any representation of location.

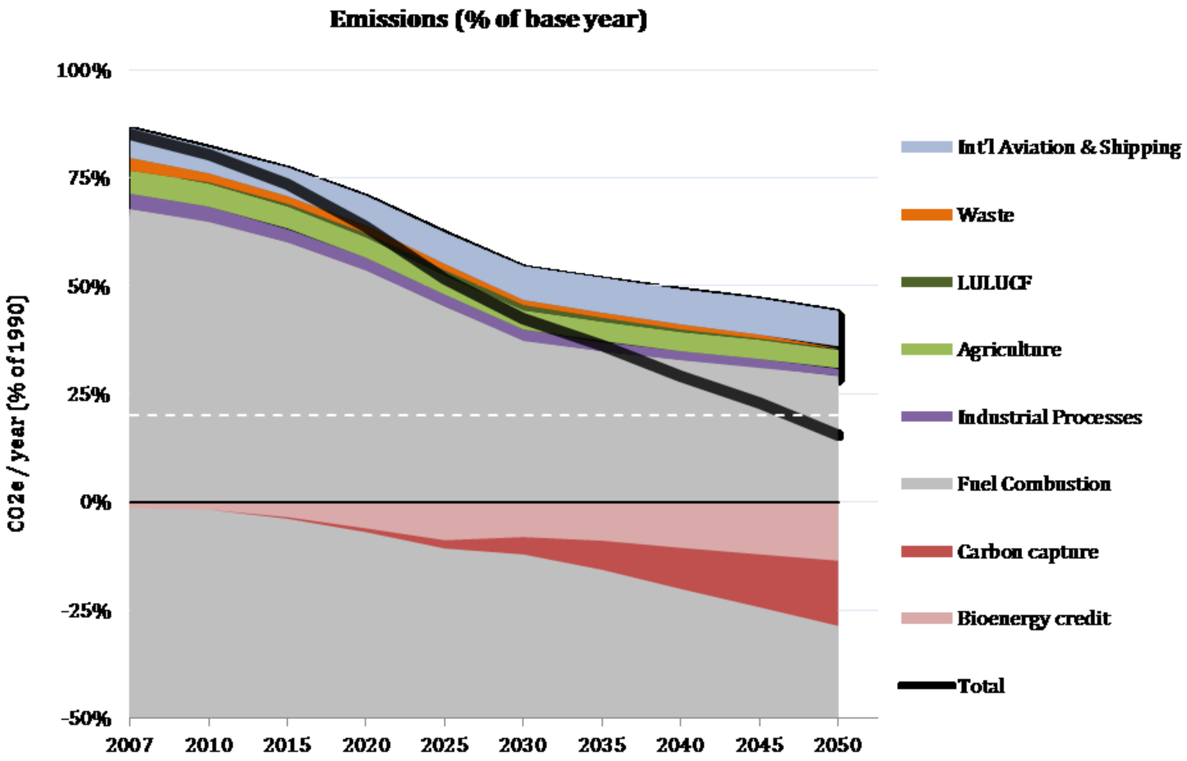


**Figure 3.12 Scenario 5 emissions trajectory.**

### 3.2.8 The 2050 Carbon Calculator's role as an analysis tool

The 2050 Carbon Calculator is well-suited for illustrating counterfactual energy trajectory scenarios and exploring some of the possible trade-offs and benefits of decarbonisation actions. It represents a top-down model of the energy economy and therefore is limited in the range and granularity of technologies it can cover. Areas in which it potentially offers advantages over other models include its incorporation of negative carbon technologies, such as biomass energy carbon capture and storage and its accounting for carbon storage from biomass growth ("bioenergy credit"). However, the assumptions and representation of technology classes (e.g. hybrid vehicles) are relatively inflexible and do not distinguish between technology implementation options. In the case of many emerging forms of energy use, this can encompass a wide range of options with different emissions characteristics. This may introduce a significant margin of error for both greenhouse gas emissions and air quality pollutants from large sectors undergoing significant shifts, such as transport might.

As the 2050 Calculator is not an optimisation model, deployment rates are based around either predefined near-term assumptions and longer-term linear rates of change. Whilst these are user editable in the spreadsheet version of the calculator, assumptions need to be exogenous. This is helpful for studies of the outcome of successful deployment targets, such as may be undertaken in the early stages of policy assessment but is likely to be a hindrance in more detailed studies.

The scenarios here all include combustion technologies and there is no option in the data input available to force some combustion sectors to zero, such as the use of fossil fuels. This may prove a challenge for exploring some scenarios in which there are zero net carbon emissions. Whilst scenarios with net emission lower than 80% can be achieved by offsetting through aggressive deployment of biomass CCS. Furthermore, because the Calculator is a description of the energy system, it focuses only on real UK emissions. It excludes the use of tradable emission reduction credits to reallocate greenhouse gas emission reductions made by other countries to the greenhouse gas emission budget that the UK reports internationally. This excludes it from exploring a further set of scenarios which allow the use of such credits in achieving net zero greenhouse gas emissions.

## 3.3 GAINS

### 3.3.1 Purpose of GAINS

The Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model has been developed by the International Institute of Applied Systems Analysis (IIASA) with the specific intention of comparing the interaction of measures to control emissions of air quality pollutants and greenhouse gases.

GAINS is a techno-economic integrated assessment model that assesses the health and ecosystem impacts of air pollutants, acidification, eutrophication and tropospheric ozone, whilst also considering the impacts of greenhouse gases mitigation measures. It was evolved from an earlier air quality emissions and impact assessment model, RAINS (Regional Air Pollution Information and Simulation), which was developed to facilitate the negotiation of international agreements on reducing air pollution. RAINS was a key tool in agreeing $SO_2$ emission limits under the Convention on Long-range Transboundary Air Pollution and in determining the content of the Gothenburg protocol. GAINS offers substantially expanded capabilities over RAINS in its modelling of $CO_2$, methane, $N_2O$ and F-gas emissions in addition to the original model's remit of ammonia, $SO_2$, $NO_x$, volatile organic compounds and particulates in size categories $PM_{10-2.5}$ and $PM_{2.5}$ (Klaassen, Amann et al., 2004) and has since proved its worth in updating the Gothenburg protocol (Amann, Bertok et al., 2012).

As an integrated model, GAINS interacts with other models in setting up and running optimisation scenarios. PRIMES is a model that describes the energy system and economy, including fuel and power production and availability, activity (e.g. usage) data, carbon process and credit availability in the EU's Emission Trading System for greenhouse gas emission reduction credits. CAPRI is a model of agricultural activity, which covers assets and production such as numbers of animals or meat, milk and grain produces, as well as activities such as fertiliser use. These are used as data input modules for GAINS runs and the output from GAINS feeds back into them when optimisation routines are run.

GAINS provides atmospheric modelling at regional (e.g. continental) scales in five year time slices, with the GAINS Europe version of the model forecasting out to the year 2030. National level versions also exist for some countries, although the native GAINS pollutant dispersion modelling tends to be replaced by a bespoke national tool. Running a basic scenario requires projections of future energy demand and agricultural production, data on emissions control or mitigation technologies, rates of application of these measures and cost data. These feed into the following components (EC4MACS, 2012):

- A description of an economy and human behaviour in terms of (i) energy demand; (ii) sectors of activity (such as agricultural processes), transport volumes and industrial production; (iii) primary energy supply and fuels supply chain. Initial energy activity data, such as fuel supply and consumption, and agricultural activity data are exogenous inputs, taken from the PRIMES energy model and the CAPRI agricultural model respectively.
- Data on emission characteristics of incumbent processes and technologies in use.
- Calculation of the impact of emission reduction or abatement measures. These include structural measures, such as energy efficiency, which deliver the same level of service to the customer and technologies that remove or reduce emissions.  This component uses data on estimates of each measure's efficacy and of how widely or severely it is deployed.
- An air pollutant atmospheric dispersion model used to calculate concentrations and deposition of air quality pollutants. GAINS currently uses the Unified EMEP Eulerian model, which has been developed by the European Monitoring and Evaluation Programme (EMEP) Meteorological Synthesizing Centre West to support the Convention on Long Range Transboundary Air Pollution. This is a Europe-wide model, which provides a spatial description of the transport of the pollutants for long range transboundary air pollution (NMI, 2018). It predicts the transport, dispersion and chemical reaction pathways of a wide range of primary and derivative pollutant emissions in the atmosphere on a 50 km x 50 km grid.

- A health and ecosystems impact model, which describes the physical effects of changes in emissions and monetises them. Greenhouse gas emissions data predicted from the emissions data feed directly into this section but air pollutant emissions data do not.

The first three of these components can represent the effect of policies in terms of the costs of measures and technology. Information on these costs is compared against the monetised costs of the benefits and detriments from the health and ecosystems impacts model to produce a cost-benefit analysis of the scenario being considered. The model can then feed altered costs and measures back into an iterative process, which offers the option to identify least-cost combinations of policy and measures needed to achieve a pre-determined outcome.

### 3.3.2 Model operation

There are two ways of running GAINS:

- The basic mode allows for scenario analysis, where an initial set of exogenously provided emission technologies, energy usages and measures generate the pollution source terms and the model simply assesses the impacts in terms of costs and the environmental benefits of different approaches to emission management.
- The optimization mode uses the feedback mentioned above to identify least cost pathways to manage the emissions and effects of air pollutants towards targets, such as those set by legislation, whilst balancing against the impacts of radiative forcing and carbon deposition (Wagner, Heyes et al., 2013). GAINS is implemented in a series of regional models, which each include data for a number of countries. It can therefore generate least cost emission policy scenarios and technology trajectories both within and across individual governmental jurisdictions.

These functions have been key drivers behind the success of GAINS in policy negotiation, particularly the ability of the model to identify the synergies and options for supranational strategies and analysis of policy proposals (EPRS, 2014; IIASA, 2017).

Access and use of these functions is not available to all. Public users have access to the results of scenario analysis only and can query the output of a limited number of modelling scenarios. These include the scenarios  from the European Consortium for Modelling of Air Pollution and Climate Strategies (EC4MACS), a group of European private and public sector organisations that developed a project between 2007-2013 to  model  and understanding air pollution and climate strategies for policy development within the EU (EC4MACS, 2012).

The GAINS model can also assign ownership of scenario datasets to select users, which offers them access to the scenario creation functions and the ability to upload new data to the model. Ownership can be limited to datasets for individual countries, allowing national-level organisations to maintain up to date energy projections based on their most recent analysis.

### 3.3.3 Structure of energy sectors and technologies

Initially, IIASA made proposals for the data on national energy use from economic activity, which forms the input for in GAINS.  Feedback on this has been offered by the governments and modelling agencies, although the initial values were taken from the PRIMES energy assumptions (EC, 2012).

All energy data falls into three areas:

- Primary fuel extraction and conversion to fuel products up to the point of use.
- Power generation, covering heat and electricity production.
- Energy end-use, subdivided into economic activity sector (industrial, domestic, etc.).

GAINS Europe considers a pre-defined range of fuel types, shown in Table 3.1, which it splits across power generation, industrial activity and domestic use. These apply to all geographical areas considered, regardless of whether a particular fuel is used or not within them.

In the case of the UK’s EC4MACS scenarios, for example, there is no use of lignite or lower grades of hard coal, as the country possesses no significant lignite resource and has economic access to preferable fuels in terms of price against energy content. However, there is a notable absence of energy from agricultural residues in UK 2030 energy scenarios, which appear in other energy models, such as the 2050 Carbon Calculator.

| **Fuel and generation types considered by GAINS in UK 2030 forecasts under EC4MACS scenarios** | |
|---|---|
| **Brown coal/lignite grade 1*** | Heavy fuel oil |
| **Brown coal/lignite grade 2 (also peat)*** | Diesel |
| **Hard coal, grade 1** | Gasoline |
| **Hard coal, grade 2*** | Liquefied petroleum gas |
| **Hard coal, grade 3*** | Gaseous fuels |
| **Fuelwood** | Hydrogen |
| **Derived coal (coke, briquettes)** | Geothermal |
| **Agricultural residues*** | Small hydro power* |
| **Bagasse*** | Solar photovoltaic |
| **Biogas (from digestion)** | Solar thermal |
| **Biomass gasification*** | Wind |
| **Biomass (solid fuel combustion)** | Hydro |
| **Charcoal*** | Nuclear |
| **Dung*** | Electricity |
| **Black liquor*** | Heat |
| **Waste fuels, non-renewable** | Waste fuel, renewable |
| **(* = Not present in EC4MACS UK 2030 scenarios: set as zero quantities)** | |

**Table 3.1: Fuel and generation types considered by GAINS in UK 2030 forecasts.**

| **Combustion emission sources considered by GAINS in UK 2030 forecasts under EC4MACS scenarios** | | |
|---|---|---|
| **Fuel conversion - combustion** | Fuel conversion - losses | Residential-commercial |
| **Chemical industry (boilers)** | Transformation sector (boilers) | Other industry (boilers; liquid and gaseous fuels) |
| **Other industry (large coal boilers; > 50 MWth )** | Other industry (small coal boilers; < 50 MWth ) | Paper & pulp (boilers) |
| **Other industry (furnaces)** | Non-energy use of fuels | Diesel generator sets* |
| **Power & district heat plants - existing coal (>50 MWth)** | Power & district heat plants - existing coal (<50 MWth) | Power & district heat plants - existing (excl. coal) |
| **Power & district heat plants - IGCC** | Power & district heat plants - IGCC with CCS | Modern power plants (coal: ultra & supercritical; gas: CCGT)* |
| **Modern power plants (coal: ultra & supercritical; gas: CCGT) with CCS** | Power & district heat plants - new (excl. coal) | Power & district heat plants - new coal (>50 MWth) |
| **Coastal shipping, large vessels** | Coastal shipping, medium vessels | Agriculture |
| **Aviation - LTO** | Construction machinery | Inland waterways |
| **Other non-road machinery** | 2-stroke engines (non-road) | Railways |
| **Buses** | Heavy-duty vehicles | Mopeds |
| **Cars** | Light-duty vehicles | Motorcycles |
| **(* = Not present in EC4MACS UK 2030 scenarios)** | | |

**Table 3.2: EC4MACS Combustion emission sources considered by GAINS in UK 2030 forecasts.**

GAINS structures energy demand by defining it for each fuel-using activity across high level areas of the economy: power and CHP plant, industrial combustion, residential and commercial building and transport.

These are subdivided into key technology families (e.g. major industry sectors, vehicle types or different power plant types and sizes) each with its own portion of consumption of each of the above fuels. Each of these has a characteristic set of combustion technologies assigned to it, with assigned emission factors. There is also an exogenous input for the composition of waste fuels, divided into food, paper, wood, rubber, textiles and waste consisting of none of these.

This allows combustion related portions of emission budgets of greenhouse gases and air pollutants to be estimated. Industrial processes that release air pollutants and non-combustion emissions of greenhouse gases, including those from fuel production, are input separately from the combustion emissions. They described in terms of volume of production (e.g. million tonnes of metal smelted), along with total emission budgets to produce a baseline scenario that does not include any measures aimed at abating emissions other than those already provided by incumbent technology.

There are two notable omissions from the current UK energy market that can be seen in the combustion sources of the EC4MACS scenarios for GAINS, as presented in Table 3.2. These are combined cycle gas turbine (CCGT) plant without CCS and diesel generator sets. Non-CCS enabled CCGT plant has been deployed in the UK since the mid-1990s and, as of 2018, there was around 33 GW of CCGT–based electricity generating capacity in the UK (BEIS, 2018f). Diesel generation was also potentially on the rise, with drivers towards its use including the ability to avoid incurring grid transmission charges because of its ability to supply energy locally and the ability to obtain high prices of electricity by providing grid balancing through the electricity capacity market. This was widely seen as a risk to air quality (Defra, 2016). It is uncertain why their deployment has not been included.

As with many of the energy trajectory models considered in this study, GAINS includes options to deploy carbon capture and storage (CCS) technology in its scenarios. CCS covers a range of emissions abatement technologies that can, in principle, be applied to any $CO_2$ producing process to prevent the $CO_2$ from entering the atmosphere. This includes combustion plant, regardless of whether it is incorporated in a power station or not.

Rather than treat CCS as abatement measure, GAINS includes it as a variation of power generation and offers CCS only as variants of coal and gas fired power stations. The impacts of this are that there are no options to reduce industrial process emission of $CO_2$ via the addition of CCS technologies. Furthermore, there is no option to represent biomass plant with CCS, which has the effect of excluding a key negative carbon emission technology from GAINS scenarios. As can be seen in the 2050 Carbon Calculator scenarios, negative carbon emissions technology can play a key role in achieving climate targets whilst still meeting energy demand. Its omission from GAINS suggests that the optimisation model runs may be excluding a key range of strategic energy options based on negative emissions.

Also notable is how GAINS treats transport. The vehicle classes in Table 3.3 are further subdivided into seven fuel types: heavy fuel oil, middle distillate (e.g. diesel and kerosene), gasoline, LPG, gas, hydrogen and electricity. Vehicle numbers and transport demand (in terms of vehicle kilometres driven) are provided for each of these fuelling types. As each vehicle in the fleet can only be assigned a single fuel type, there is an intrinsically limited ability for GAINS Europe to describe the energy demand of multi-fuel vehicles such as electric / fossil fuel hybrids or LPG / gasoline dual fuel vehicles or for it to include of any dedicated emission characteristics of multi-fuel vehicles in the emission source terms. Electricity use in vehicles appears to be seen only as being taken from the grid.

Furthermore, whilst overall liquid biofuel consumption in transport is documented in the data, there is no information on how it is deployed in blends. This can have a significant impact on emissions, as the emission characteristics of internal combustion will vary with fuel specification. Whilst standard fuel specifications, such as EN590 for diesel and EN228 for petrol, are well understood and are presumably accounted for in the model, burning fuel blends with biofuels is likely to produce different emissions of air pollutants (AQEG, 2011; Traviss, 2012). Added to this, as emissions also vary with engine configurations, it is important to know how these are distributed throughout the national vehicle fleet: an engine configured for a <10% blend of biofuels will perform differently than one optimised for a either a wide range of blends or for 100% biofuel product. This is true for both biofuel gasoline replacements such as ethanol (López-Aparicio, Hak et al., 2014) or diesel replacement such as plant oil methyl esters (Lapuerta, Armas et al., 2008; Basha, Gopal et al., 2009; Xue, Grift et al., 2011). As it stands, GAINS has no such capability.

| **Classification of transport in GAINS** | |
|---|---|
| **Road Vehicles** | Non-road vehicles |
| **Heavy-duty buses** | Maritime, large vessels, >1000 GRT |
| **Heavy-duty trucks** | Maritime, medium vessels <1000GRT |
| **Motorcycles, mopeds and cars with 2-stroke engines** | Agriculture and forestry vehicles |
| **Cars and small buses with 4-stroke engines** | Civil air traffic - national and international, as reported in energy balances |
| **Light commercial trucks with 4-stroke engines** | Mobile sources in construction and industry |
| **Motorcycles with 4-stroke engines** | Inland waterways |
| **Rail transport** | Off-road sources with 4-stroke engines (military, households, etc.) |
| | Off-road sources with 2-stroke engines |

**Table 3.3: Classification of transport in GAINS.**

Hydrogen in GAINS can act as an energy carrier for transport, power generation and industrial heat. There is no option, either in the energy consumption or emissions abatement input data sheets, to specify whether its production is from natural gas (as much of it is at the time of writing), or from a lower carbon source, such as reformation of biomethane or production via a chemical or electrochemical cycle from water. This also means that the model cannot incorporate emission reduction measures for hydrogen resulting from changes in production process or end use.

The EC4MACS scenarios for the UK have very little hydrogen use: it only has a role in the transport sector and in only around 5000 vehicles by 2030, which consume about 0.1 PJ or 28 GWh of hydrogen-carried energy between them. This contrasts with some of the scenarios postulated in other models this study considers, which have significantly more hydrogen usage. The apparent inability of GAINS to include alternative pathways for hydrogen production and use may be a contributing factor to this: if there are no technologies with lower emissions or lower costs for hydrogen to switch to, switching will not occur. The burdens of hydrogen as an energy vector will remain high and there will be little incentive to deploy it.

The representation of hydrogen and CCS both highlights a vulnerability of all the optimisation models in this study: if technology options are not detailed or flexible enough, pathways using these options will be excluded from the model's runs. If the next most effective technology is based on a different energy vector, it can have a substantial impact on the energy technology families the model chooses to follow. The limited ability of GAINS to model hydrogen technologies and the constraint of CCS being an option only for gas and coal combustion plant could result in misrepresentation and greater uncertainty on whether the technology trajectories that the optimisation model settles on are indeed least cost. This is because it is impossible to tell whether the adoption of better described technologies over less well described ones is driven by the former being genuinely more attractive or by there being no clear pathway for the model to adopt them.

### 3.3.4 Treatment of abatement measures and implications for uncertainty

The abatement module of GAINS covers around 460 different emissions mitigation and abatement technologies, spread over combustion plant, agricultural and industrial processes and transport. Market penetrations of these measures into each sub-sector, in the form of percentage uptake, are used to estimate shifts in budgets of emission away from the baseline scenario and to calculate the cost of achieving this. These measures tend to be technology-based solutions that reduce emissions from a given level of energy demand, rather than measures such as energy efficiency technologies that reduce emissions by reducing energy demand and thus combustion and fuel use. Energy efficiency measures are not presented explicitly in GAINS input data. However, they still can be partly represented by the adoption of more efficient energy conversion technologies, such as more efficient heaters or the adoption of LED lighting. This presents a challenge for representing pure demand-side efficiency technologies, such as improved insulation, which do not rely on energy conversion. This could be imposed as an exogenous reduction in energy demand, but there is no clear way of associating the costs of these measures with this reduction.

The accuracy of this technique for assessing the impact of abatement measures depends on knowing the current size and predicting the future size of each sector that each technology applies to. The example of insulation provides one source of uncertainty.. As a further example, an assumption of a given market penetration for low volatility coatings can only yield a meaningful figure if one can confidently predict the overall size of the relevant coatings market in terms of surface area to be covered. Likewise, the accuracy with which one can predict how much of the UK’s demand for various feedstocks, such as refined metals or industrial chemicals, can be satisfied by domestic production is key to predicting the emissions and the impact of abatement measures from these sectors. The success of this depends on the ability to correctly forecast the retention of these sectors by UK industry, as opposed to a further shift towards imported materials. Such data will have significant influence on the output of the model.

In contrast, some areas can be predicted with greater accuracy, with passenger vehicles and domestic heat demand being good examples. The reason in both cases is the product lifetime for that market.

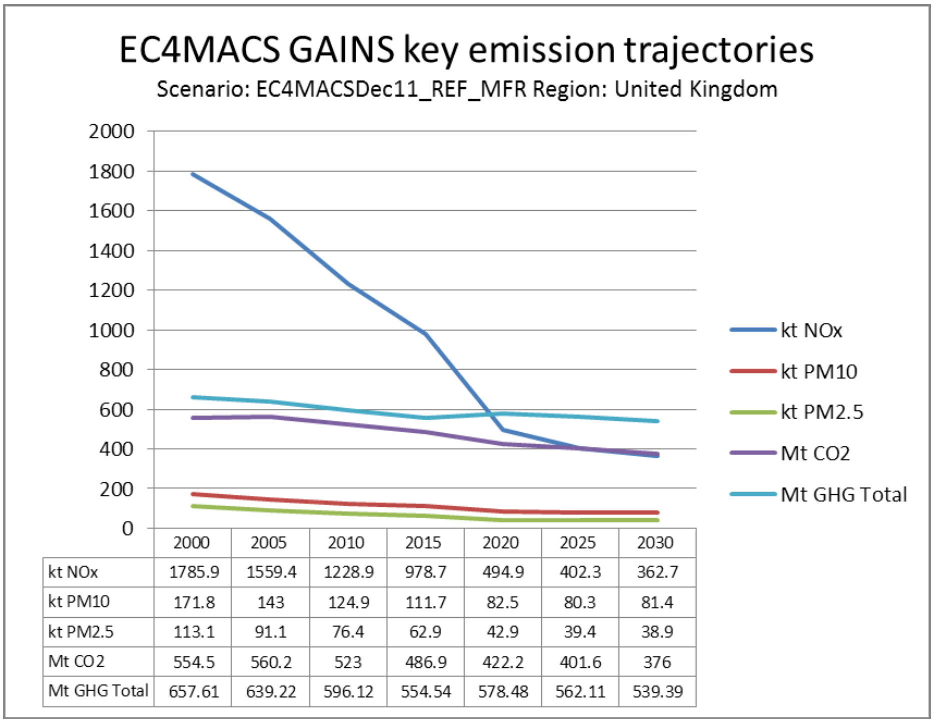
Road vehicles have an average lifetime of a little over a decade and have a clear forward map for the near future in the likely aims of abatement measures in the form of emission standards for regional markets (e.g. the Euro standards in European markets). Providing that there is not a disruptive change in transport demand, it should be possible to estimate the number and type of passenger vehicles in various scenarios, along with emissions, with more confidence than for industrial process emissions. This should hold true for shifts between transport mode, such as a greater use of buses, trains or even greater car sharing, as these can still be related to the demand for passenger kilometres, which can be derived from vehicle kilometres via known average vehicle occupancies.

In the case of domestic heat, the service demand is created by the number of dwellings, which tend to have an even longer lifetime. Housing models for the UK suggest that around 70% of the dwellings expected to be in use in the middle of the 21st Century had already been built by the year 2010, which implies a relatively low margin of error on domestic heat demand by mid-century, in the absence of major change.

This would imply that the principle areas of uncertainty lie in pure demand side measures such as reducing heat loss, which influence the overall amount of heat required by users independently of the source of heat. Uncertainty over the potential efficiency of technologies also depends on geographical factors, as may occur in the case of heat pumps: the more efficient heat pumps that extract heat from the ground require land to deploy them on; those that extract heat from the air require no land availability but are less efficient. The geographical factors influencing how many of each type may be deployed are not covered by GAINS.

### 3.3.5 EC4MACs Energy trajectories

As detailed above, GAINS allows few users the opportunity of creating wholly new scenarios and those used in this study are those developed by the EC4MACs programme. EC4MACs has involved itself in both air pollution and climate change aspects of EU policy, both of which influence the UK’s national objectives in these areas.



| | 2000 | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|---|
| kt NOx | 1785.9 | 1559.4 | 1228.9 | 978.7 | 494.9 | 402.3 | 362.7 |
| kt PM10 | 171.8 | 143 | 124.9 | 111.7 | 82.5 | 80.3 | 81.4 |
| kt PM2.5 | 113.1 | 91.1 | 76.4 | 62.9 | 42.9 | 39.4 | 38.9 |
| Mt CO2 | 554.5 | 560.2 | 523 | 486.9 | 422.2 | 401.6 | 376 |
| Mt GHG Total | 657.61 | 639.22 | 596.12 | 554.54 | 578.48 | 562.11 | 539.39 |

**Figure 3.13: EC4MACS GAINS emission trajectories.**

UK air quality policy objectives have been driven largely by EU agreements in terms of limit values and emission budgets. In contrast the UK has two separate sets of objectives on climate: its contribution towards the EU wide target of achieving a 20% reduction from 1990 emission levels of GHGs by 2020 (which equates to around a 16% reduction from 2005 UK GHG emissions by 2020, or 584 Mt $CO_2$e) and its self-imposed decarbonisation trajectory under the Climate Change Act of an 80% reduction on emissions of GHGs from 1990 levels by 2050.

This can be seen in the EC4MACS GAINS trajectories for the UK shown in Figures 3.13 and 3.14, in the $CO_2$ emission reductions. The 578 Mt $CO_2$e modelled for 2020 is consistent with the EU contribution target, but it falls short of the 433 Mt $CO_2$e figure for 2020 that the UK's Committee on Climate Change provided as an indicative target in its advice in setting the UK's carbon budgets up to 2035 (CCC, 2016).

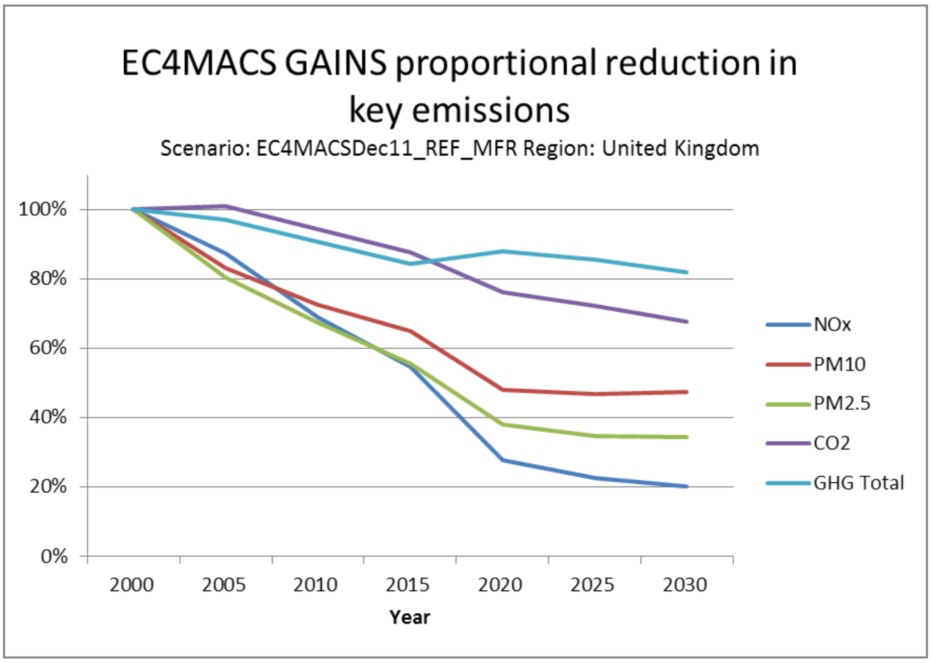
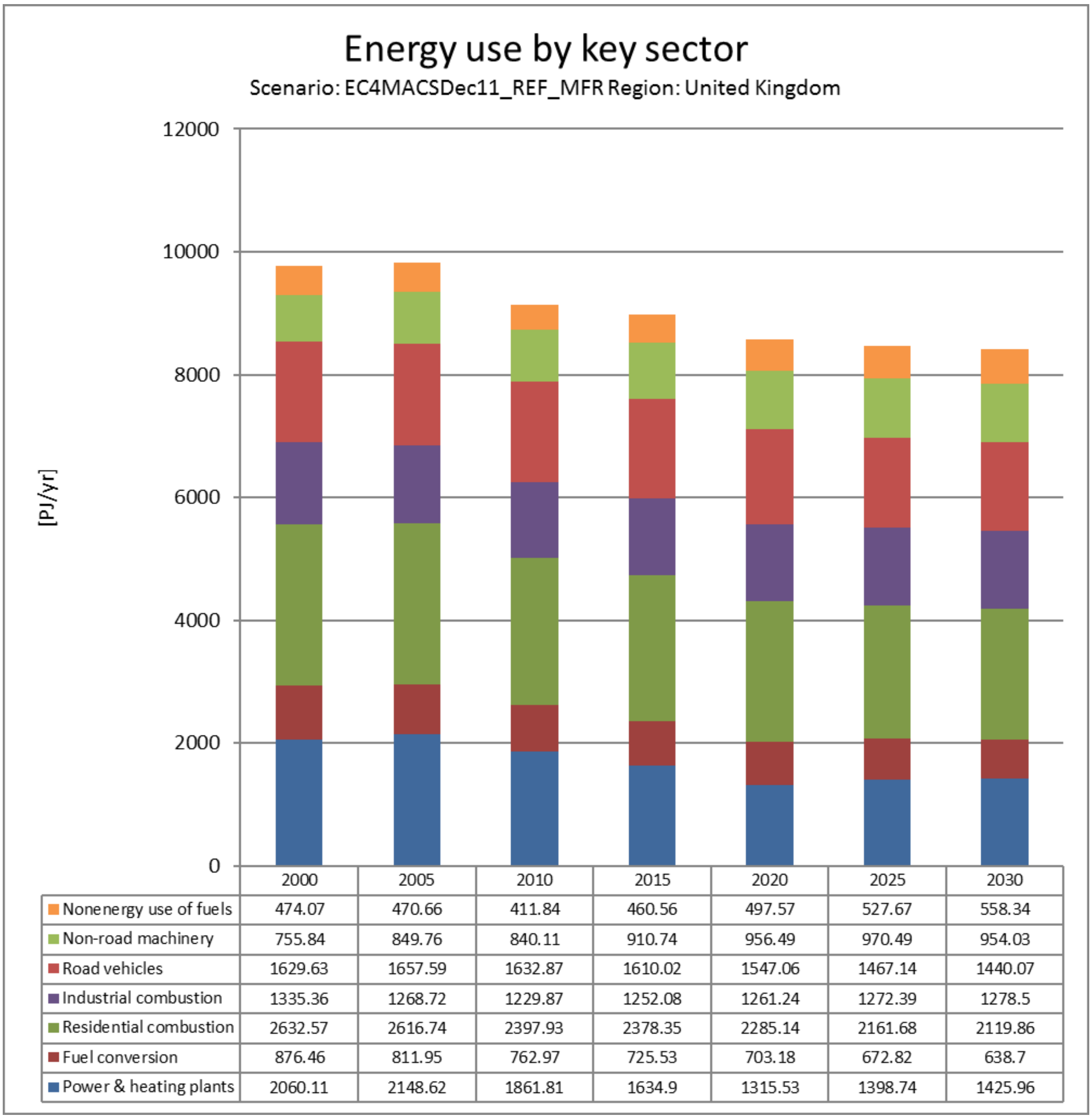


**Figure 3.14: EC4MACS GAINS proportional emissions reductions.**

In comparison, $NO_x$ and particulate matter emissions see proportionately greater reductions by mass in the same period.

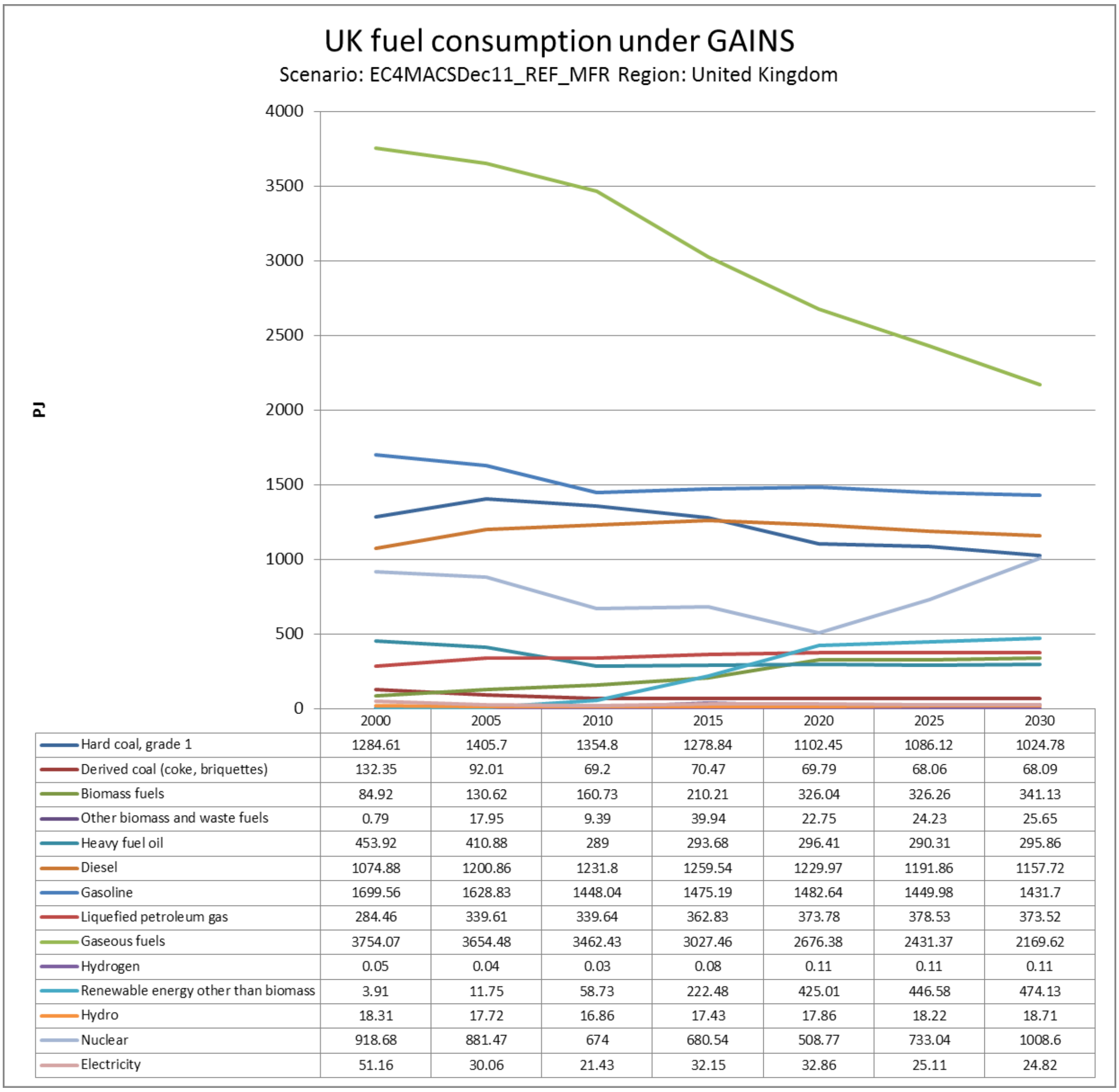
Overall, as shown in Figures 3.15 and 3.16, UK energy use in this scenario falls by around 14% over the 2000 – 2030 period. This is driven (Figure 3.15) by a modest fall during this time of around 260 PJ / year each from hard coal and petrol (gasoline) consumption and a large fall of about 1500 PJ / year in gas consumption. This is offset by increases in consumption of 256 PJ / year of biomass fuels and 470 PJ / year of non-biomass renewable energy generation.

The large fall in gas use corresponds to significant falls in energy use by residential combustion and power plant, which likely indicates both a shift away from domestic gas boilers and gas fired power plant, combined with increasing fuel efficiency of both these technologies.



| | 2000 | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|---|
| 🟧 Nonenergy use of fuels | 474.07 | 470.66 | 411.84 | 460.56 | 497.57 | 527.67 | 558.34 |
| 🟩 Non-road machinery | 755.84 | 849.76 | 840.11 | 910.74 | 956.49 | 970.49 | 954.03 |
| 🟥 Road vehicles | 1629.63 | 1657.59 | 1632.87 | 1610.02 | 1547.06 | 1467.14 | 1440.07 |
| 🟪 Industrial combustion | 1335.36 | 1268.72 | 1229.87 | 1252.08 | 1261.24 | 1272.39 | 1278.5 |
| 🟩 Residential combustion | 2632.57 | 2616.74 | 2397.93 | 2378.35 | 2285.14 | 2161.68 | 2119.86 |
| 🟥 Fuel conversion | 876.46 | 811.95 | 762.97 | 725.53 | 703.18 | 672.82 | 638.7 |
| 🟦 Power & heating plants | 2060.11 | 2148.62 | 1861.81 | 1634.9 | 1315.53 | 1398.74 | 1425.96 |

**Figure 3.15: EC4MACS GAINS sectorial energy use.**



| | 2000 | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 |
|---|---|---|---|---|---|---|---|
| Hard coal, grade 1 | 1284.61 | 1405.7 | 1354.8 | 1278.84 | 1102.45 | 1086.12 | 1024.78 |
| Derived coal (coke, briquettes) | 132.35 | 92.01 | 69.2 | 70.47 | 69.79 | 68.06 | 68.09 |
| Biomass fuels | 84.92 | 130.62 | 160.73 | 210.21 | 326.04 | 326.26 | 341.13 |
| Other biomass and waste fuels | 0.79 | 17.95 | 9.39 | 39.94 | 22.75 | 24.23 | 25.65 |
| Heavy fuel oil | 453.92 | 410.88 | 289 | 293.68 | 296.41 | 290.31 | 295.86 |
| Diesel | 1074.88 | 1200.86 | 1231.8 | 1259.54 | 1229.97 | 1191.86 | 1157.72 |
| Gasoline | 1699.56 | 1628.83 | 1448.04 | 1475.19 | 1482.64 | 1449.98 | 1431.7 |
| Liquefied petroleum gas | 284.46 | 339.61 | 339.64 | 362.83 | 373.78 | 378.53 | 373.52 |
| Gaseous fuels | 3754.07 | 3654.48 | 3462.43 | 3027.46 | 2676.38 | 2431.37 | 2169.62 |
| Hydrogen | 0.05 | 0.04 | 0.03 | 0.08 | 0.11 | 0.11 | 0.11 |
| Renewable energy other than biomass | 3.91 | 11.75 | 58.73 | 222.48 | 425.01 | 446.58 | 474.13 |
| Hydro | 18.31 | 17.72 | 16.86 | 17.43 | 17.86 | 18.22 | 18.71 |
| Nuclear | 918.68 | 881.47 | 674 | 680.54 | 508.77 | 733.04 | 1008.6 |
| Electricity | 51.16 | 30.06 | 21.43 | 32.15 | 32.86 | 25.11 | 24.82 |

**Figure 3.16: EC4MACS GAINS UK fuel consumption.**

This overview of the GAINS model was undertaken at roughly the mid-point in the timeline of this scenario, where verified data was available up to 2016. This showed the real-world emissions of the UK in 2015 to exceed those in the EC4MACS scenarios by 150% and 177% for $PM_{10}$ and $PM_{2.5}$. real world estimates of PM emissions are also higher than predicted, with new estimates for wood burning and sources such as non-exhaust emissions which are not in GAINS (NAEI, 2019). $NO_x$ exceeded the levels in the scenario  by a small (~1%) margin, but showed signs of slowing its rate of reduction (Wakeling, Passant et al., 2018). Real-world $CO_2$ emission was 83% of the EC4MACS scenario and total greenhouse gases 89% (Brown, Broomfield et al., 2018).

The reason for the underestimation of the rate of fall of $CO_2$ is clear from the data: the EC4MACS figures used in GAINS led to the underestimation of the rate of growth of renewables other than biomass and appears to have overestimated costs. This can be attributed partly to policy decisions in the UK leading to greater incentives to deploy such renewables and partly to a more rapid fall in cost of deployment. However, it is not attributable to the type of technology used, which comprises mostly wind and photovoltaic electricity generation and solar thermal heating, for which operational emissions are near zero, regardless of the specific technology type.

By comparison, the overestimation of the rate of fall of particulates may provide evidence of the model's inability to account for the technology used. Total petroleum diesel and petrol (gasoline) use in 2015 is estimated as 2734 PJ, which is 97% of the actual 2805 PJ estimated UK consumption of petroleum (BEIS, 2018i). Total biomass energy demand in 2015 was only 61% of the scenario predictions at around 130 PJ (BEIS, 2018j), including gaseous biomass-derived fuels.

These figures suggest that the EC4MACS GAINS scenario predictions of energy consumption are not unreasonable for these energy types, which are key contributors to particulate emissions. Despite the levels of their real-world use being similar to scenario predictions, the real-world particulate emissions are larger than the predictions by a significant margin. A credible explanation of this would be a failure of the model to estimate accurately the real-world emissions of the technologies used, with the relative size of the error suggesting that much of the contribution to this may be in its estimates of petroleum fuels and the transport sector. This would be consistent with the level of detail with which the model can describe emergent vehicle technologies and, potentially, changes in operational standards and requirements for current technologies.

This would imply that there is a risk that the current methodology for representing technologies in GAINS is unreliable for predicting least-cost energy technology trajectories to meet air quality objectives. The degree of this risk may be linked to the level of granularity or diversity with which GAINS can represent the technologies being introduced.

*GAINS' utility as an analysis tool*

A better understanding of the above inaccuracies would be facilitated by the ability to compare the model's behaviour in counterfactual scenarios, to assess the sensitivities of different sectors. At the time of writing, there are barriers to this: the access restrictions for most classes of GAINS users prevent them creating and running their own, comparative scenarios. This hinders the use of sensitivity analysis with GAINS, making it difficult to compare the relative contribution of the individual energy sources to emissions budgets. This lack of open access may limit the utility of the tool in policy assessment, as a lack of sensitivity analysis in counterfactual scenarios limits the capability to assess policy risk through exploration of the impacts of marginal changes in the cost or availability of energy sources on emission budgets.

## 3.4 UK TIMES Model

### 3.4.1 Purpose

The UK TIMES Model is a predictive optimisation model of the UK energy system. It was developed by the UCL Energy Institute Energy Systems team, using a model generation system developed by the OECD International Energy Agency aimed at technoeconomic policy analysis of the long-term evolution of energy system pathways. UK TIMES takes a bottom up approach to describing the energy system and builds a description on an activity by activity level, using linear programming to determine lowest cost technology trajectories for future energy and emissions scenarios (Daly and Fais, 2014).

UK TIMES has been used by UK government departments and advisory groups in developing the 5th Carbon Budget. This describes changes the UK economy needs to implement in the 2028-2032 period to continue along a Greenhouse Gas emissions trajectory required to meet the 2050 objectives of the 2008 Climate Act. It has also been developed with the research community in mind, as it is a fully open source model and has potential applications in examining not only future energy systems, but also their interaction with other influences on energy use and greenhouse gas emission, such as land and water resource use.

### 3.4.2 Aim of MARKAL, TIMES and the UK TIMES

UK TIMES has been generated using TIMES. This is a model generation system, developed by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency to produce scalable modelling software, capable of describing energy systems at different geographical levels (from local to entire global regions). TIMES is based on its widely used predecessor, MARKAL: the Market Allocation Modelling Framework, which offers a highly scalable market optimisation model for assessing the least cost options of energy supply.

As an optimisation system, models derived from the MARKAL framework and its successors balance demand for energy against marginal increasing costs for energy supply. These costs can include factors and constraints such as limits on carbon emissions.

MARKAL has been used to construct models for policy assessments on global and national scales. This has included global studies by the OECD on the impacts of hydrogen deployment as an energy carrier, the effects of introducing carbon capture and storage into fossil generation, the potential impacts of nuclear energy on greenhouse gas emissions and options for energy efficiency measures. The version of MARKAL developed to describe the UK energy system has been used by universities and successive UK Government energy departments to underpin impact assessment of the Climate Change Act (2008) and to quantifying the cost of options to meet long-term carbon reductions targets (IEA, 2008).

The TIMES model generation system has been developed as a successor to MARKAL. Both models are dynamic, partial equilibrium economic optimisation systems that aim to describe the energy system. Some of the ways that TIMES goes beyond MARKAL's capabilities include (IEA, 2009):

- Flexibility of time slices it calculates against, allowing periods of a single time series to have more frequent assessments than other parts of the same series or of time series for scenarios in GAINS or the 2050 Carbon Calculator.
- The ability to apply seasonal, weekly or daily patterns to the behaviour of technologies (such as electricity storage.
- More flexible, easier specification of the time periods over which data is valid, which helps scenario design.
- Better descriptions of variability in technology behaviour, such as might be seen when operating combustion plant with different fuels or fuel mixes.
- Ability to model the non-operational parts of technology lifecycles, such as the investment and the decommissioning phases.
- Updated mathematical descriptions of climate impacts

TIMES models exist at global scale, regional scales (a pan European model has been developed by the European Commission's Joint Research Centre), and country level for the US, China and several European countries. Its intended user base is therefore very similar to GAINS, since both can operate as scalable models to identify the least cost way of delivering an energy system to meet a certain set of policy requirements. The difference between the two lies in their origin and aims.

GAINS was developed from tools designed to analyse the least cost options for managing air quality pollutants in future energy scenarios. Greenhouse gas emissions and costings were added to these to produce GAINS. By comparison, TIMES and MARKAL were designed to analyse only the least cost options for managing emissions of greenhouse gas emissions from energy (IEA, 2009). Whilst UK

TIMES now has a limited ability to assess the impact of air pollutants, there is no native integration of air pollutant emission into any versions of the base TIMES model generation system.

### 3.4.3 Model structure

A TIMES-based model consists of three types of elements (Loulou, Goldstein et al., 2016):

- “Commodities” – energy resources, services and products that make up the value chain of energy supply. These include products such as raw and intermediate materials, finance, fuels, and energy services that fulfil demand. Pollutants and wastes from the delivery of these, including air pollution, also count as commodities.
- “Processes” – technologies that consume, transform or move commodities, such as refineries, power plant, energy end use devices (e.g. vehicles, boilers and electrically operated devices), industrial processes or the operation of energy transmission and distribution infrastructure.
- “Commodity flows” – which do not normally represent physical assets, but represent a process applied to commodities in the model, such as the act of electricity generation from an energy source.

The information required to define these include:

- Energy services demands such as heat, light and different modes of transport.
- Extraction costs and availability of primary energy supplies.
- A description of energy generation plant, in terms of its operational and build cost, fuelling, operating efficiency and availability and remaining lifetime.
- Assumptions of future technology availability, costs and performance.
- Assumptions about energy supply and trade.

Energy efficiency measures are represented by changes in technologies, represented by switching from one process or commodity flow to another one. The exception to this is the adoption of pure demand-side energy efficiency measures that are not based on adopting improved versions of energy conversion technologies such as heating or lighting. Unlike GAINS, TIMES can represent the impacts and costs of such measures by describing them as processes without an energy input commodity. This allows reduction of energy consumption and the costs of doing so to be integrated into the model.

These allow a user to create a baseline scenario that uses linear optimisation routines to calculate the technology trajectory of an energy system in the absence of any constraints other than minimum cost. Counterfactual scenarios can then be run, with constraints on aspects such as emission budgets of greenhouse gases or levels of deployment of certain energy products.

TIMES models estimate emissions of greenhouse gases from the scenarios they create and can incorporate a damage model to describe the indirect costs of these emissions. UK TIMES includes a version of the climate change damage costs model currently in use by the UK.

UK TIMES is based on functions of supply and demand of energy, corresponding to primary energy production and end-use (UCL, 2015). It consists of 3 initial resource and energy supply datasets (Figure 3.17):

- Primary physical and financial products (e.g. supply and extraction of primary energy resources or creation credits and permits in emission accounting systems).
- Processing and delivery of consumable energy products (e.g. petrochemical products, hydrogen).
- Electricity generation and supply, including embedded generation

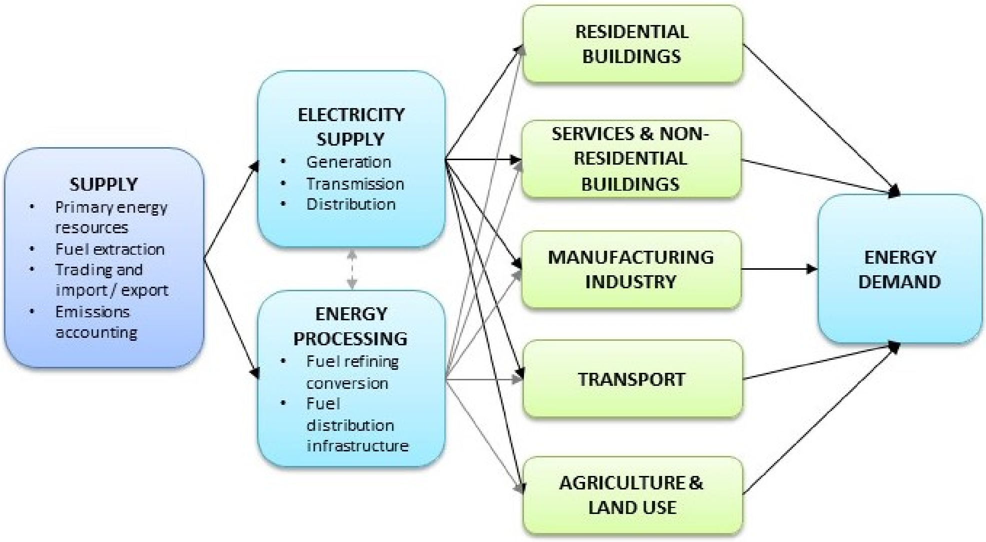


**Figure 3.17: Structure of UK TIMES**

Of the various types of energy service, only electricity is represented as a supply side commodity. Other services, such as heat and transport demand are represented as consumption of energy products by equipment (i.e. “processes”).

Energy consuming sectors are categorised in the same manner as the Digest of UK Energy Statistics (DUKES), which is the UK Government’s main public dataset of national energy use. These are:

- Residential sector – the population’s homes.
- Manufacturing industry.
- Services sector – consumption by buildings and non-manufacturing service activities.
- Transport – use of energy by vehicles.
- Agriculture and use of land for purposes other than the above.

*Electricity generation*

Power generation in UK TIMES’s electricity supply module consists of coal, oil, biomass, nuclear and waste fired thermal plant. Nuclear is subdivided into reactor types and biomass includes multiple combustible fuels, covering poultry litter, high and low quality wood pellets and straw (Dodds, Daly et al., 2015).

Gas fired plant includes conventional open and combined cycle gas turbine power stations and gas engines. Gas electricity generation is classified as being generated from either natural (fossil) gas, biogas from anaerobic digestion, biogas from landfill sites or biogas from sewage wastes. Despite the comparatively wide selection of biogas and biomethane derived from decomposition processes, the UK TIMES electricity supply module includes no description of technologies that allow direct gasification of solid biofuel for power generation or carbon capture and storage (CCS).

A reason for this is that these technologies are classified as energy conversion processes and appear in the energy processing module used for that. CCS is represented as a set of standalone commodities, each specific to an individual power plant type, which can be applied to that power plant and are defined in terms of kilotonnes of $CO_2$ captured and stored (i.e. the commodity is the negative emission). However, there appear to be no processes linked to how this commodity is produced to describe the cost, emissions, energy consumption and other operational details of CCS.

Biogas from gasification also appears as a commodity, along with an entry for biogas production from anaerobic digestion. Furthermore, process data also exists for biogas from anaerobic digestion, but not from gasification. This delineates a clear pathway for the production processes, output and use of biogas from anaerobic digestion in UK energy scenarios, but provides questionable coherence for other forms of biogas: there are no commodities or processes defined for this or any other of the modules that appear to represent the production of the landfill or sewage gas in the electricity module and there is no definition of a process that might correspond to the production of biomass. This appears to suggest that UK TIMES in its current configuration may represent the production of biogas from gasification but not its use and can represent the use of landfill and sewage gas and certain types of CCS technology without clear means of producing it.

In some situations, such as the use of sewage gas at waste water treatment plants, where the resource is entirely consumed on site, this is unlikely to make a difference, as the energy and emissions from plant are likely to be integrated into the assigned emission factors. It may provide a barrier to representing integrated gasification power plant, such as integrated gasification combined cycle (IGCC) power plant, from scenarios and may therefore constrain the deployment of biomass feedstock in electricity generation scenarios.

The UK TIMES architecture can thus represent negative emissions technology through biomass fuelled CCS systems in a manner that GAINS cannot. There are limitations on this: for example, in the version of the model reviewed currently there is no clear pathway for industry to use biomass CCS. Consequently, this places a limitation on how far one can deploy the commonly proposed development of bioenergy carbon capture and storage, which plays a role as a negative emissions technology in scenarios of the UNFCCC Intergovernmental Panel on Climate Change and scenarios generated by the UK 2050 Carbon Calculator.

There is no clear representation of $CO_2$ transport infrastructure for CCS in the model. This may lead to underestimation of the deployment costs of CCS and negative carbon technology and an overestimation of build. A side effect of this is that there is also no representation of the spatial distribution of this infrastructure. This is key to understanding both the physical and financial feasibility of CCS deployment, as sites using CCS must somehow connect to this infrastructure to operate. This may be by establishing a direct connection to a $CO_2$ pipeline and disposal facility or by using road transport to ferry $CO_2$ to a pipeline access point. The remoteness from pipelines will increase the barriers to access CCS technology and, assuming that CCS infrastructure access will not be evenly available across the UK, these barriers and the costs of overcoming them will be different for the same technologies, depending on their location.

*Heat Generation*

Heat is not represented as an individual sector in UK TIMES, as it is generated by the use of fuels by the five consumption sectors in boilers and other heat using processes, such as furnaces and cooking equipment. Thus, CHP does not appear as a form of electricity generation in the electricity module. Likewise, other on-site forms of heat generation, such as solar thermal panels, are assigned to the consumption sectors.

*Transport*

Road vehicle types in UK TIMES are represented by:

- Cars
- Buses
- Two-wheel passenger transport
- Light-duty goods / vans
- Heavy-duty goods

In the base year 2010, four powertrain technologies represent car passenger transport: Petrol, diesel and LPG variations of ICEs and petrol and diesel variants of hybrid electric vehicles (HEVs) (Daly, Dodds et al., 2015). The model then accounts for the introduction of the following range of vehicle fuelling and powertrain options:

- Battery electric.
- New internal combustion engine vehicles configured for diesel, petrol, CNG, LPG and flex-fuelled petrol-ethanol mixtures up to 80% ethanol content (E85).
- Hydrogen fuel cell vehicles.
- Non-plug in diesel, petrol and hydrogen fuel cell hybrids.
- Plug in diesel, petrol and hydrogen fuel cell hybrids.

Differentiating between vehicle types can be important: for example, diesel light vehicles are more popular in high usage situations, such as company fleets, and drive on average 50% farther than petrol cars, whilst hybrid and battery electric vehicles tend to have more usage (although not necessarily more distance travelled) in urban situations. UK TIMES accounts for this by using vehicle activity based on DfT traffic statistics, which include vehicle kilometres and numbers travelled for petrol and diesel light-duty vehicles (cars and vans), as well as for the other vehicle types mentioned above. These are derived from the GHG emissions figures from the National Atmospheric Emissions Inventory: the dataset that the UK government uses for reporting compliance with international agreements on annual emission budgets for greenhouse gases and air pollutants. These include two decades worth of estimated data on total vehicle kilometres travelled by vehicles in the three common subdivisions of driving environment: urban, rural and motorway.

One notable issue is that of vehicle kilometre estimates for hybrid electric cars. UK TIMES assumes that HEVs conform to the same drive cycle as the rest of the UK's car fleet, but this is questionable in the real-world. UK adoption of hybrid vehicles has been driven, at least in part, by policies such as the London Congestion Charge, leading to a geographical distribution skewed towards urban areas. This may imply that hybrids are, on average, used much more for short urban journeys than their non-hybrid counterparts, which may lead to hybrid vehicles covering shorter average distances with a higher power demand stop-start drive cycle. This would mean that UK TIMES might overestimate the proportion of light vehicle transport service demand (in terms of vehicle km) fulfilled by hybrid vehicles, it might also be underestimating the vehicle power demand and it subsequent impact on emissions.

Similar arguments may apply to LPG vehicles, for which a similar assumption has been made in comparison to petrol cars. This may mean that the fuel consumption and power demands are underestimated, which would correspond respectively to an underestimation of $CO_2$ and $NO_x$ emissions.

The ability of TIMES models to describe variable behaviour within a technology may allow more accurate descriptions of some key emerging vehicle technologies in a manner that others may not. A case in point is their above-mentioned ability to vary the efficiency of a combustion technology according to its fuelling, which may have applications in modelling the variability described in the next chapter of hybrid vehicles' emissions behaviour at different states of battery charge.

*Introduction of air quality*

Just as GAINS has been adapted from RAINS to accommodate greenhouse gas emissions, so a version UK TIMES was adapted from its base version in 2015 to include assessment of emissions of six classes of air quality pollutants:

- Nitrogen oxides ($NO_x$)
- Sulphur dioxide ($SO_2$)
- $PM_{10}$
- $PM_{2.5}$
- Ammonia ($NH_3$)
- Non-Methane Volatile Organic Compounds (NMVOC)

Emission factors for each of these pollutants are stored in a lookup table in spreadsheet format. They are assigned on a per process basis and have been taken, where possible, from the National Atmospheric Emissions Inventory (NAEI) data (Aether, 2015). These factors tend to be defined in terms of the amount of pollutant emitted per unit of energy service produced, with units of kilotonnes of pollutant per petajoule used for non-transport technologies and grams of pollutant per kilometre for vehicles. An advantage of this is that the UK TIMES takes its greenhouse gas emissions data from the NAEI's sister database, so the sectoral coverage of the air quality and greenhouse gas data should be identical.

The NAEI is an emissions budget accounting system that has been designed to facilitate the reporting of annual releases of air pollutants under various international agreements. It is therefore optimised to assess processes that currently contribute to air pollution, rather than those that might yet do so. Consequently, data on many emerging and future technologies that the UK TIMES chooses to deploy in its scenarios need to be sourced separately. Sources are from UK government reports assessing these technologies, emissions reporting from countries where these technologies are already being used and placeholder values based on knowledge to date of a technology in development (Terry and Palmer, 2016).

The air pollutant budgets generated by this adapted version of UK TIMES are not fed back into the model and thus cannot be used in the cost optimisation process. UK TIMES energy technology trajectories therefore cannot account for the costs and impacts of air pollution. However, they can provide an informed indication of the impacts of future energy scenarios on air pollutant budgets and these have the potential to be calculated and applied to overall costs post-hoc.

### 3.4.4 UK TIMES and spatial modelling

*Spatial distribution of air pollutants*

Unlike GAINS, with its associated air pollutant dispersion model, UK TIMES lacks any form of inbuilt spatial resolution. It is only intended for modelling emission budgets from the energy system and has no way of describing where such emissions will be released. Thus, again unlike GAINS, it cannot provide on its own any kind of assessment of exposure to the population of the emissions and consequently cannot assess their health impacts and the associated damage costs of energy use.

This does not mean that UK TIMES cannot contribute to modelling the impacts of UK air pollution. Unlike GAINS, UK TIMES energy and air quality components are based around the Digest of UK Energy Statistics and the UK’s NAEI database and thus has the same sectoral architecture as the UK Integrated Assessment Model and derivative tools that are used for modelling and predicting the physical distribution of air pollution on a national scale. Thus, it may be feasible to use the emission budget output of UK TIMES as direct input into these models to better understand the damage costs of scenarios.

UK TIMES's sectoral architecture is the same as the UK Integrated Assessment Model (UKIAM), which is a model used for predicting the geographical distribution of air pollutant concentrations in the UK. Thus, a degree of true spatial modelling for air pollution may be achievable using UK TIMES outputs feeding into UK-wide air pollution and dispersion models such as the UKIAM. This would need to assume that the emission sources that are currently represented in UK TIMES, such as population centres, transport infrastructure, farming activities and power generation, do not shift location significantly and the "footprint" of each sector remains the same. Such factors are influenced by many government policies, including those on planning, development and agriculture and it is doubtful that these would remain the same over the coming decades.

Unlike the national air quality modelling tools, UK TIMES also describes the introduction of new technologies and sources and there is greater uncertainty over the location of these. Some new sources will inevitably be tied to existing infrastructure for the foreseeable future: for example, new cars will always be found in the same location as road infrastructure. However, there is far less certainty about the location of other technologies, such as decentralised power and heat generation, and this will introduce associated uncertainty into any spatial modelling of pollution and calculation of associated costs.

### *Location impact on infrastructure costs*

UK MARKAL, UK TIMES's predecessor, manages to accommodate infrastructure issues to a degree through the development of a version which splits the UK into regions. At the time of writing, a UK TIMES version of this had not yet been developed.

Lack of spatial modelling of energy infrastructure also may limit the ability of UK TIMES to assess the deployment costs of certain technologies. It has been mentioned in the example of CCS, where the distance to $CO_2$ transport and final storage infrastructure is undefined in UK TIMES. This introduces uncertainty into the final system cost and location of any CCS enabled plant, where costs of $CO_2$ transport infrastructure allow it to be deployed and when the roll out of $CO_2$ transport infrastructure allows it to be built. It also applies to any new infrastructure to transport hydrogen, should its use as an energy carrier by widely adopted. This will affect when and where atmospheric emissions take place throughout the evolution of an energy scenario, the public exposure to these and the consequent health and environmental costs, none of which are represented in the UK TIMES optimisation process.

Location dependent elements of costs that depend on providing supporting network infrastructure are not unique to CCS. Most new electrical generation plant require some additional grid infrastructure and the overhead costs of providing this can vary significantly with plant or generation type. Offshore wind, which can require offshore networks of hundreds of kilometres in length, is another example of energy generation with potentially high location dependent costs. The build costs of these and the connection costs of individual wind turbine arrays depends both on the location of the wind turbines, the network topology of the grid and the technology used to build the connectors (De Decker and Kreutzkamp, 2011).

Furthermore, the intended functionality of offshore portions of a grid may range from providing a simple link to an offshore generation array to providing added value by linking offshore power generation to multiple separate onshore grids and thus acting additionally as an interconnector. A potential example of the latter is that considered by the North Seas Countries Offshore Grid Initiative (NSCOGI, 2014).

These are all spatially dependent variables that should impact on the system cost of offshore wind deployment and, in particular, the marginal cost of additional offshore wind once first-of-a-kind offshore grids are deployed in an area. Uncertainty over their cost will have a significant impact on the level of confidence that once can have in the technology trajectories derived from technoeconomic optimisation models such as UK TIMES and GAINS.

### *UK TIMES's role as an analysis tool*

Of the models considered in this study, UK TIMES and the TIMES family of models have the most diverse representation of emerging energy technologies and the most adaptable structure for representing new technologies.

TIMES is a comparatively flexible model generation system in comparison with GAINS and is designed with adaptability in mind. Whilst TIMES does not generate models with integrated air quality assessment as part of their optimisation functions, the adaptable nature of the model generation system allows the creation of energy models that might map onto existing models of air pollution, such as is the case with the UK TIMES. Post-hoc analysis of air quality impact is therefore an optional extra for UK TIMES and TIMES models in general, although successful representation requires compatibility with existing air quality models of the region under question to be considered in the sectoral design of the model.

TIMES' lack of spatial information about energy resources limits the model to determining an optimised capacity of energy supply, with fixed assumptions about infrastructure build cost, which may provide a source of inaccuracy for the modelling of energy economies covering geographically large areas.

In the case of UK TIMES, the description of some emerging technologies does not currently extend to the full range of variable characteristics, as is seen in its approach to novel vehicle types. This excludes a clear assessment of the transport sector. Nor are certain pathways yet completely represented, such as biomass CCS. Whilst the structure of the UK TIMES model allows for the inclusion of the latter, including the former may require a different approach to the description that allows more granularity to the wide range of different technologies in the sector.

## 3.5 Energy scenario comparison tools for air pollution

### 3.5.1 Challenges of high-level policy assessment

Air pollution policy assessment requires easy, high-level comparison of how policy measures affect pollutant emissions from different sectors and sources. This is before undertaking a more in-depth analysis of options likely to deliver effective results.

The above models are unsuitable for such a purpose: GAINS and TIMES / UK TIMES tools are aimed at detailed energy scenario building. They are not optimised for undertaking quick assessments, because of the need to define a large number of parameters, the time that they take to run and the software requirements and expertise needed to use them. For similar reasons, the models used to predict levels of air pollution in the UK, which cover the physical transport, diffusion and chemical reactions of air pollutants, are also burdensome to use for quick assessment. The 2050 calculator can provide quicker assessment of energy scenarios, but only allows limited consideration of the contribution of sectors and sources to pollution.

### 3.5.2 RAPID and AIM tools

In the light of concern over how to compare energy scenarios' air quality implications, ready reckoning tools have been developed to assist high-level UK policy assessment. These are intended as a fast and easy to use system for estimating the impacts of shifts in UK air quality pollutant emission budgets in key activity sectors without the need to run a full predictive model. Two such tools, the Rapid Air Pollution Impacts Diagnostics (RAPID) tool and the subsequent Abatement Impact Monetisation (AIM) tool have been developed by Imperial College.

Unlike GAINS, TIMES / UK TIMES and the 2050 Calculator, these are not a models of the overall energy system, but tools to examine how specific measures within it affect air pollutant emissions sources. Both tools’ lists of pollutant sources are derived from the UK Integrated Assessment Model (UKIAM), which calculates the spatial distribution pollutant concentrations across Great Britain, based on emissions budgets and locations of major emissions sources and sectors. UKIAM can assess pollution exposure for the population and for environmentally sensitive areas and calculation health and environmental damage costs. It can also be used for predictive modelling of future air quality scenarios from hypothetical sets of emissions source data and calculating damage costs.

The aim of RAPID is to allow the user to propose changes in future energy use and pollutant emission budgets and estimate the response in terms of changes to environmental parameters and health impacts. The pollutants covered are $SO_2$, $NO_x$, ammonia and the two most common size fractions of particulates ($PM_{10}$ and $PM_{2.5}$). Output is expressed in terms of annual per sector figures for acidification potential in a sector (in Meq), eutrophication potential through nitrogen deposition (in kilotonnes N deposited) and changes in emissions of $NO_x$ and the $PM_{10}$ and $PM_{2.5}$ particulate size fractions. Costs and savings are expressed out to 2030.

Configuring and running UKIAM can be impractically complex for quick policy analysis, due to the number of data sources used. RAPID uses a baseline scenario that assigns emission budgets to UKIAM sources. It then calculates the impacts of these budgets by applying the health damage costs per unit of emission used by the UK's Department of Environment, Food and Rural Affairs.

RAPID was developed for assessing the air quality implications of the scenarios in the Committee of Climate Change's 4th carbon budget for the UK, which covers the years 2023-2027 and this remains its only deployment in national policy analysis (ApSimon and Oxley, 2013).

AIM (Abatement Impact Monetisation) is an evolution of RAPID that has been made available more widely to UK Government. It applies emission budgets from the same sources, but then applies an "impact factor" to each sources' budget. These impact factors are derived from the geographical distribution "footprint" the emissions from each source conforms to and how this coincides with the distribution of population and (for health) and of sensitive areas (for environmental impact). This allows estimation of exposure to pollution and an improved scaling of damages.

### 3.5.3 Structure of RAPID and AIM

Both tools are spreadsheet-based calculators. RAPID establishes a baseline energy scenario in yearly intervals to set pollution emissions and impacts by combining four key types of data:

- Pollutant source activity, by nationwide distribution of sectors, processes and large point sources. Geographically, this is based on the UK Integrated assessment model's 1 km x 1 km grid.
- Emission factors for sources for $SO_2$, $NO_x$, $PM_{10}$, $PM_{2.5}$ and $NH_3$.
- Impact factors for emissions.
- Damage costs of emissions.

As a tool to assess national scale change, RAPID omits phenomena with highly localised effects, including the impact of $NO_2$ concentration. As one comes down from wide to national scale, local effects and pollutants become more important.

For the baseline scenario, energy usage for each sector was provided by the CCC. Emission factors were taken from the NAEI. The NAEI offers a further breakdown by offering proportional energy demand within each of these sectors by technology type (e.g. vehicle powertrains), key industry sector and by individual major sources in the power generation sector for the initial years of the scenario. It also provides the air quality pollutant emission factors for many of the technologies that are currently deployed. Emissions factors for novel technologies that are not yet deployed, such as carbon capture and storage, do not appear in the NAEI and so have been taken from technical data from developers or assumptions from policy under development (ApSimon and Oxley, 2013). Appropriate emission factors from growing technologies, such biomass heating, are uncertain due to the variability in systems available and their still maturing market, so they use a figure taken from policy assumptions and available market data that matches that of the Renewable Heat Incentive.

Counterfactual scenarios are generated from the baseline scenario by varying the activity of emission sources that, except for the agricultural sector, aim at reducing energy-related air pollutant emissions. They are spread across the following sectors, activities and policy measures:

- **Electricity generation –** Conventional coal and CCGT gas generation and the introduction of CCS-enabled versions of these power plant. Biomass fired generation is available, but only as non-CCS plant. Reduction of emissions from electricity generation also reflect increasing efficiency of electrical devices in all sectors, as changes in air pollutant emissions from this occur at the point of generation.
- **Heat provision –** Residential and non-residential heat; efficiency increases in space and water heating; efficiencies in providing industrial process heat; bioenergy use in space and water heating, industrial processes; biomass fired district heating.
- **Transport –** Emissions savings from the introduction of zero emission vehicles: electric cars, light goods vehicles and fuel cell hydrogen buses are treated as separate measures. Societal and behavioural measures, such as modal shift of transport (e.g. to biking, walking or public transport), more efficient driving styles, more efficient goods distribution logistics or the avoidance of travel (e.g. through remote working) are also presented as distinct measures.
- **Residential energy efficiency –** reduction in gas consumption; reduction in heating oil consumption; reduction in coal consumption.
- **Non-residential energy efficiency –** reduction in gas consumption; reduction in heating oil consumption.
- **Industrial energy efficiency –** reduction in gas consumption; reduction in heating oil consumption; reduction in coal consumption.
- **Agriculture –** Covers only livestock and its food supply chain, rather than arable farming. This results from an early aim to help policy makers understand the effects of dietary change in society and the impacts of reduced meat and dairy consumption.

The policy measures, such as the introduction of hydrogen fuel cell buses or the use of biomass fuels drive characteristic shifts in the emission sources. This is expressed as the amount of energy production avoided each year from each emission source. An increase in biomass boiler use for heat production, for example, reduces the burning of coal, gas and oil in industry, residential buildings and non-residential buildings. Each measure reduces the use of these in each sector by characteristic ratios. The avoided use of these fuels allows the calculation of savings off annual emission budgets for the air pollutants. Additional emissions from the introduction of biomass combustion sources are expressed separately.

RAPID only covers direct changes in emissions from the sectors considered and it does not cover indirect effects. Thus, emissions from upstream supply and processing of fuels do not change with the changing volumes of fuel use in a sector: a reduction in reduced transport emissions that stems from reduced road fuel combustion does not lead to a corresponding reduction in emissions from industry that might be associated with a fall in fuel production. There is some logic in this: a reduction in domestic use of UK-produced road fuel does not necessarily prevent that fuel still being produced and used elsewhere. Likewise, a fall in the use of imported fuel would have no effect on UK upstream emissions. However, the primary reason that RAPID does not account for this is that it does not attempt to model the entire UK energy system, but simply tries to describe the impact of reducing emissions from specific sectors of the energy economy.

AIM does away with RAPID’s user definable baseline scenario and a time series of years. It provides a snapshot of the impact of changes in pollutant emissions from a selected set of measures affect health impacts, environmental deposition of pollutants and costs of these. Unlike RAPID, it includes both $PM_{2.5}$ and $NO_2$ health effects. It is intended to help select cost-effective abatement measures and compare costs of implementation with benefits. Instead of using damage costs per ton it uses “impact factors” which have been calculated separately for each pollutant from each source in the UKIAM.

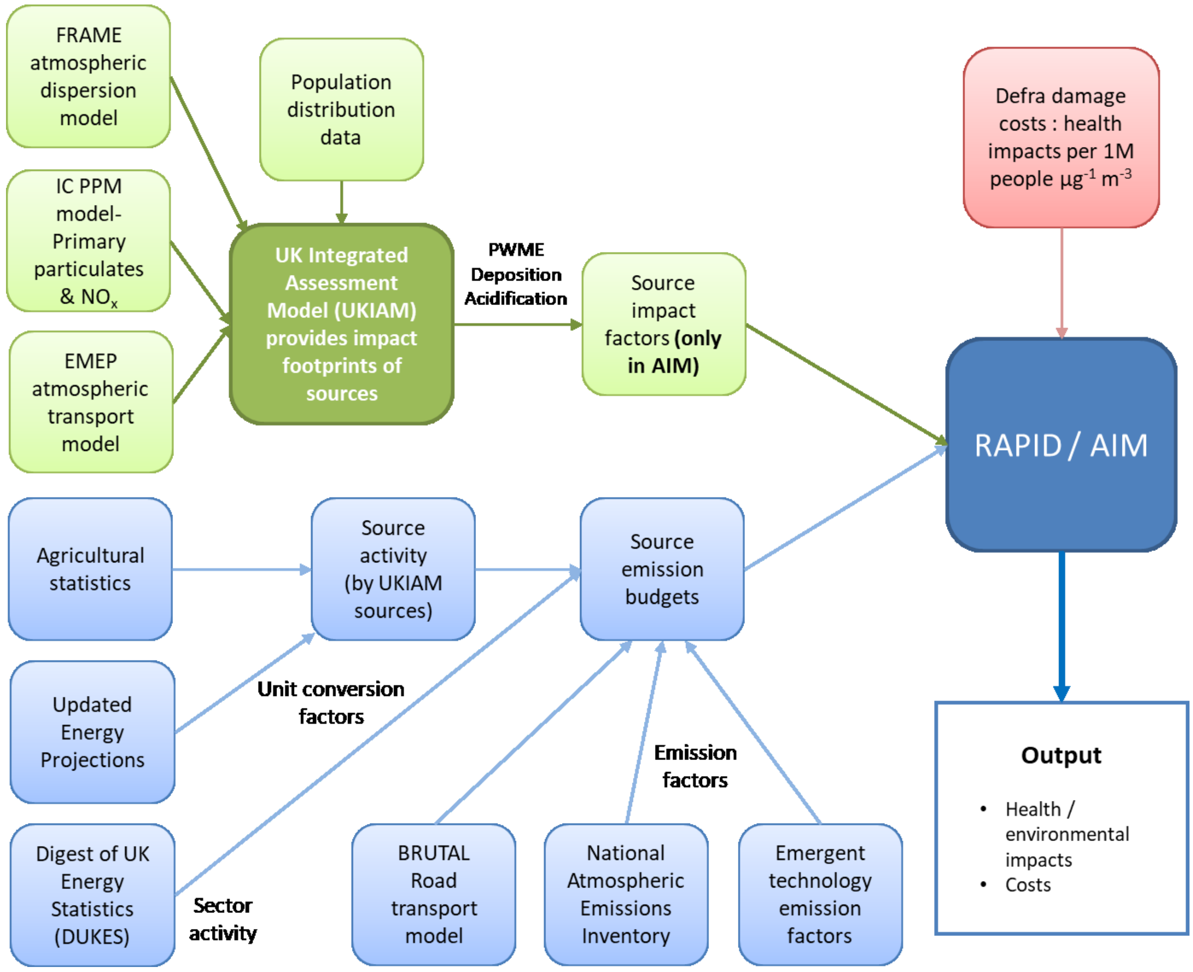


**Figure 3.18: Data sources for RAPID and AIM**

Impact factors describe the effect on UK population exposure to $PM_{2.5}$, and to $NO_x$, resulting from unit emission reductions from each source. Combining changes in pollutants' emission budgets from specified measures with the impact factors for the appropriate sources provides an estimate of the exposure of the UK population, from which health effects can be derived and monetised.

AIM thus offers more detailed spatial information on the characteristics of different sources and the dispersion of pollutants from them, relative to populated areas, than the Defra damage costs alone can. If the change in $CO_2$ and GHG emissions resulting from each abatement measure were included, AIM could provide an overall view of both the air quality and climate benefits.

*Data sources*

Present day source activity for RAPID's baseline scenarios is based on the data used by the Committee on Climate Change's 4th carbon budget assessment, which itself is based on the UK Government's Updated Energy Projections (UEP).

UEPs present a view of how the UK's consumption and production of energy and emissions of greenhouse gases might be expected evolve over the following next 20 years without a change in policy (BEIS, 2018g). They offer a "business as usual" scenario of energy demand and supply against which policy actions can be assessed for objectives such as the retail cost of energy, energy security and meeting greenhouse gas reduction and energy system decarbonisation objectives. In most studies they are used to derive greenhouse gas emissions, but in RAPID, the NAEI air pollution emission factors are applied to sectors' activity.

Many of the sources in RAPID and AIM are very high-level nationwide activities and some of these are described only in terms of a code conforming to the Selected Nomenclature for Air Pollution (SNAP), which aggregates multiple sources into broad categories. Some tend to be relatively small contributors to air pollution, such as solvent use (SNAP 6). Others, such as transport or industry, are broken down in more detail by activity or technology type, due to the very distinct characteristics these have. Very large combustion sources, typically power stations, are listed individually.

When combined with population distribution data, UKIAM modelling allows the calculation of population weighted mean concentrations of pollutants. This reflects the degree to which the population is exposed to annual releases of each pollutant. Nitrogen deposition and acidification impact factors are expressed simply in changes to the aggregate budget for these for Great Britain as a whole.

The impact factors scale linearly with emission budgets. This assumes that there are negligible higher order effects in the ranges of emission budget changes expected in RAPID and AIM scenarios. There is also an assumption for AIM that the spatial relationship between sources and the exposed population remain the same. As the impact factors for particulates and $NO_x$ are based on population weighted mean exposure, any change in the location of either of these would affect the path they are transported over and the amount of diffusion and dilution they are subject to before reaching a populated area. This would change the value of the impact factor.

Damage costs in RAPID are currently limited to health impact and are derived using the damage assessment model proposed by the UK's Department for Agriculture, Food and Rural affairs (Defra, 2019a). These are presented in the output in terms of their financial costs. Whilst the impact factors also include an estimate of years of life lost per tonne of pollutant emitted, these are not used in the RAPID output.

Environmental impact is presented in quantitative terms and as damage costs.

### 3.5.4 Limitations

*Baselines*

RAPID's use of a baseline scenario, against which all air pollution reduction measures are assessed as counterfactual scenarios, means that the tool would need updating depending on how rapidly the baseline scenario becomes outdated. The first versions of RAPID were based on UEP38v7 data, which was originally published by the UK Government in 2008. Energy prices have evolved considerably since, both in the volatility of fossil fuel prices and the cost of deploying low carbon electricity generation: between 2008 and 2018, oil prices varied between around USD 150 and around USD 30 per barrel (Bolton, 2019), whilst the cost of offshore wind generation in the UK fell by 32% between 2012 and 2016 (ORE, 2016).

Additionally, as the 2050 Carbon Calculator demonstrates, the anticipated deployment of some forms of generation has taken place considerably faster than was originally expected. Photovoltaic generation is a high profile example of this: as of 2018, PV installed capacity in the UK was around

12.8 GW by the end of 2017, which matches the anticipated capacity in reasonably ambitious scenarios of the 2050 calculator for the 2030s.

AIM avoids this potential uncertainty by avoiding a baseline altogether.

*Scope of emission sources*

Neither tool includes estimates of greenhouse gas emissions, as they are only intended to describe air pollution. In theory, it would be possible to generate greenhouse gas emissions estimates for the combustion processes represented here. However, it is likely to be easier to use the output of a full energy system model to feed into AIM. This would require the model's output data to be formatted to match the emission sources used by AIM, which suggests that data from the UK versions of MARKAL or TIMES would be better choices than that from GAINS.

The use of an external energy model would also overcome the following two factors:

AIM (and RAPID) only include energy derived air pollutant sources. Many sources of greenhouse gases that do not emit air pollutants are excluded from AIM and RAPID. The absence of these would prevent the accurate representation of net changes to the greenhouse gas budget, as elements such as the greenhouse gas intensity of bioenergy supply chains would not be represented. This could mask emissions that might offset reduction in greenhouse gas emissions from reduced combustion and result in overestimation by the model of net greenhouse gas emissions savings.

Neither tool includes electricity generation that does not act as an air pollutant emission source. This means that the key sectors of non-combustion renewables and nuclear energy in power or heat generation are not represented. Although this is not a barrier to calculating air pollutant emissions from a given scenario, the undefined levels of non-combustion generation would prevent the tool from fully describing electricity and heat production.

*RAPID and AIM as analysis tools*

RAPID and AIM are not intended to be used as full system energy models, but as estimators of air pollution budgets and their environmental and health impacts for future energy scenarios. The design of the tool around impact factors per unit emission change of individual sources suggests make them most appropriate for assessing marginal changes in energy scenarios based on existing sources, rather than large scale changes in emission source. Whilst the tools do not include greenhouse gases, the emission intensities of these from the combustion sources in RAPID, such as coal and CCGT power plant is known and an estimate of annual emissions from these is could be calculated, if the model were to be developed further.

AIM has potential as a post-hoc tool for assessing the air pollution impacts of the 2050 Carbon Calculator and the UK versions of the MARKAL and TIMES models, based both on its capabilities and in the way that it categorises the UK energy economy, AIM may also be valuable with UK TIMES by providing a comparative assessment for UK TIMES's air pollution budget estimation, which would also include the impact of secondary pollutants.

## 3.6 Comparison of models

The models and tools considered here are all built for specific purposes, with capability and limitations reflect these. GAINS and TIMES / MARKAL models take a "bottom-up" approach, which aim to describe the energy system through aggregating descriptions of the individual technologies in use. The 2050 Carbon Calculator uses a "top-down" methodology, which aims to describe the aggregate behaviour of energy use sectors.

| Tools comparison table | | | |
|---|---|---|---|
| | **2050 C Calculator** | **GAINS Europe** | **UK TIMES** |
| **Geographical extent** | **UK** | **Europe, with national level data available.** | **UK** |
| **Sectors covered** | **Production:** Electricity generation and fuel supply chain, including hydrogen for transport.<br>**Consumption**: Lighting & appliances, industrial processes, transport, heating & cooling.<br>Others:<br>Agriculture and land use. | **Production:** Electricity generation and fuel supply chain, including hydrogen.<br>**Consumption**: Transport, heat production by sector.(Energy data derived from PRIMES model)<br>Others:<br>Agricultural emissions (fed in form CAPRI model). | **Production:** Primary energy production, electricity and fuel supply chain.<br>**Consumption**: Residential, manufacturing industrial, service, agriculture, transport.<br>Others:<br>No accommodation of non-energy emissions from agriculture or land use. |
| **Energy efficiency representation and costing** | Efficiency measures represented as explicit actions. | Efficiency measures represented by switching technologies that convert energy and estimating demand reduction from others. Costs only attributed to the former. | Efficiency measures represented by switching technologies that convert energy and estimating deployment of others. Costs attributed to all. |
| **Air pollution model** | Emission factors – sector budgets available internally, with simplified output. | Emission factors + dispersion model | Emission factors |
| **Air pollutants considered** | Particulates ($PM_{10}$) $NO_x$, $SO_2$, non-$CH_4$ VOC | Particulates ($PM_{10}$ and $PM_{2.5}$) $NO_x$, $SO_2$, non-$CH_4$ VOC, $NH_3$ | Particulates ($PM_{10}$ and $PM_{2.5}$) $NO_x$, $SO_2$, non-$CH_4$ VOC, $NH_3$ |
| **Secondary pollutants** | Formation of secondary pollutants is not included. | Secondary particulates and ozone are included in the GAINS dispersion model, but may not be when this is replaced with | Formation of secondary pollutants is not included. |

| | | | |
|---|---|---|---|
| | | national models. | |
| **Accommodation of transboundary pollution** | Transboundary air pollution is not included. | Transboundary air pollution is accounted for in Europe-wide models. | Transboundary air pollution is not currently included. |
| **Climate forcing emissions** | $CO_2$ | $CO_2$, $N_2O$, $CH_4$, F-gases | $CO_2$, $N_2O$, $CH_4$, HFCs |
| **Interdependency of GHGs and air pollutants** | None | None | None |
| **Vehicle powertrains** | IC, EV, PHEV, Fuel cell | IC, EV, Fuel Cell | IC, EV, HEV, PHEV, |
| **Hybrid vehicles** | Only plug-in hybrids | No discrete representation of hybrids – battery and $H_2$ fuel cell vehicles are represented. | Yes |
| **Vehicle fuels** | Diesel, petrol, hydrogen (for fuel cells), electricity use for EVs and PHEVs. | Diesel, petrol, gaseous hydrocarbons, hydrogen (for fuel cells), LPG, electricity use for EVs. | Diesel, petrol, LPG, hydrogen (for fuel cells), low biofuel blends, E85 bioethanol blends, CNG, electricity use for EVs and PHEVs. |
| **Liquid biofuels** | Liquid biofuel production represented as a proportion of all liquid fuels used in transport and heating. | No explicit representation of liquid biofuels supply, but proportions of vehicle fuel consumption are assignable to biofuels. Provision for liquid heating fuels is absent. | Multiple options for liquid biofuels are represented in transport. |
| **Bioenergy** | Biomass combustion is treated as a portion of solid fuel use. | Biogas from digestion | Biomass subdivided into multiple combustible forms. |
| **Carbon capture and storage** | Represented as discrete power plant types, deployable for any capacity of generation in a limited selection of | Represented as additional variants of coal and gas plant only. | Represented as processes that are applied additionally to specific generation and industrial |

| | | | |
|---|---|---|---|
| | fixed ratios. | | technologies. |
| **Negative emissions technology** | Represented partly as a specific set of technologies with negative emissions budgets (air capture & geosequestration) and partly through biomass CCS | Not capable of representation | Represented through combination of biofuel feedstock production and CCS enabled versions of combustion plant power generation. |
| **Cost modelling output** | Basic high and low estimated energy system build costs. | Exact cost assumptions of energy system | Exact cost assumptions of energy system |
| **Cost optimisation** | None. AQ pollutant costs estimates are an output. | Includes impacts of GHGs and AQ pollutants | Includes impacts of GHGs. AQ pollutant costs are output, but not included in optimisation. |
| **Spatial factors** | No spatial resolution related to energy system. Population weighted mean exposure represented in assumptions on air pollution damage costs, based on current distribution of sources. | Spatial resolution for health impacts and air pollution, using the same low-resolution spatial grid as the EMEP pollution model. No spatial resolution related to energy supply. | No model-wide spatial resolution related to energy supply. A symbolic figure intended to represent transport for fuel distribution is used. No representation of back-end infrastructure (e.g. CCS or ash removal.) |
| **Time slicing** | Fixed time slicing. | Fixed time slicing. | Flexible time slicing within the time scale being modelled. |
| **User scenario creation** | Full capability for users to create and share scenarios | Most users can only view scenarios. Some users can submit new data. Few users can run scenarios | Model is open source, but requires licensed software to create and run scenarios. |

**Table 3.4: Comparison of energy technology trajectory modelling tools**

Regardless of these two approaches, some of the policy measures that these tools described are technology specific and therefore have detail on the technologies these measures are based on. This is especially the case in emerging technologies. An overview of the main differentiating points between the tools is presented in Table 3.4.

*Deployment constraints*

UK TIMES, like GAINS, will aim to meet a certain target confined by constraints, whilst the 2050 Carbon Calculator will simply build energy technologies at the rate that the user decides. The Carbon Calculator can thus end up producing scenarios with significant excess supply capacity or under capacity of electricity generation.

The combination of “bottom-up” approach and optimisation methodology of GAINS and TIMES / MARKAL means that technology deployment rates and emissions budgets in these models are constrained when certain criteria are met in the model’s calculations. Examples would be energy demand being satisfied or deployment costs exceeding a given price – usually those of the next most expensive technology to deploy. This results produces output scenarios which remain within certain bounds of realistic deployment.

The “top down” approach of the Carbon Calculator, requires the user to define exogenously many of the parameters that are calculated internally in GAINS and TIMES. These include terms of deployment rates of generation technologies and demand side measures that affect consumption. Cost is not automatically constrained, which can lead to scenarios being generated where the lowest carbon supply technologies meet peak demand, rather than probable demand. This can lead to scenarios that use overcapacity of a technology to meet emission targets, with a resulting high cost to the energy system, due to much of the generation capacity of that technology being unused for much of the time.

A clear example of this would be the meeting of this would be a scenario where peak electricity demand is fulfilled by deployment of a high proportion of nuclear power plant limited only by the maximum build rate. This can lead to scenarios being proposed with a significant overcapacity of nuclear generation. In a real-life situation, nuclear energy is a generation technology that is frequently run at maximum capacity to supply baseload electricity. Overcapacity this would deliver inefficient revenue generation from electricity supply, from most plant being run below maximum output for most of the time, and could further increase costs by reducing plant lifetime, as this is an effect on many nuclear power plants of load-following electricity demand by varying plant output. It may also be technologically unfeasible, as there are limits to the rate at which nuclear plant can load-follow. The two “top-down” tools have no constraint against this.

*Technological and economic lock in*

Representation of technological lock-in and lock-out is another notable differentiator.

The cost of technology shift is influenced by the value of the incumbent energy infrastructure, which in part depends on its remaining lifetime. This can make the rapid, successive adoption of multiple technologies a costly option: the deployment of high value energy infrastructure with a long economic lifetime creates a disincentive to adopt other technologies until its residual value has decreased to an acceptable point.

The 2050 Carbon Calculator accommodates this by assuming infrastructure remains in use for a specified economic lifetime, after which it is assumed that it is decommissioned. The build rates in the model reflect assumptions on the cost per installed unit of capacity for energy provision infrastructure and an expected lifetime, but no more.

GAINS and the TIMES models both accommodate fuller descriptions of the lifetime. Both incorporate investment costs, recognising the fact that a proportion of the cost of energy generation is capital expenditure financing the building of the project in advance of it generating revenue to repay this and yield profit. This includes an assessment of interest rates and can lead to a reasonable estimation of payback time for the project.

The TIMES family of models also considers decommissioning costs, when the project ceases to generate revenue, but still entails costs. These increasingly detailed approaches to describing project finances are likely to yield progressively more realistic descriptions of the cost implications of assets, their economic lifetimes and degree of lock in and the cost considerations of their early replacement.

*Technology representation*

A key vulnerability of all these tools is the ability to describe the performance of emerging low carbon technologies sectors. Many of these, such as electrification and hybridisation of vehicles, CCS systems, grid scale electricity storage and energy demand side management measures can each be provided through multiple emerging technologies. The performance characteristics of these may not be well understood and those that are understood may not be easily accommodated by the parameters used by the tools to describe technologies, which are largely designed around discrete technology types with well-defined operating characteristics.

Even relatively mature technologies, such as wind and photovoltaics, face challenges in being represented. Temporal and meteorological changes that drive variations in renewable generation are poorly represented, especially in models that deal with average annual demand. Seasonal variations in wind directions and strengths are examples of phenomena that cannot be encompassed by annual average assumptions on capacity factors. This can lead to inaccurate estimations of the likelihood and severity of oversupply or shortfalls of generation from these technologies.

Spatial distribution of plant may also have an impact, as both weather events at any one time and average meteorology vary with location. The annual generation from smaller numbers of large turbines in a limited number of locations is therefore likely differ from a more widely-distributed fleet of a larger number of smaller turbines. As neither size nor spatial aspects of wind are included in any of the considered models, this will increase uncertainty over costs and power generation and may lead to misrepresentation of the technology's deployment in optimisation models.

Furthermore, technology trends, such as the average size of wind turbines can affect capacity factors of wind farms. The trend over recent years has been towards larger, higher output turbines with longer blades. These sweep greater areas and lead to higher generation capacity factors than shorter bladed models.

Two case studies of where misrepresentation can occur, with hybrid vehicles and with distributed generation, are presented in Chapters 4-6 of this study. The risk of such misrepresentation is that optimisation models then choose to deploy suboptimal technologies, which can lead to suboptimal decisions in energy infrastructure investments and policy.

Variable performance of single technologies is also a challenge to represent in these tools. TIMES-generated models, including UK TIMES, appear to be most capable in accommodating this. These use methods used to define the behaviour of a technology that allow its emissions and energy consumption to vary conditionally with input parameters such as the fuel it is using. This can help provide a more refined description of flexible fuel vehicles and of power and heat production using different biomass options. It may also help to analyse scenarios in which emerging non-energy measures, such as smart, adaptive control systems can lead to increases in the energy efficiency in existing technologies. Examples of these cover smart, adaptive heating controls in buildings and the potentially more efficient driving style offered by autonomous vehicles.

Given that all these models tend to describe the energy system in terms of energy supply, and conversion on order to satisfy demand, energy efficiency technologies that are not based on more efficient energy conversion are a challenge to represent. The models achieve this with variable success, with costing only being effective if they are represented explicitly.

*Coverage and integration of air pollutants*

The way models cover air pollutant emissions affects their capabilities to compare the effects of reducing them against reducing greenhouse gas emissions. All models estimate emissions budgets of acid gases and particulates, but the 2050 Carbon Calculator does not consider air pollution impacts from ammonia or other forms of reduced nitrogen. These may be significant air pollutants in scenarios from the Calculator, given its incorporation of CCS power and of biomass CCS as key low carbon and negative carbon technologies. These can depend on amine-based solvents, which act as a source of ammonia. Their absence may mask some of the trade-offs of deploying these technologies.

Whilst the 2050 Calculator, GAINS and UK TIMES attempt to estimate the scale of changes in air pollution, only GAINS currently appears able to feed elements of these into an economic optimisation routine. The limitation on this is that the optimisation appears to relate to the activity levels of the air pollution sources and not to their spatial distribution. GAINS will use the air pollution data to optimise on how much of a technology can be deployed and operated but will not attempt to indicate the best location for the technology to reduce impacts and their costs. The other models simply attempt to assess the air pollutant budgets emerging from an energy scenario.

GAINS is arguably currently best placed to identify optimum trade-offs between greenhouse gas and air pollutant reductions due to this integration, although it is limited in its ability to account for the costs and levels of deployment of energy efficiency measures that do not depend on energy conversion. It also is the only model to include a spatial distribution of air pollution. However, to fully explore the relationship between climate abatement measures and energy options and how costs vary, it will need to be run in a non-optimisation mode.

UK TIMES has the richest and most flexible description of technologies and may be more effective than GAINS at exploring the wider energy trajectory options, but it has more limited capabilities for assessing air pollution impacts. It has no true spatial descriptions and the UK TIMES's adaptation to describe air quality generates emissions budgets after the energy system optimisation has been run.

### 3.6.1 Coping with changing policy objectives

Another contributor to uncertainty is policy objectives, which can change rapidly with changes in public opinion, government or policy itself. A key objective is the eventual level of decarbonisation that a country aims for and the date that it is achieved by. The Climate Change Act (2008) requires an 80% reduction from 1990 levels of greenhouse gas emissions by 2050 and some of these tools were designed around assumptions that this would be the eventual target. At the time of writing, an amendment to alter the Climate Change Act's target from an 80% reduction to a 100% reduction is in legislative process. This would create a legal obligation for the UK to emit net zero greenhouse gas emissions by the year 2050.

A zero net emissions target would likely have a significant impact on combustion energy technologies, effectively preventing the combustion of any $CO_2$ emitting fuels unless their emissions to the atmosphere could be prevented or offset in some way. This would likely prevent fossil fuel combustion without any form of carbon abatement. It would also likely affect biomass combustion which, although low-carbon, is generally not zero carbon, and potentially and constrain combustion of hydrogen and other potential fuels to those manufactured in a zero carbon manner (e.g. ammonia, hydrogen or, potentially, synthetic hydrocarbon fuels made from atmospheric $CO_2$ using zero-carbon energy).

Such a change would also profoundly alter the national emission budgets of air pollutants, removing many major sources of NOx and of particulate matter. The degree to which this occurs would likely depend on the degree to which combustion continues with low-carbon fuels. However, a switch to an energy economy that wholly avoids fuel combustion, such as one dependent entirely on nuclear and non-combustion renewable energy would likely virtually eliminate combustion $NO_x$ and limit emissions of other air pollutants to non-combustion sources.

Some of the models discussed here do have the ability to represent such a change by remove certain processes from the energy economy completely. Fossil fuel combustion and plant can be removed from UK TIMES and, in principle, may be removable from the PRIMES model that handles the description of the energy system in GAINS analysis. The 2050 Carbon Calculator, on the other hand, does not include the option to do this easily, as it would require significant rewriting of the spreadsheets in the model. An essential change would be to prevent the Calculator supplying any energy demand from fossil fuels that exceeds low-carbon resources.

### 3.6.2 Other similar models

The tools considered in this chapter have been identified as those used for policy analysis, covering the UK's energy system and emissions budgets. Other energy analysis tools have been developed that attempt to overcome some of the limitations seen in those discussed here, although they have no capability of assessing air pollution impacts. Those most closely aligned with the analysis this study focuses on include:

**ESME, developed by the UK's Energy Technologies Institute.** This is a sector based technoeconomic energy systems optimisation model that has been built to undertake Monte Carlo analysis of energy technology decarbonisation trajectories. ESME's probabilistic approach makes it suitable for sensitivity analysis of the costs of new energy scenarios, including insight into the impacts or errors and poor representation of technologies (Pye, Sabio et al., 2015). ESME also includes a limited degree of spatial resolution, dividing the UK into 12 onshore and 9 offshore regions, which it uses to impose development constraints and costs such physical support infrastructure (e.g. for $CO_2$ or H2 transport and for electricity grid connections) (Heaton, 2014). ESME includes greenhouse gas emission budgets but does not cover any air pollutant emission budgets.

**DynEMo** is a tool developed by University College London' Energy Institute that aims to generate energy system trajectories up to 2050 that integrate consumer behaviour and response on a wider basis than simply costs of energy sources and infrastructure (Barrett and Spataru, 2015). It also includes factors such as climate and weather conditions and lifestyle choices such as dwelling type and occupancy. DynEMo's aim is to understand how renewable and other energy technologies are integrated into an existing energy system and pays attention to fuel switching. DynEMo does not currently calculate emission budgets of greenhouse gases or air pollutants. In principle direct (combustion) carbon emissions could be calculated from the energy sources in the model and their usage.

### 3.6.3 Addressing variability in models

The models detailed above face limitations in describing and simulating accurately the issue of variability in future energy systems, particularly those with a high level of electrification. These tend to be systems where technologies using combustible fuels, such as heating and vehicles are replaced with those using electricity. Energy systems in scenarios with high electrification face a greater challenge in balancing production and demand of energy, due to the fact that the electricity transmission and distribution system cannot act as a store of energy in the same manner that fuel distribution systems can: electricity must be generated at almost the same rate at which it is consumed. Short term changes in supply and demand are therefore more significant in highly electrified energy systems.

Wind and solar are two key renewable sources of electricity, but are highly variable over in both short and long term: they can vary instantaneously, daily and seasonally. Furthermore, they lack the ability that large combustion-fuelled and hydroelectric plant has to store a small amount but crucial amount of energy as angular momentum in electromechanical generators. This reduced the ability for wind and solar generation plant to supply sufficient energy to maintain the alternating current frequency of the electricity grid when a sudden change in power demand occurs.

An increase in technologies driving electricity demand, such as a shift to electrical heating, cooling and transport can lead to much greater fluctuations in power demand over all time scales than is seen at the time of writing. Very long distance electricity transmission, together with energy storage for electricity and for low-carbon heat (such as batteries, pumped storage, thermal stores and the low-carbon generation of hydrogen) can help manage this variability and match supply and demand on an electricity grid. However, these emerging technologies are poorly represented in the aforementioned models – particularly in how they account for the impacts of temporal variability on different timescales and of spatial variability.

A key limitation in the models considered earlier is spatiotemporal resolution: they are designed for considering long term trends over entire energy system. They therefore tend to use time-slices of years and have little capability to describe regional variations in energy demand and resources. Studies suggest that this approach can lead to overestimation of the generation from variable renewable electricity sources (Pietzcker, Ueckerdt et al., 2017).

The accurate representation of high variability requires both high time and spatial resolution. This is a characteristic of operational simulation of power systems, which tend to use models that make predictions over much shorter time ranges than long-term energy system trajectory models such as GAINS or UK TIMES. Electricity dispatch models assess this by considering variation over minutes or hours of parameters such as power demand across localised areas, grid capacity limitations, interconnection availability, fuel prices, and electricity market bidding structure. The challenge is to integrate data from these into higher level models (Ringkjøb, Haugan et al., 2018).

Models that have not been used in national policy making in the manner of GAINS or UK TIMES and which have therefore not been included in the main part of this analysis are being developed in an attempt to meet this challenge.

One example of such a model is HIRES (the high spatial and temporal Resolution Electricity System model). This applies much higher spatial and temporal resolution to energy systems than previously mentioned models and can accommodate real meteorological data on which to estimate the capacity and variability of renewable energy generation. In addition to this, it also offers detailed options to constrain build capacity and rates of resources to specific locations and omitting, for example, protected areas where build may not be an option. This ability to be specific about location also appears to be likely to improve accuracy on weather data for sites where meteorology-dependent renewable generation is likely to be deployed.

HIRES can also offer supplementary capability to energy trajectory models in a manner that can help overcome some of the limitations mentioned. It has been used successfully in conjunction with UK TIMES to explore the robustness and carbon intensity of high electrification, low-carbon, high renewable, nuclear baseload energy systems for the island of Great Britain and the Scottish islands (Zeyringer, Price et al., 2018). Scenarios explored achieved the 80% reduction on 1990 greenhouse gas emissions specified under the UK Climate Change Act (2008) and thus had similarities with the scope of Scenario 2 of the 2050 Calculator scenarios. This study used real-time meteorological data to drive intermittent renewable electricity generation and split the electricity grid into 17 geographic zones.

## 3.7 Conclusions

The approaches used by many models of the UK's energy system that cover air pollutant emissions to describe the behaviour of emergent energy technologies present risks to the quality of the models' output. These can arise from limitations in the methodologies' capability to describe the way efficiency, consumption of fuels and atmospheric emissions vary with operation and with specific technology solutions. They can also arise from limitations on how technologies' deployment is described, which may arise from a lack of ability to describe spatial aspects of deployment, such as distribution of emission sources and population or the amount of supporting distribution and supply infrastructure required for them to operate.

A contributor to uncertainty is that emerging energy technologies have immature markets with a high rate of technical change and multiple technical approaches. Another is that some emerging technologies may have much greater operational variability in behaviour and factors that affect this than incumbent technologies. The methodology used by models may not be able to encompass these changes. Decentralised energy and hybrid vehicles both offer examples of such technologies and are considered in following chapters.

These limitations can affect the accuracy with which models can forecast emission budgets, health and environmental impacts and costs. They may pose a greater risk for output quality of optimisation models which have outputs that are highly cost-sensitive and lead to unrealistic scenarios of technology deployment. They may also limit models' ability to highlight trade-offs between benefits in reducing greenhouse gas emissions and air pollutant emissions, by introducing greater inaccuracies in predicted emission budgets and damage costs, as well as cost effectiveness of technology choices.

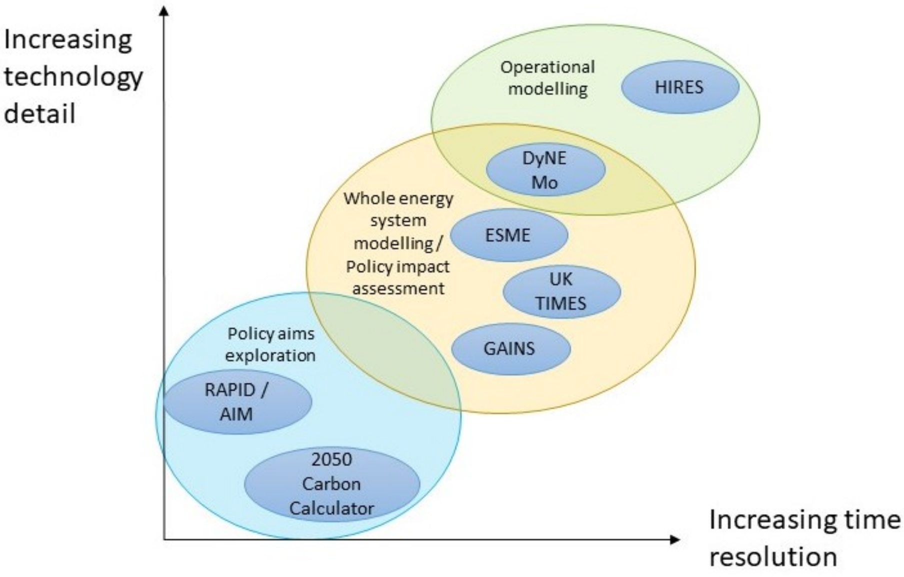


**Figure 3.19: Functional relationship between models**

Despite these limitations, the 2050 Carbon Calculator, GAINS and the adapted version of UK TIMES are suited to exploring the co-benefits and trade-offs between measures to reduce greenhouse gas emissions and air pollution. The optimal use of the models varies, based on the level of detail and resolution in the model and a comparison of those mentioned in this study is shown in Figure 3.19. This use varies, ranging between high-level exploration of policy aims over the longer term to detailed operational modelling over the shorter term.

The RAPID and AIM tools are better suited for high level analysis of the outcome of energy scenarios from the models and may offer more comprehensive coverage of pollutants (e.g. secondary particulates) than some of the models do. They may also provide a convenient way of assessing the air quality impacts of scenarios from other energy system models, such as ESME and DynEMo, as long as the output of these models can be formatted to match the emission source sectors or RAPID or AIM.

The 2050 Calculator is best suited to analysing the relationship between air pollution and greenhouse gas emissions on a sector basis. The air quality adapted version of UK TIMES is more capable of demonstrating the impact of individual technology choices within sectors, although this is subject to the above caveats on how well those technologies are represented

Clarity and transparency on the interrelationships may be improved by modification of the models' output to provide sectoral budgets of air pollutants. The 2050 Calculator already calculates emission budgets at a sectoral level but does not display them. RAPID and AIM also work on a sector basis, but consider changes in emissions, rather than emission budgets.

UK TIMES uses a technology-based, rather than sector-based form of representation. As this is based on emission sources represented in the UK NAEI and DUKES energy consumption data, aggregation of air pollutant budgets in to sectors appears to be feasible. It is not clear how easily GAINS might be configured to provide air pollution sectoral emissions budgets.

# 4. Case study – CHP cogeneration for district heating in London

## 4.1 Introduction

### 4.1.1 District energy

District heating and cooling systems (also called district energy networks) provide heat and cooling services, usually as steam or hot or cold water, via a network of insulated pipes to multiple buildings in a common geographical service area (e.g. a neighbourhood or a city). This enables users to share sources of heating and cooling in a manner that is not possible with un-networked, highly localised systems, such as the per-building or per-dwelling use of boilers, heat pumps, air conditioners or refrigerators that is currently common in the UK.

District heating and cooling sources of heat and cooling can be multiple and diverse, enhancing the energy security of the system: if one source fails, others are available. They can offer the opportunity for buildings to access low-carbon heating and cooling that may not be possible from un-networked systems: an individual building or dwelling may not be able to install a ground source heat pump or may not have sufficient external space for solar thermal panels, but energy from these can be delivered to it across a district heat network.

Thus, district energy networks offer considerable potential for decarbonising heat and cooling supply. This will be enhanced the more the electricity network also decarbonises. Electricity is needed to operate heat pumps, which are a major potential heat resource but, being electrically operated, can only deliver zero-carbon heat if they are operated from a zero-carbon electricity supply.

Such networks also have the potential to increase the efficiencies in energy and cost with which heat and cooling services are provided and with which their environmental impacts facilities are managed. Generation facilities can benefit from economies of scale: per unit of delivered energy, the maintenance costs and operating efficiency of large plant can be lower than for domestic scale installations. Higher efficiency air pollutant abatement technology options become available, such as flue gas aftertreatment to reduce $NO_x$ from gas plant and VOC and PM emissions from biomass plant. This is, of course, additional to the considerable scope for avoiding air pollutant emissions altogether though the enhanced ability district energy networks offer to deliver heat from non-combustion technologies.

Benefits can also arise from the supply chain: the transport requirements and environmental impacts of delivering solid biomass fuel to a single large heat plant feeding a network can be significantly lower than delivering the same fuel to a large number of buildings, each with an individual boiler.

District energy networks have seen significant deployment in areas with high population densities and high demand for space and water heating. Cities in northern and central Europe, particularly in Scandinavia and in the former communist states, are often-quoted examples of district energy pioneers and many of these continue this tradition of innovation.

Sweden, for example, started developing district heat in the 1940s. Up until the 1980s this tended to be delivered by burning fossil fuel in either boilers or cogeneration systems. Since then, the number of sources have decarbonised and diversified: most of the heat sources using combustion have shifted to biomass fuels and been supplemented with heat pumps using ambient environmental heat, industrial waste heat or from efficiency measure such as flue gas heat recovery. In 2015, it is estimated that only about 8% of heat in Sweden’s district energy systems came from fossil fuel combustion (Werner, 2017).

The typical operating parameters have also shifted: early networks were designed to use high temperature hot water in ducted pipes. More recent systems have tended to operate at low temperature, using highly insulated pipes buried below ground (Lund, Werner et al., 2014). This may facilitate the use of heat from environmental heat pumps or heat recover systems, which often have lower output temperatures than combustion equipment.

Denmark has six large district-heating networks across its major urbanised areas and 400 smaller schemes. Together these serve around 63% of Danish households. The number of large-scale CHP units has remained roughly constant since the 1990s, delivering around 60 PJ heat annually to the country. A similar contribution of around 25 PJ has been provided by dedicated district heating units. Most growth has come from small scale CHP and heat and / or power form auto producers – sites that generate their own energy and export surpluses (DEA, 2015).

Most Danish district heating is combustion based, with almost 50% coming from waste to energy plant and the remainder from natural gas and coal. A shift away from this looks likely, as Danish policy targets aim for at least 50% of electricity to come from wind, potentially reducing the demand for CHP in the country and increasing the opportunity for electricity-driven heat sources, such as heat pumps. Some heat pumps are already used on the system, as Danish district heat systems tend to incorporate heat storage facilities as part of the network.

Scandinavian countries are not the only example of such diversification and decarbonisation in heat sources for district networks: water source heat pumps are planned to be used in a district energy system on the river Clyde (Coates, 2019).

### 4.1.2 Cogeneration

Cogeneration is the production of electricity together with heating and / or cooling services from the same facility. It has its origins in commercial and industrial applications, where the heat demand and electricity demand of activities on individual sites

Generally, cogeneration uses internal or external combustion plant to drive mechanical electricity generators, with the waste heat being delivered and sold to customers for heating or being used to run absorption chilling equipment for cooling. The exception to this is CHP based on fuel cells, which produce heat and electricity by electrochemical means from hydrogen or from low molecular mass hydrocarbons or alcohols.

CHP fuel cells currently tend to lend themselves to individual domestic heating systems, due to their unit size and electrical output and to the temperatures they achieve, but are currently limited in size and in the temperatures they can reach. For this reason, it is assumed that combustion technology has a role to play in heat networks

### 4.1.3 CHP in district energy

Combined heat and power (CHP) district heating offers a more efficient use of energy from thermal plant than the separate generation of heat and electricity. In general, CHP based district heating relies on relatively small combustion plant compared to power stations, to provide heat suitable for space heating and domestic and commercial hot water applications. Many large power stations with thermal output in the gigawatt range, including most UK nuclear ones, use thermal generation units that can provide this kind of CHP, but this potential remains untapped. In the UK, studies of real-world potential demand have been undertaken for many centralised power stations, but no energy supplier has yet chosen to deploy it on a heat network.

Part of this appears to be a matter of size of power plant in relation to location and size of heat demand: heat distribution infrastructure is more expensive to build than electricity distribution infrastructure and heat cannot be transported efficiently as electricity over long distances. Because of this, the availability (and often proximity) to a CHP power station of a minimum reliable ongoing heat demand to make the supply economically feasible is a key requirement. This is generally referred to as an anchor load and there are few such loads close to large power stations in the UK. Another influence is the low number of deployed heat networks in the UK for large CHP to feed into.

This is in contrast to countries in which both district heating was deployed earlier, which has allowed power plant with both gigawatt-rage thermal output and CHP generation to be constructed. Such is the case of Siekierki power plant in Warsaw, which has been providing the city with up to 2078 MW heat and 607 MW power since 1961 and is based well within the metropolitan area.

Smaller CHP is deployed in the UK and plant capacities range up to tens of megawatts of thermal output. Most of these networks tend to be limited in geographical extent and serve specific residential developments and local anchor loads.

### 4.1.4 District energy and CHP in London

The extensive use of heat networks as a future means of distributing heat from CHP to urban areas is a scenario considered in policy options by successive UK's energy ministries, including the Department for Business, Energy and Industrial Strategy and, prior to this, the Department for Energy and Climate Change. London's regional tier of government, the Greater London Authority, also considers it as an option. Whilst energy models such as GAINS and UK TIMES can describe certain aspects of this option, such as the fuel $CO_2$ emissions and heat service demand, they have limited capability for describing other impacts with high spatial dependence. These can include the impact on air quality impact and trade-offs that depend on the system design, as well as overall network deployment costs.

It should be appreciated that CHP is not the only technology capable of delivering district heat in London. Many other district energy options exist, including those described above in Scandinavia, Scotland and Poland. Further options are offered in the form of individual installations (i.e. non-district energy) of solar thermal heating, air and ground source heat pumps and even, potentially, individual CHP installations. Individual CHP installations of fuel cells offer the opportunity to provide both heat and power efficiently without emissions of combustion related air pollution, whilst to delivering the necessary fuel, whether hydrogen or natural gas, using the existing gas network infrastructure.

As discussed above, the deployment of district heating is a demonstrated method of improving the efficiency and reducing the cost of supplying heat in high population density locations over that of multiple individual heating installations. District energy CHP offers likely efficiency improvements in terms of energy, carbon and cost for providing district heat

### 4.1.5 Applying the UKIAM model to London

Analysis of the atmospheric pollutant impacts of the introduction into London of CHP cogeneration plant to supply district heat using the UK Integrated Assessment Model (UKIAM) is provided as an illustration of the capabilities and limitations of key energy technology trajectory models to consider the implications of changes in future energy infrastructure, as well as an illustration of trade-offs between greenhouse gas and air quality releases in such scenarios. The UKIAM was chosen because of its use by the UK government to produce its official modelling and statistics on air quality emissions and impact and its ability to account for some spatial aspects of scenarios. Whilst the UKIAM calculates air annual average pollution across the entire UK, it can also be used to consider more localised situations and it was used in such a manner for this study.

One limitation of the UKIAM being based on annual average emission is that its description of meteorological conditions, such as wind roses and precipitation patterns, are also based on annual averages. It cannot, therefore, provide detailed modelling of phenomena such as intra-annual variation (e.g. hourly or daily averages) in concentrations of emission as the result of weather or of weather driven formation of secondary pollutants, such as the photochemical production of ozone with changes in insolation.

Scenarios were chosen for London in which electricity generation from large power stations, distant from population centres and the use of domestic boilers for heating and hot water purposes are displaced by the introduction of combined heat and power (CHP) generation plant feeding district heating networks.

## 4.2 Scenario Generation

A limitation that the 2050 Pathways Analysis Tool, UK TIMES and GAINS have in common is that none of these models have been configured for the description of energy scenarios of a scale of less than the whole UK. An alternative approach to scenario generation was therefore needed to provide spatial source distribution, energy demand and emissions characteristics.

In this case, the UK's National Atmospheric Emissions Inventory and the US Environmental Protection Agency's CHP Database were considered for providing CHP emission factors and the London Heat Map and the London Decentralised Energy Capacity Study were used for the remainder of the data.

The analysis was undertaken for this study by the author in 2012 and considers the displacement of generation from Didcot B: a large, centralised combined cycle gas turbine (CCGT) fired power plant proximate to London. Gas fired facilities are seen as the most likely marginal electricity plant typically operating and therefore represent the most likely to be displaced by the introduction of CHP.

It should be noted that at the time of writing, although the most marginal plant on the UK grid is coal fired, this plant is unlikely to be displaced by the introduction of CHP. The amount of UK electricity generated by coal is in steep decline, with a 26% year-on-year reduction (BEIS, 2018k) observed by mid-2018, and the proportion of the time across the year when no coal fired power plant operates is increasing rapidly. By October 2025, all remaining large conventional coal-fired power plant in the UK are expected to close due to legislative reasons. Given the current existing level of heat network build in London and the fact that very limited installation of new heat networks in London may be achieved in the time before this date, it would be unrealistic to assume that such new CHP would offset electricity generated from coal burning.

| Technology / Fuel | g $CO_2$e emitted per kWh fuel net energy content | Efficiency | g $CO_2$e emitted per kWh electricity generated |
|---|---|---|---|
| **Coal-fired boiler plant** | 308 | 39% | 790 |
| **Combined Cycle Turbine Natural Gas** | 184 | 52% | 354 |
| **Open Cycle Turbine Natural Gas** | 184 | 40% | 460 |
| **Reciprocating Engine Natural Gas** | 184 | 37% | 497 |
| **Reciprocating Engine Diesel (Gas oil)** | 271 | 45% | 602 |

**Table 4.1: UK governmental estimates of carbon intensity for fossil fuel fired electricity generation (HoC, 2015).**

| Technology / Fuel | New plant ($mg/Nm^3$) | Existing plant ($mg/Nm^3$) | Legislative Basis |
|---|---|---|---|
| **Coal / solid biomass / liquid open combustion > 300MWth** | 200 | 200 | IED |
| **Combined Cycle Gas Turbine** | 50 | 50 | IED |
| **Open Cycle Gas Turbine** | 50 | 50 | IED |
| **Reciprocating Engine Diesel** | 190 | 190 | MCPD |
| **Reciprocating Engine Natural Gas** | 95 | 190 | MCPD |
| IED - Industrial Enmissions Directive 2010/75/EU; MCPD – Medium Combustion Plant Directive 2015/2193/EU | | | |

**Table 4.2: UK governmental $NO_x$ emission concentration limits for fossil fuel fired electricity generation (HoC, 2015).**

This is significant in considering the benefits of CHP, as coal or diesel generation of electricity without cogeneration is estimated to produce $CO_2$ emissions per kWh of electricity generated that are considerably greater than combined cycle gas turbine (CCGT) plant or open cycle gas turbine (OCGT) plant; $NO_x$ emissions from solid fuel plant are variable, but the limit value on the maximum concentration of $NO_x$ emissions permissible from coal plant is 4 times greater than those from CCGT or OCGT plant (DECC, 2011). These are maximum limit values defined by EU Directives and as such are the same across the EU. Available models of plant hardware are designed to meet these requirements and tend to be available across the whole EU market, so differences emissions are unlikely to vary on a national scale.

By contrast, the power station gas turbine plant being displaced by CHP has the lowest levels of emissions of that considered in Tables 4.1 and 4.2. However, with its proximity to London, discontinuing its use was likely to lead to the greatest potential falls in $CO_2$ emissions and exposure by the population of London to $NO_x$ from large, centralised generation plant.

### 4.2.1 The London Decentralised Energy Capacity Study

In 2011, the Greater London Authority (GLA) currently set itself the target of delivering 25% of London's energy from decentralised sources by 2025 (GLA, 2011). To gauge the technical potential for achieving this, the Greater London Authority (GLA) undertook the London Decentralised Energy study. This examines the potential for deployment of renewable, low carbon and high-efficiency generation technologies for heat and electricity. The options considered include the use of medium and small-scale renewables as well as fossil fuelled combustion CHP plant within the city boundaries and the use of large power stations outside the city to deliver heat via long-distance heat network.

The study proposed several scenarios, the evolution of which are considered out to the early 2030s, which depend on the degree of coherence in national and local policy across the UK. These are:

1. *Business as usual:* 2010 Energy prices are assumed with a 9% discount rate, with little investment in decentralised energy or renewables.
2. *National action:* Gas supply is constrained, with corresponding price increases. This drives investment in renewables and a decarbonisation of the electricity grid to 192 $gCO_2\ kWh^{-1}$ by 2031. A medium discount rate is used, reflecting risk sharing between public and private sectors.

3. *Regional Action:* There are few supply constraints, but local and regional government policy is aimed at deploying renewable and decentralised energy. The electricity grid decarbonises to 296 $gCO_2$ $kWh^{-1}$ by 2031. Low discount rates are assumed, based on funding largely coming from governmental grants.
4. *Ambitious Action:* Gas pricing is similar to the National Action scenario, but this is combined with policies aimed at promoting renewable and decentralised energy at all levels of government. Rates of deployment are high, due to a planning regime that is favourable to energy developments and represents a theoretical (but unlikely) near term shift away from using natural gas. As with the Regional Action scenario, discounting rates are low.
5. *Co-ordinated Action:* Similar national and regional level supporting actions to the Ambitious Action scenario are combined with a high gas price and a very high electricity price. A medium discount rate is used and the level of district heat network deployment is around the centre of the range used in these scenarios.

At the time of writing, UK electricity supply most closely resembles the National Action scenario: policies have driven enough renewable energy deployment to reach grid carbon intensity of 170 g $CO_2$ $kWh^{-1}$, slightly below the assumed value for this scenario..

For the scenarios in this case study, the “Co-ordinated” scenario was used, which assumes the greatest incentives for CHP and which delivers around 24 TWh / year of energy to London from multiple sources within the urban area. These include waste gasification and biomass combustion plant, photovoltaic cells, small and medium wind turbines, as well as gas turbine CHP plant. 17 TWh / year of energy is supplied by district energy CHP plant running on combined cycle gas turbines (CCGT) rated at up to 50 MWe. Other significant CHP components include 1.3 TWh / year of “medium sized” biomass fired CHP and 964 GWh / year running on gas engines.

This case study explores the air pollution and climate impacts of the CHP elements of the “Co-ordinated” scenario.

### 4.2.2 The London Heat Map

District heating run off CHP plant represents a significant opportunity for achieving London's ambitions for decentralising energy production. In order to identify where this could best be implemented, the London Heat Map was undertaken as a project between the GLA and the London Boroughs (GLA, 2012). It provides information on existing district heating systems, maps demand for heat across the city and identifies opportunities for new networks.

A key concept in this is the "anchor load", which provides a significant, dependable year-round demand for heat, independently of the domestic market. Anchor loads are important in establishing the financial viability of a district heating system. Seasonal and daily fluctuations of demand that occur from domestic heating demand represent a degree of uncertainty of income, and therefore financial risk, for suppliers of district heat.  Having an anchor load as a customer for a heat network can help reduce this risk by providing a reliable source of heat demand, and thus income, which is independent of the domestic market. Typical anchor loads include hospitals, leisure centres and facilities using steam in industrial processes.

It would be possible to base CHP entirely around anchor heat loads – indeed this could be economically favourable through maximising utilisation of the plants' capacity in much the same manner as developers might aim to maximise the capacity of a large centralised power plant. However, the objective of the GLA is to encourage the decarbonisation of London's energy and delivery of heat from CHP stations to residential customers is likely to provide advantages in terms of the net decarbonisation of heat and power.

### 4.2.3 CHP plant type and distribution

#### *Spatial distribution*

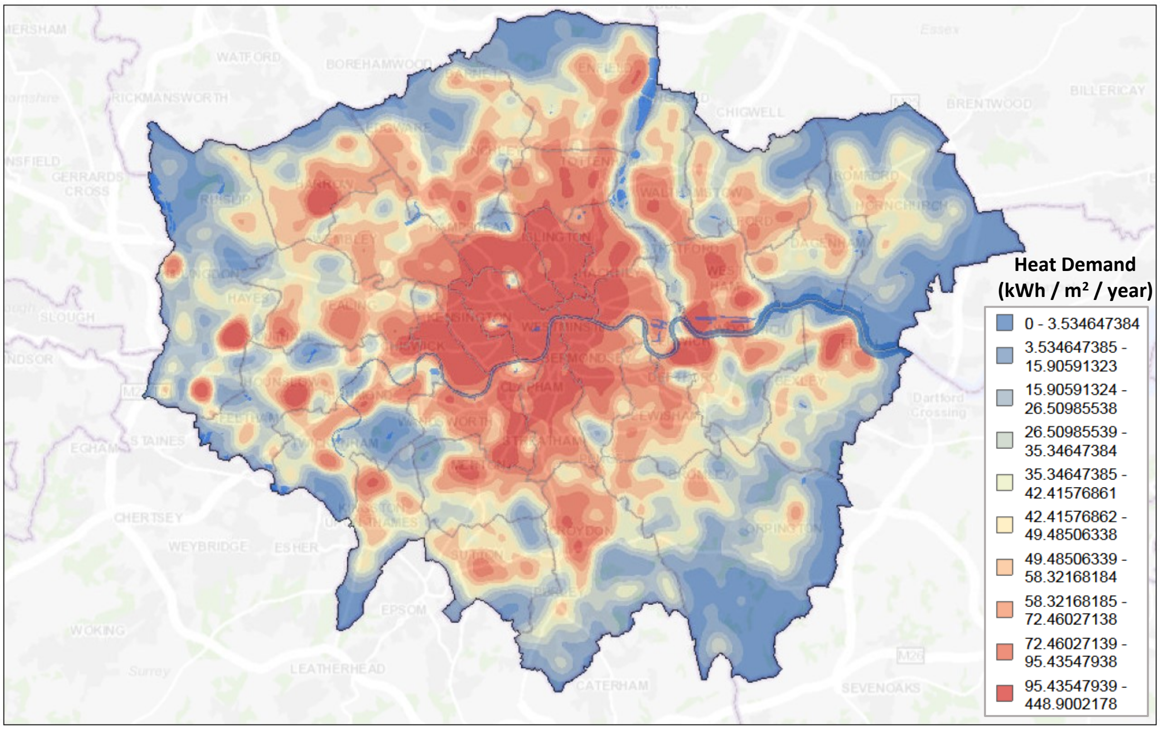
The spatial distribution of CHP plant in the scenarios used in this study corresponds to the areas of London with the greatest co-location of heat demand and anchor loads, which is defined by the top

20 % of areas of co-location of residential and commercial load match. Figure 4.1 shows the distribution of heat demand (first map), with the top 20% area represented in black. The location of CHP plant in the scenarios used was confined to this area.

There are a number of existing examples of CHP heat networks London run by an energy sources similar in scale to the CCGT plant considered here. One is the SouthEast London CHP plant, SELCHP, which uses waste to energy to power a 35MWe electrical generation plant and provide diretict heating. Another is the Citigen network in the City of London, which is powered by a 30 MW gas / diesel generation plant. This provides 12.5 MWe to the national grid and 14 MWth to several heat and absorption-chilling anchor loads, including the Smithfield meat market, as well as the more seasonably-variable demands of the arts complex and residential areas of the Barbican Estate. Together, these represent what is a realistic demand pattern, with a mixed customer base that appears to be similar to the type of heat networks portrayed in the Decentralised Energy Capacity Study.

Several options exist for the deployment of CHP, which range from discrete, small, unnetworked heat sources of the type that might be used for heating a single building to large, highly networked sources of tens of megawatts electrical and thermal output. The current level of development of Citigen delivers heat as far as 2.5 km from its source by pipe length, so it is assumed that sufficient heat demand exists within 2.5 km of a plant of this size to use all its prodcution.

London Heat Map - Annual heat demand by area



London Heat Map - highlighting top 20% residential & commercial load match

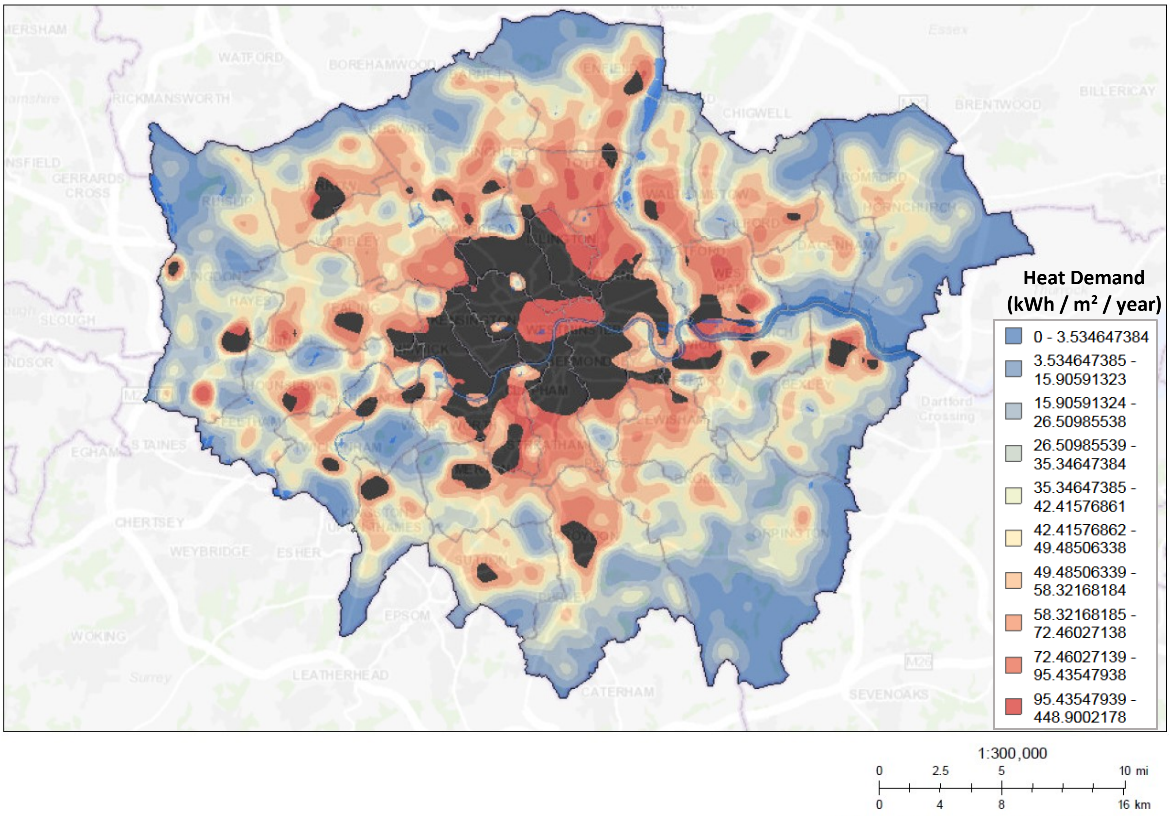


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**Figure 4.1: Annual heat demand in London: 20% best match for co-location of London heat demand and anchor loads overlayed in black. (GLA, 2012).**

To reflect this in these scenarios, this is the maximum limit placed on network length from any consumer to a heat plant. It results in a distribution of:

- A large central zone in the City and immediately adjacent boroughs, where the heat networks could in theory be interconnected, with CHP plant spaced no more than 5km apart.
- Individual "islands" of heat network in the outer boroughs, which extend no further than 2.5 km from the plant.

The scenarios here account for this by placing centralised CHP generating stations no more than 5 km apart across the central zone and at the centre of the "islands" of coincidence of high demand and anchor load. It should be noted that the extent of heat networking within central London is an extreme case, which might conceivably be arrived at as an end-point of several decades of development. Also, there is no obligation to place heat sources in a particular place on the network. A uniform average distribution of plant of this size the central zone has been chosen in order to represent a scenario of heat networks growing simultaneously and joining up, rather than a single large network being enlarged through extension.

*Plant type*

The GLA's co-ordinated scenario delivers approximately 17 TWh / year of overall energy from large CCGT plant. However, there is no obvious market driver for them to be CCGT-based if another technology can supply the energy equally as economically, as the properties of the electricity delivered to the end-user will be independent of the plant type. By contrast, the overall environmental impact, in terms of climate change and $NO_x$ air pollution, depends very strongly on both the generation technology and the way it is deployed: the flue gas emission height and surrounding environment of combustion sources will have a significant influence on the local population's exposure to its emissions.

This case study therefore diverges from the GLA's scenarios by trying to consider the most favourable ways, in terms of $NO_x$-based air pollution or minimisation of plant build, to shift away from the current practice of generating discrete power from centralised stations and heat from highly decentralised domestic equipment, to producing both from large CHP plant. This is done through comparing the following scenarios:

A. *Base case:* London continues to rely on centralised power generation from the National Grid for electricity and on incumbent technology (largely electric and gas boiler technology, with some electrical resistance heating) for heat provision. Gas boiler efficiency improves, but there is no shift away from the use of boilers for heating.

B. *CCGT CHP with 70 m effective stack height:* CCGT CHP plant of generation capacities between 30 MWe and 70 MWe provides around 17 TWh of energy as 8.8 TWh of electricity and 8.0 TWh of heat. The stack height of 70 m corresponds to a chimney of around 35 m and around 35 m plume rise before dispersion occurs.

C. *CCGT CHP with 20 m effective stack height:* As above, but it is assumed that planning regulations limit the height of chimneys, resulting in the combined height of chimney and plume rise before dispersion occurs being 20 m.

D. *Gas engine CHP with 70 m effective stack height:* Instead of gas turbines, gas fired reciprocating engines are used to provide the CHP. This is currently the way in which Citigen operates and would represent a failure to shift towards CCGT technology for larger CHP. Gas engines are more scalable than gas turbine plant and may provide a route to smaller scale startup of a heat system, expanding to larger volumes in the future. A supplementary scenario, D1, is also explored, which considers the case of the deployment of a single gas-engine plant.

E. *Gas engine CHP with 20m effective stack height:* As above, but in common with the corresponding CCGT scenario, the combined height of chimney and plume rise before dispersion occurs is 20 m. A supplementary scenario, E1, is also explored, which considers the case of the deployment of a single gas-engine plant.

F. *Biomass fired CHP with 70m effective stack height:* Instead of gas turbines, biomass-fired, steam turbine plant with a 70m effective stack height and a fluidised bed combustion system is used to provide the CHP.
G. *Biomass fired CHP with 20m effective stack height:* Biomass-fired, steam turbine plant with a 20m effective stack height and a fluidised bed combustion system is used to provide the CHP.

### 4.2.4 Rationale and limits of feasibility and of scenarios

*Stack height and modelling accuracy*

With the exception of D1 and E1, these scenarios can be considered extreme cases of deployment of individual technologies and have been chosen to stress the sensitivity of $NO_x$ concentration to the key parameters of plant type, fuel and stack height. Consequently, these include values of these that, whilst not feasible, do serve as good illustrations. Whilst 70m is an entirely likely stack height for large CHP plant, a 20m stack height is not. However, the 20 m stack scenarios do serve to give an indication of the potential effect on $NO_x$ concentrations of limiting the height of stacks in energy centre developments where occupied buildings may exceed the stack height. Additionally, they may provide a rough approximation of the dispersion of emissions from a high concentration of a small number of plant in a relatively low rise area.

In the central area of London, however, the reliability of average concentrations from the 20m stack height scenarios is likely to be impaired. The increased concentration of relatively high buildings, together with a street canyon effect, will modify the dispersion of air pollutants. The 20m stack scenarios may still describe the average concentrations of air pollutants in a 1 km grid square, but the height at which unimpeded dispersion occurs is likely to be significantly different from that in non-urban areas. Both pollution hotspots and areas screened from pollutant emissions sources by buildings will be masked. Furthermore, the population in taller buildings (especially that fraction of it that is closest to the sources) may be exposed to higher concentrations than the modelling will suggest.

*Plant type*

Whilst the London Decentralised Energy Study does include 17 TWh of CCGT generated energy, it does not specify the size of the plant. In comparison, scenarios B and C assume all CCGT plant is large, resulting in what could be considered the minimum number of plant deployable within an urban area.

Scenarios D and E propose larger gas engine plant that, whilst possible to site are likely to be unattractive to do so. As the largest sizes of individual reciprocating gas CHP engines are in the range of several megawatts, it is likely that a plant of several tens of megawatts electrical output would have several such engines sited on it. This limits the minimum size of site. The Citigen site has two engines and occupies an area of around 2500 m$^2$ and four storeys high (not including the flue). If site area were to scale with generation capacity, sites for the larger energy plant would be around 7500 m$^2$ to 17500 m$^2$, making adequate sites difficult to obtain in central London.

Furthermore, although the use of multiple engines on a site might make uninterrupted generation more robust, due to the low probability of all engines failing simultaneously, the use of a high number of individual engines per site is likely to bring higher maintenance and operational overheads. This could lead to a disincentive to deploy large multi-engine sites and restrict gas reciprocating engines to smaller sites, decreasing the likelihood of development of high stacks.

*Reduction in centralised power generation*

All scenarios assume that any electricity generated will decrease the demand on Didcot B Power Station. This is a 1360 MWe CCGT power station and is the closest large generation plant to London.

Assigning emission reductions to a power station may appear counterintuitive, as it seems to imply that the decreased load on the wider national grid by the introduction of CHP to a locality would be allocated to a single power station, rather than spread across all stations on the grid. In the short term, this would be reasonable grounds to reject this approach. However, this study considers the impacts of distributed CHP in London over a much longer period, during which centralised power stations are likely to be decommissioned and new ones constructed.

In this context a reduction in centralised generation demand is reflected in the lack of need to build additional new stations, rather than a shared reduction in the need to generate. This would indeed lead to any reductions in centralised power generation in future scenarios being assigned to the location at which a new power station would otherwise have been constructed.

### *Exclusion of power station CHP*

The impact of air pollutant emissions per unit of energy generated tends to fall with increasing scale of plant. This would suggest the least-impact manner of delivering the entire heat load would be from centralised power plant, remote from London. Such a supply scenario this would require the development of high capacity heat transmission infrastructure in a manner that is not clearly defined in the London study in terms of plant type and location. For this reason, it is not included in this case study.

However, were heat from centralised generation plant to be used, it is questionable whether or not reliance on a small number of large generation facilities is desirable in terms of supply security for a large city such as London. Whilst electricity supplies to London are supported by generation across the whole national electricity grid and the failure of a number of these can be tolerated before consumers experience effects, heat would be delivered from specific power stations feeding directly into the heat grid. A failure of a heat supplying power station may therefore be more likely to result in customers being deprived of heat than of electricity from a conventional one. Given the size of London and the need to maintain adequate building temperatures for its inhabitants in the colder months of the year, a reliance on a small number of power stations to provide heat might increase the risk to energy security significantly.

It should be noted that this London study accommodates the geographical characteristics of London. The approach taken in other district heat schemes varies across the world and local solutions depend on local needs. Warsaw does have large power-station scale heat and power generation plant, but it is important to note that this is located within the city. Systems in Sweden rely on a greater diversity of heat sources, which include small plant.

### 4.2.5 Domestic combustion emissions

*Emission factors*

Emissions factors used for domestic combustion (AEA/Defra, 2011) all assume an average reduction of $NO_x$ emissions per kWh to 87.6% of 2010 emissions by the year 2020, with no further improvement afterwards – a fall from $2.34 \times 10^{-3}$ kt $NO_x$ $Mth^{-1}$ to $2.05 \times 10^{-3}$ kt $NO_x$ $Mth^{-1}$. Much of this is due to increasing average efficiency of domestic boilers, as older models are replaced with more efficient ones. Beyond 2020, this improvement is not expected to continue, due to saturation of the boiler market with high efficiency models as the result of three factors:

- The average lifetime of a domestic boiler is around 10 years
- Condensing boiler models rated at A rate or above have been on the UK market since the late 1990s.
- UK legislation generally requires new domestic boilers to be condensing, driving maximum market penetration of this technology.

| Year | Source | Fuel | Pollutant | Projected EF (kt $Mth^{-1}$) |
|---|---|---|---|---|
| **2010** | Domestic combustion | Natural gas | $NO_x$ | 0.002339892 |
| **2015** | Domestic combustion | Natural gas | $NO_x$ | 0.002179679 |
| **2020** | Domestic combustion | Natural gas | $NO_x$ | 0.002051508 |
| **2025** | Domestic combustion | Natural gas | $NO_x$ | 0.002051508 |

**Table 4.3 : Projected $NO_x$ emission factors for domestic combustion. Source (AEA/Defra, 2011)]**

This has the effect that boiler efficiency increases between 2010 and the early 2020s and remains constant afterwards. The impact on domestic combustion emissions from gas is to reduce $NO_x$ emissions by around 11% as in Table 4.3.

*Known sources of error*

The fall in $NO_x$ emission is not directly proportional to the increase in boiler efficiency, as other sources of domestic gas combustion, such as cooking, act as $NO_x$ sources. These are not assumed to improve in efficiency, so an 11% decrease in $NO_x$ from domestic combustion represents a decrease of more than 11% in $NO_x$ per unit energy from boilers. The assumptions made in this case study over domestic combustion are that:

(i) A shift to district heating offsets domestic $NO_x$ overall, rather than only that generated by the use of gas boilers.

(ii) The $NO_x$ emissions offset by the boilers per unit of energy delivered are in proportion to the average $NO_x$ emission factor for domestic gas and not for the emission factor of the actual boilers.

(iii) A shift to district heating in a house on the gas network has no impact on the use of gas for purposes other than space heating and domestic hot water.

Assumptions (i) introduces a small, but ultimately quantifiable biases into the calculation. Assumptions (ii) and (iii) introduce biases that will only be quantifiable in retrospect.

- Assumption (i) imposes a predictable optimistic bias, overestimating the reduction in $NO_x$ emissions due to two effects. Firstly, district heating will only result in direct offset of $NO_x$ emission from gas use in space and water heating. It does not reduce the $NO_x$ emission or need for combustion for other purposes, such as cooking. Secondly, $NO_x$ emissions per unit of heat from boilers falls up to 2020, whilst emissions from other uses (providing the property remains on the gas grid) stay the same. The result is that, up to the 2020s, the proportion of domestic $NO_x$ from boilers falls. The proportional error is:

$$\frac{E(gas)_{boiler}\cdot EF_{boiler}}{E(gas)_{domestic}\cdot EF_{domestic}}$$

Where E(gas) is the average amount of energy consumed as gas for particular equipment, EF is the average emission factor for that equipment, *boiler* indicates applicability to space and water heating equipment only and *domestic* indicates applicability to the equipment used by the whole household or using that space and water heating.

- Assumption (ii) imposes an optimistic bias, overestimating $NO_x$ emission reductions because some of the heating offset will be electrical in nature. Its displacement will not result in a $NO_x$ emission. The proportional optimism bias from (ii) would be approximately the same as the proportion of houses shifted to district heating that are electrically heated. It should be noted that this is an approximation for two reasons.

Firstly, it is not known whether the same proportion of electrically heated properties would take up district heating as gas properties. It may be that the higher costs of heating by electricity result in a greater proportion of electrically heated properties shifting to district heat. Secondly, in electrical heating still results in indirect $NO_x$ emissions from the electrical generation at a power station that would otherwise have been used to run the domestic electric heaters. As the emissions will occur remotely from London and will be subject to diffusion, the expected impact on $NO_x$ exposure within London from this is expected to be very small. However, it should be noted that the bias introduced on national $NO_x$ emission budgets will be proportional to the product of the proportion of houses shifted to district heating that are electrically heated and the proportional difference in end-use $NO_x$ emission factors for domestic boilers and electrical heating.

- Assumption (iii) creates a pessimism bias, underestimating $NO_x$ emissions, stemming from assumptions about fuel switching. The proportion of gas used in households for purposes other than water and space heating remains around 3.4% (DECC, 2012b; BEIS, 2018h). Most of this is for high grade heat that tends to be used for cooking. There remains a real but unknown chance that a shift from gas heating might eventually shift a household away from the gas network entirely, so that its direct $NO_x$ emissions from gas combustion fall to zero.

This may be driven by the costs of maintaining a connection to a distribution network in order to deliver much-reduced gas demand, leading to the cost per unit of gas consumed increasing to an unacceptable level in comparison to other energy products. The overall magnitude of this bias is not predictable in advance but could range up to 3.4% if all houses shifting from district heating were to move away from gas.

## 4.3 Results of modelling

The following modelling results use the input data on CHP scenarios developed by the author as part of this study and were generated by the author using the UKIAM modelling system, developed by Imperial College, London. It should be noted that the UKIAM model includes annual average meteorological data, based on multiannual meteorological datasets.

### 4.3.1 Base scenario (Scenario A)

The base scenario considers London in the mid-2020s without any improvement in decentralised energy infrastructure. Average annual $NO_x$ concentrations vary from 11 µg $m^{-3}$ at the perimeter of London to around 80 µg $m^{-3}$ in the centre of London. The majority of London varies between 20-30 µg $m^{-3}$. The contribution to this from transport is very significant although the roads are not marked in outline, and $NO_x$ concentrations are associated with the routes of major roads, including the M4, M40, M1 and M11 motorways.

Any change in emissions from transport, such as a shift in powertrain technology or fuel type, would likely have a highly significant effect on $NO_x$ emissions. Changes beyond 2020 in transport are beyond the scope of this study, so to allow the impact of the technologies under consideration to be considered in isolation, only the difference in average annual $NO_x$ concentrations ($\Delta NO_x$) between this base scenario and the counterfactual scenarios is considered.

### 4.3.2 CCGT CHP Power Plant (Scenarios B & C)

Both scenarios in which CCGT plant provide heat to London and power to the grid show distinct falls in $NO_x$ concentration close to the location of the generation plant, but increases in $NO_x$ at greater distances. The overall budget for $NO_x$ emission in London in this scenario would be increased by around 1061 tonnes per year.

In the case of CCGT plant with 70m stacks (Figure 4.2), local $\Delta NO_x$ minima of -2.6 µg $m^{-3}$ to -1.5 µg $m^{-3}$ are seen, whilst nearby maxima of mainly around 0.2 µg $m^{-3}$ occur, with a couple of instances of around 0.6 µg $m^{-3}$ being observed in isolated pockets near Edmonton and Dollis Hill. The large areas of relative decrease near the plant can be attributed to the fact that flue gases rise to 70m, are transported at altitude, diffuse and only then fall to the altitudes at which $NO_x$ concentrations are being considered. This provides ample path length for diffusion and dilution of the flue gas plumes, so that their contribution to ground level $NO_x$ concentrations is relatively small.

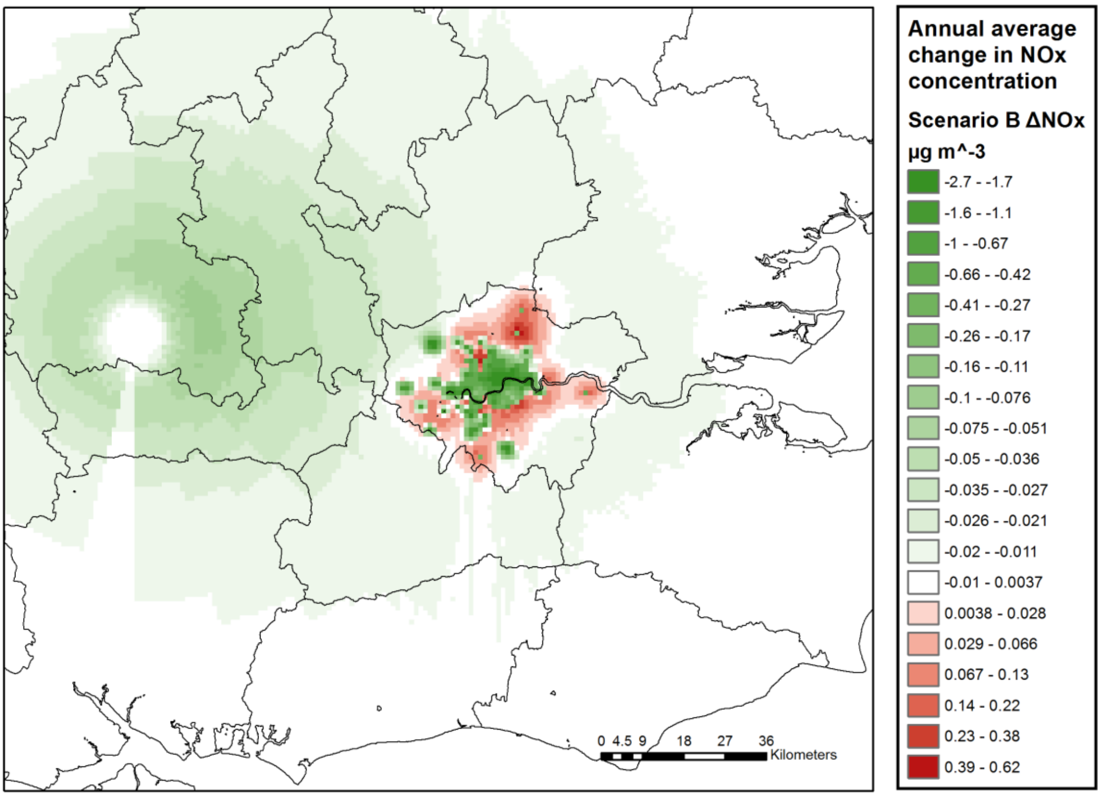

**Figure 4.2: Change in average annual $NO_x$ concentrations for 70m stack height CCGT scenario.**

In the area of Didcot power station, only negative $\Delta NO_x$ can be seen. Although these are centred on the power station, there is a zone directly around it that shows virtually no change. This can also be attributed to plume rise, transport and dilution, as the emissions that are being offset would not normally tend to be found in the area immediate to the plan. A reduction in the emission budget for the source would therefore be expected to have very little effect in this area. The “slice” of little change seen to the south of the plant is due to UKIAM’s definition of the wind rose.

It should be noted that in the 70m stack height scenario, the higher concentration increases are achieved over very small areas and all relative increases in $NO_x$ within the London area are much smaller in magnitude than the relative decreases. This suggests a net decrease in average $NO_x$ concentrations for London and benefits in terms of the air quality impacts of $NO_x$ emissions from heating buildings.

In the case of the 20m stack height of scenario C, the same plume rise and transport effects have a much shorter path length to take place over before impacting ground level $NO_x$ concentrations (Figure 4.3). Greater areas of higher $NO_x$ increase can be observed, with $\Delta NO_x$ maxima of 3.1 µg $m^{-3}$ and 4.3 µg $m^{-3}$ in Edmonton and Dollis Hill respectively and 1.5 µg $m^{-3}$ for other maxima. The wider zone of increased pollution typically has values of 0.5 µg $m^{-3}$ $\Delta NO_x$. Zones of decreased pollution but have local $\Delta NO_x$ minima of -1.5 µg $m^{-3}$ with typical values outside these minima of between -0.5 µg $m^{-3}$ to -0.2 µg $m^{-3}$.

Conversely to the case of CCGT plant with a 70m stack, the areas of positive $\Delta NO_x$ are larger than those of negative. Combined with the relative magnitude of the local concentrations predicted, this suggests a net increase in average annual $NO_x$ concentrations and a detrimental impact on the air quality impacts of $NO_x$ emissions from heating buildings.

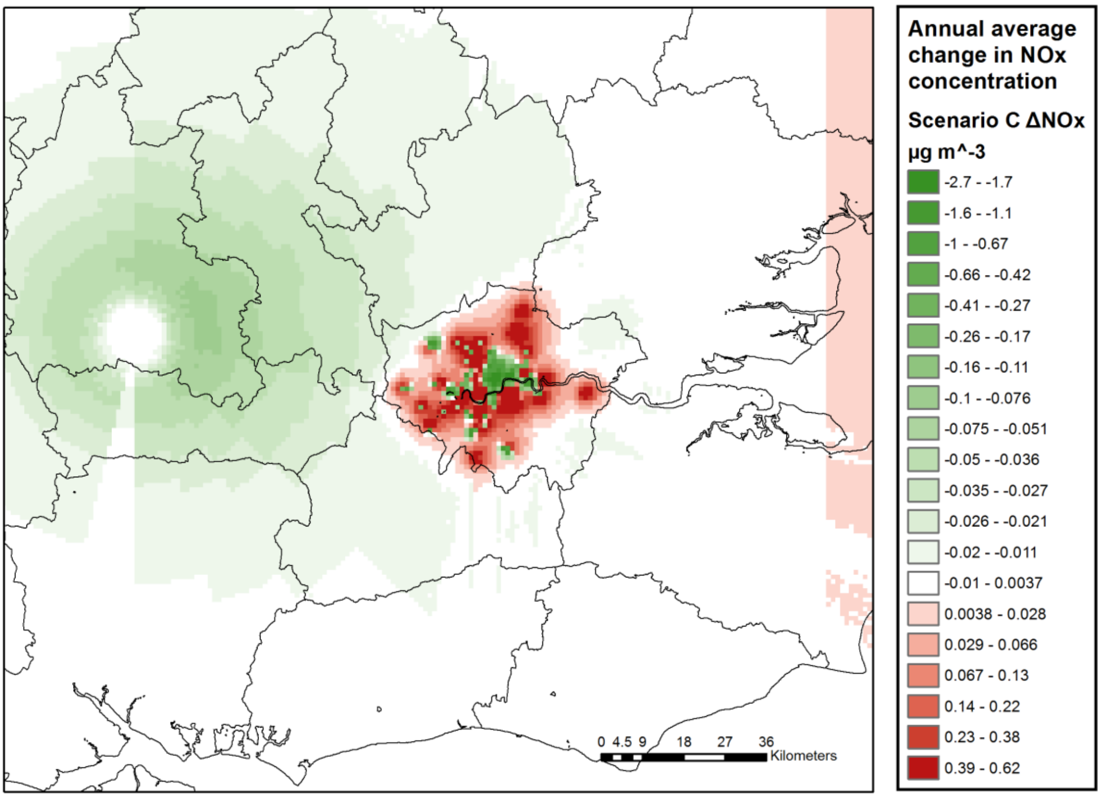

**Figure 4.3: Change in average annual $NO_x$ concentrations for 20m stack height CCGT scenario.**

It should be noted that the degree of increase and decrease of $NO_x$ concentration in scenarios B and C is never more than 18% in any one location and, in most locations, is in the order of a couple of per cent.

### 4.3.3 Gas engine power plant (Scenarios D and E)

The equivalent scenario to B and C using gas engines in place of gas turbine plant results in a marked increase in $NO_x$. An overall additional budget of 15477 tonnes of $NO_x$ is emitted each year above the base scenario. If $\Delta NO_x$ for scenarios D and E were displayed on the same scale as for the scenario B and C results, much of the area in and around London would fall into the highest class, masking fine detail. An expanded scale is therefore used, which allows better gradation around the sources whilst still showing the increased $NO_x$ across much of south-eastern England. (Figure 4.4 & Figure 4.5).

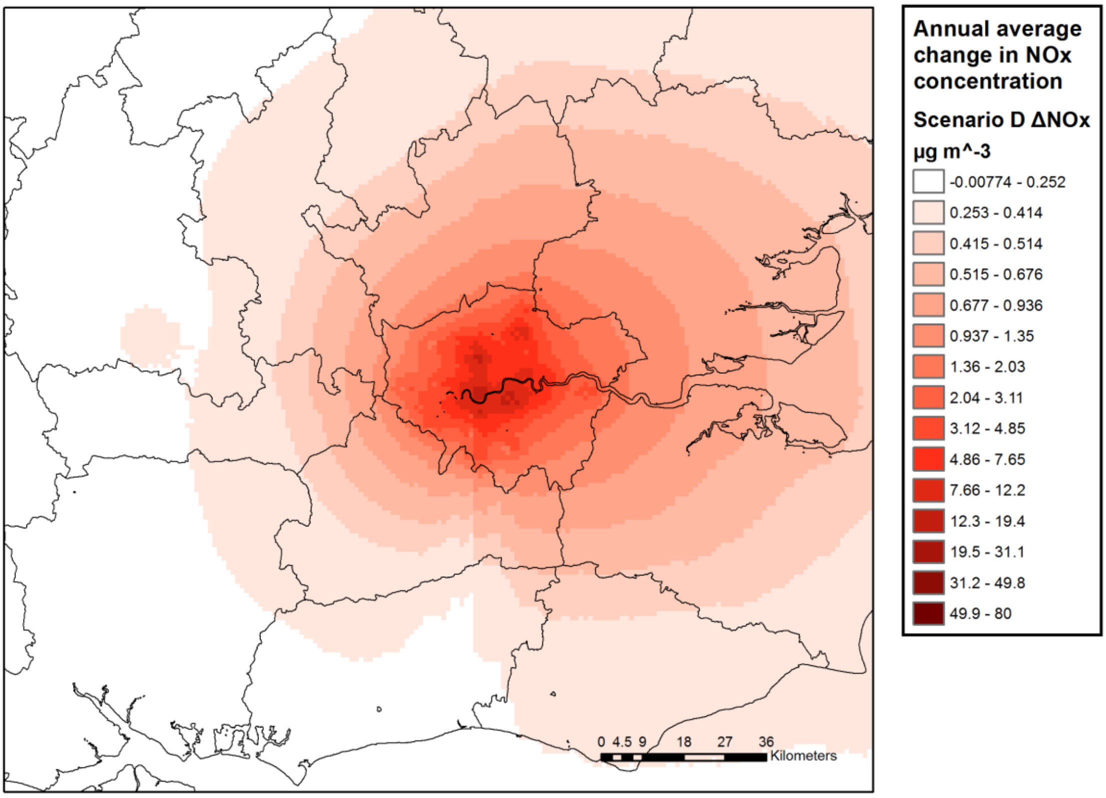

**Figure 4.4: Change in average annual $NO_x$ concentrations for 70m stack height gas engine scenario.**

In scenario D, where 70m stack heights are achieved, the higher maxima for $\Delta NO_x$ are between around 13 µg m$^{-3}$ to 16 µg m$^{-3}$, with others being around 4 µg m$^{-3}$ to 10 µg m$^{-3}$. Typical $\Delta NO_x$ values within London outside these maxima range from around 1 µg m$^{-3}$ to 5 µg m$^{-3}$, with the areas of lower $\Delta NO_x$ surrounding the maxima of lower $\Delta NO_x$.

If the stack height is lowered to 20m, as in scenario E, the higher maxima $\Delta NO_x$ increase to around 50 µg m$^{-3}$ to 80 µg m$^{-3}$, with others being around 12 µg m$^{-3}$ to 17 µg m$^{-3}$. Typical background values within London outside these maxima range from around 1 µg m$^{-3}$ to 5 µg m$^{-3}$, with the areas of lower $\Delta NO_x$ surrounding the maxima of lower $\Delta NO_x$. Typical $\Delta NO_x$ values within London outside these maxima range from around 1.5 µg m$^{-3}$ to 7 µg m$^{-3}$, with the areas of lower $\Delta NO_x$ surrounding the maxima of lower $\Delta NO_x$.

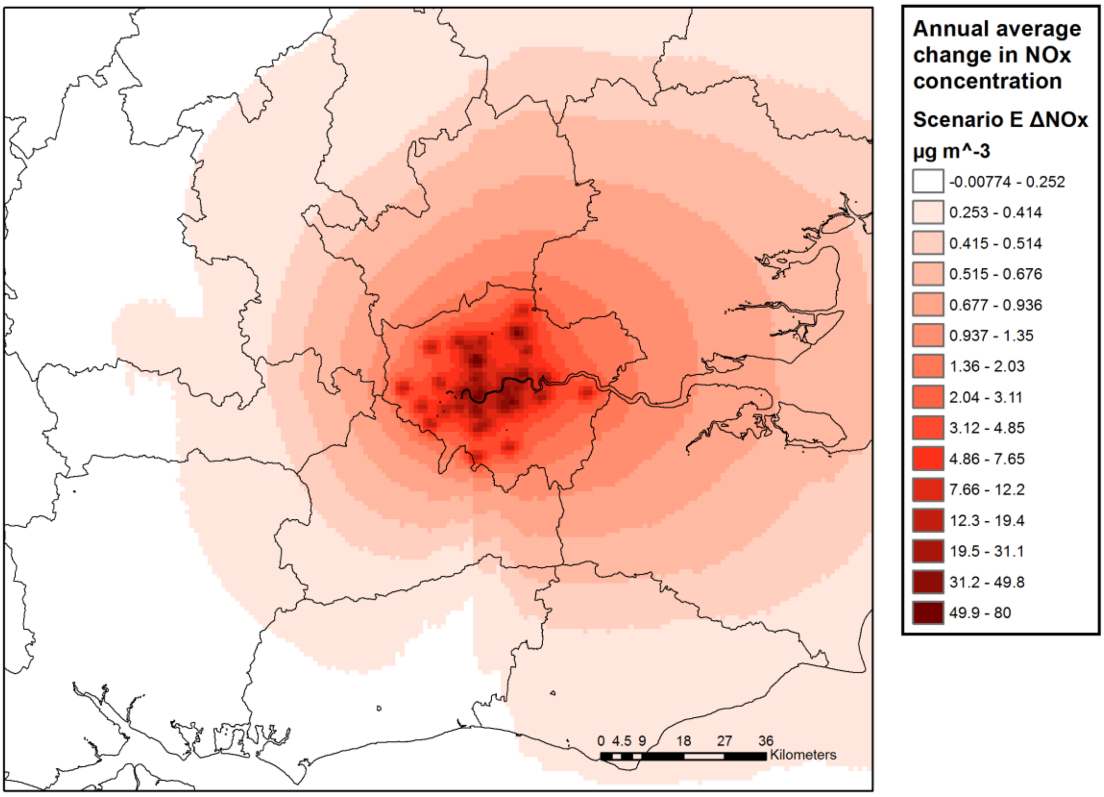

**Figure 4.5: Change in average annual $NO_x$ concentrations for 20m stack height gas engine scenario.**

Apart from the expected increases in $NO_x$ concentration in scenarios D and E, the key differences they have to the CCGT scenarios are that they show no areas in London in which $\Delta NO_x < 0$ and thus no areas that experience any air quality benefits in terms of $NO_x$ emissions.

Furthermore, the majority of London is subject to a greater $\Delta NO_x$ than any maximum in scenarios B and C. Some of the areas with the highest $\Delta NO_x$ in scenario E are subject to more than a threefold increase of the average annual $NO_x$ concentrations that they are in scenario A (Figure 4.6).

The widespread introduction of internal combustion gas engine CHP plant would also have a wider impact, and roughly half the area of southeast England is subject to a $\Delta NO_x > 0.25$ µg $m^{-3}$.

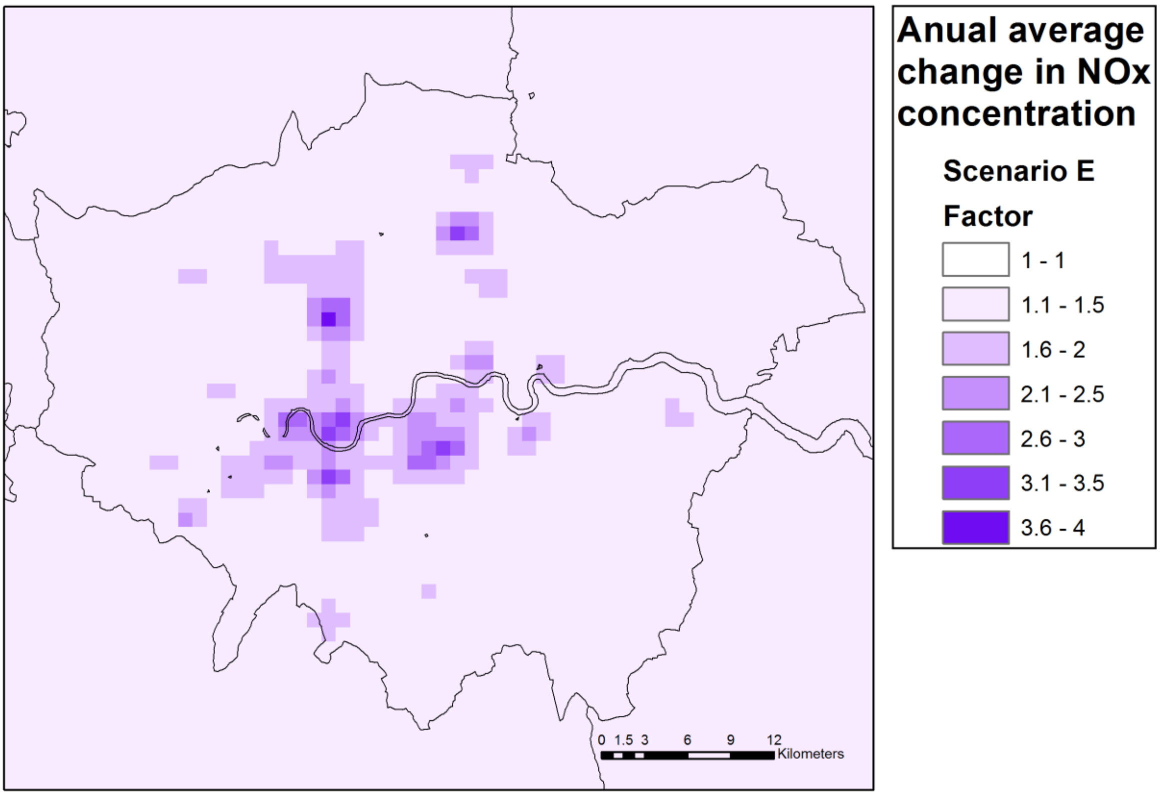

**Figure 4.6: Annual average change in $NO_x$ concentration for scenario E against the base scenario A.**

### 4.3.4 Limited gas engine deployment (Scenarios D1 and E1)

The realistic prospects of such a wide roll out of large internal combustion engine plant are small: maintenance, cooling, safety and site availability at the scales of generation unit considered here tend not to favour gas engines. However, it is worth considering the impact of the more feasible prospect of limited build of this type of plant, as there may be unique drivers for a small number of sites to use large gas engine or a larger number of sites to use small to medium gas engine.

One hypothetical example would be the introduction of an additional 40 MWe of generation capacity at the Citigen site, using internal combustion gas engines. This would expand the site capacity using the technology already incumbent there and is represented by scenarios D1 and E1 for 70m and 20m stack heights respectively (Figure 4.7 & Figure 4.8). In both cases 1440 tonnes of $NO_x$ additional to the Scenario A are emitted within London each year, 406 tonnes of which come from the single new gas engine plant.

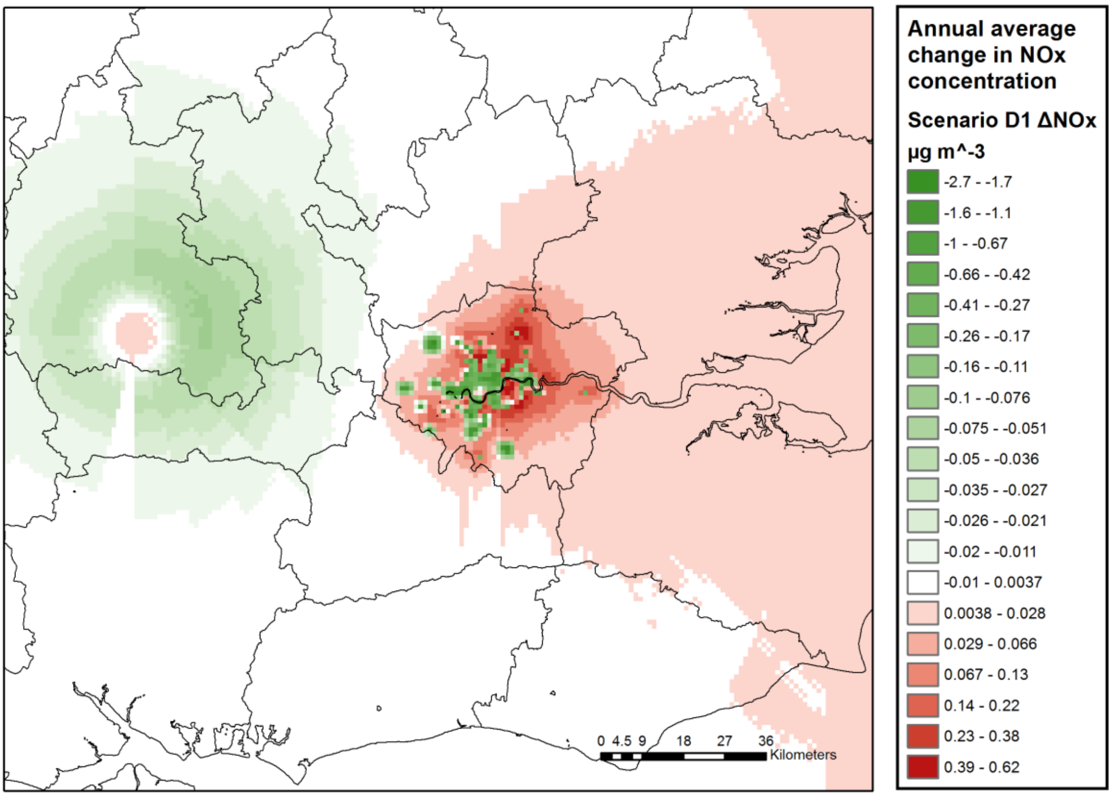

**Figure 4.7: Change in average annual $NO_x$ concentrations for 70m stack height in limited gas engine scenario.**

Using NAEI emission factors for gas engines, scenario D1 still shows a substantial increase in Δ$NO_x$ over scenario B. Whilst falls in average annual $NO_x$ concentrations still occur near Didcot, there is a very slight increase in the immediate area of the power station and in the area between London and the coast, where the benefits of reduced emissions from Didcot are outweighed by the increased emissions from London.

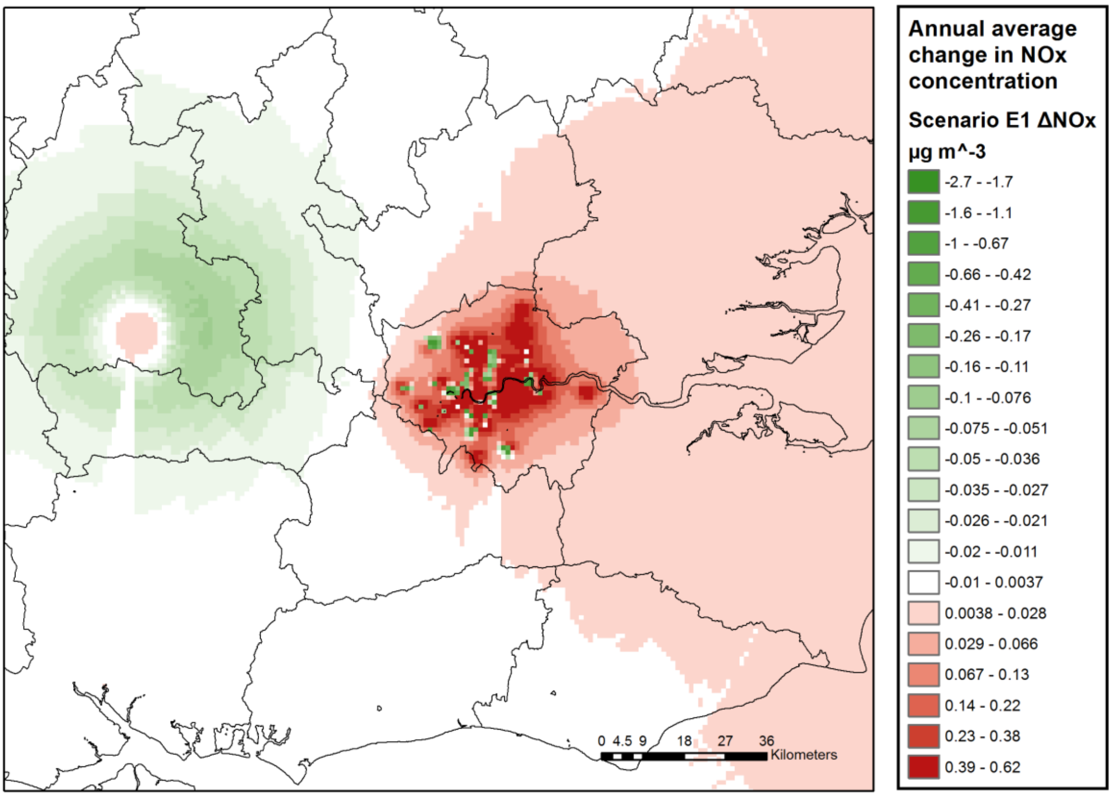

**Figure 4.8: Change in average annual $NO_x$ concentrations for 20m stack height in limited gas engine scenario.**

Typically, Δ$NO_x$ for a given location in inner London in scenario D1 is around 0.1 μg m$^{-3}$ to 0.3 μg m$^{-3}$ higher than in scenario B. The highest local Δ$NO_x$ maxima are around 0.6 μg m$^{-3}$, as can be seen in the immediate vicinity of the Citigen site, Edmonton, Dollis Hill and Lambeth. Despite this, there are still substantial areas where an average annual decrease in $NO_x$ concentration can be seen, of a magnitude several times than that of the shift seen in the areas of greatest positive Δ$NO_x$. The positioning of these suggest benefits to central London in terms of $NO_x$ and suggest that there may still be a benefit for London overall.

In the corresponding scenario E1, which differs from D1 in having a stack height of 20m, the areas of high $\Delta NO_x$ within London are much greater and the areas seeing a fall in average annual $NO_x$ concentration are substantially reduced. Most locations have less than 0.5 µg $m^{-3}$ higher $NO_x$ in scenario E1 than scenario C. The higher maxima of $\Delta NO_x$ tend to lie between 1 µg $m^{-3}$ to 4 µg $m^{-3}$, although the area around the site of the gas engine CHP plant experiences a $\Delta NO_x$ value up to 20 µg $m^{-3}$ higher than scenario C.

The $NO_x$ concentrations in scenario E1 are comparable with those of a related study (Gomez Agurto, 2012), which also suggests a maximum increases in $NO_x$ in any one location by around 20 µg $m^{-3}$ for the limited deployment of gas engine CHP with a stack height of 20m. Furthermore, it sees maximum $\Delta NO_x$ fall to around 12 µg $m^{-3}$ with a 30m stack height. Taking both studies together, they suggest that not only do reciprocating gas engines have a much greater effect on $NO_x$ emissions than CCGT plant, but that even for limited deployment of CHP systems with high characteristic emissions of a regulated air pollutant, such as gas engine plant, the impact of stack height on average pollution levels and exposure can still be very significant. This may be even more important in the future with the increase in taller buildings in central London and the resulting impact on flue gas dispersion.

### 4.3.5 Biomass CHP plant deployment (Scenarios F and G)

The London Decentralised Energy Study also proposes biomass as a fuel for CHP plant. The characteristics of the plant have also been investigated by the Gómez Agurto study (Gomez Agurto, 2012) and have been chosen to correspond to values used by the European Commission (European Comission, 2006).

This represents a solid biomass fuelled fluidised bed combustor driving a boiler and steam turbine: a widely used technology that can be considered good practice. It is assumed that any gaseous biofuels such as biomethane will use technologies and have emission characteristics in common with the previous gas-fuelled scenarios.

In line with previous scenarios, 70m and 20m stack heights are used and all CHP plant is assumed to be biomass. For the 70m stack height case of scenario F (Figure 4.9), the emissions still affect a wider area more severely than a CCGT only scenario but are, nonetheless, very marginal across most of southeast England. $\Delta NO_x$ values only exceed 0.1 µg $m^{-3}$ in the immediate vicinity of London. The remaining $\Delta NO_x$ expected from the scenario is low enough for the reduced emissions from Didcot to bring marginal air quality benefits to a significant area of Oxfordshire although, as in scenarios B, C, D1 and E1, this has the greatest effect some distance from the power station itself.

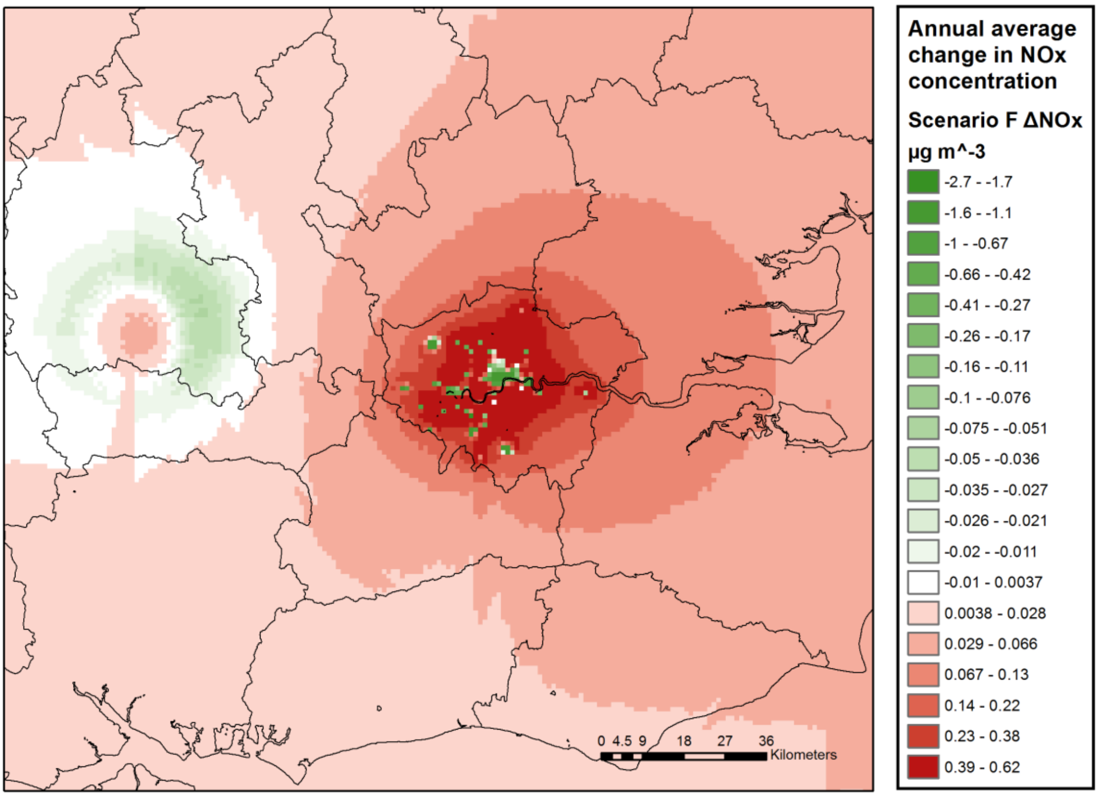

**Figure 4.9: Change in average annual $NO_x$ concentrations for 70m stack height in biomass CHP scenario.**

The highest $\Delta NO_x$ maxima observed are in the order of 1.5 µg $m^{-3}$, with much of the rest of central London showing between 0.4 µg $m^{-3}$ and 1 µg $m^{-3}$. There are still zones of negative $\Delta NO_x$ minima within London and the greatest reduction in average annual concentration is around -1.5 µg $m^{-3}$.

For scenario G (Figure 4.10), the 20m emission stack height variation of large biomass fired CHP, $\Delta NO_x$ maxima as high as 12.9 µg $m^{-3}$ can be observed in certain 1km squares. However, most maxima are around 2 µg $m^{-3}$ to 5 µg $m^{-3}$. Whilst the lowest $\Delta NO_x$ values are still negative, these only fall as low as 0.7 µg $m^{-3}$ and occur in very few of the grid squares.

As the area over which negative $\Delta NO_x$ occurs is a small fraction of the total in both scenarios F and G, and it appears that there would be a negative impact on air quality in London by widespread use of this type of biomass CHP.

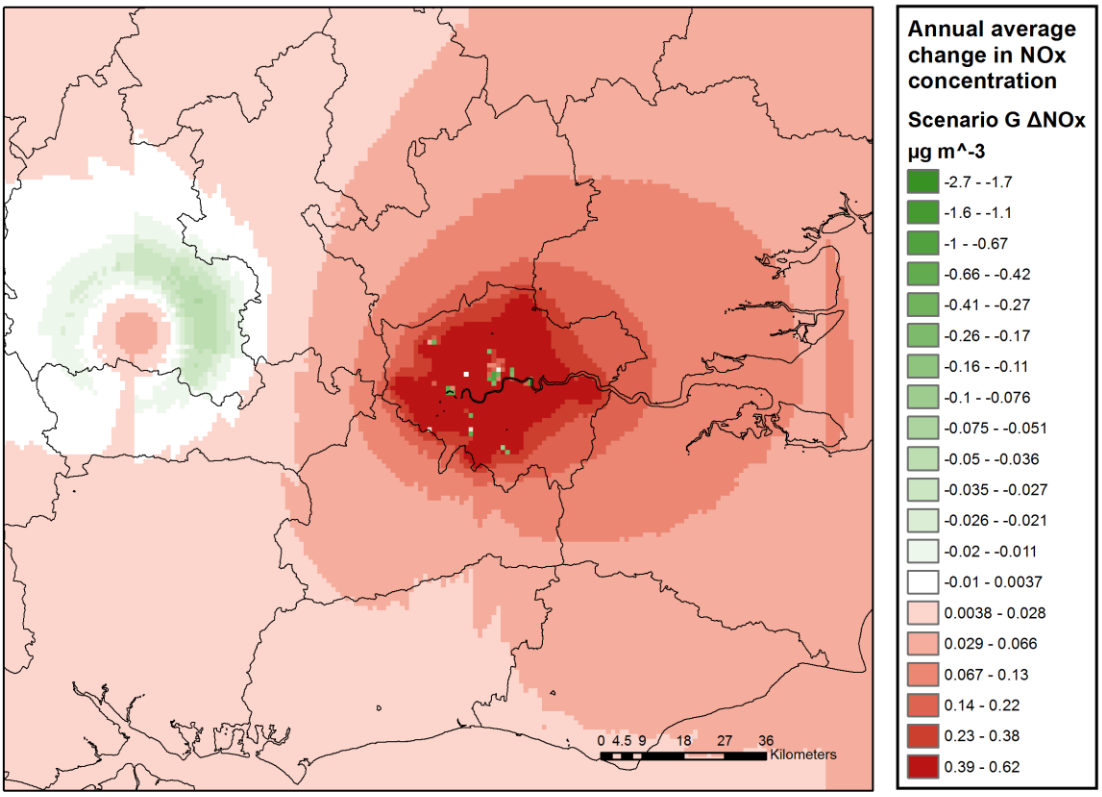

**Figure 4.10: Change in average annual $NO_x$ concentrations for 20m stack height in limited gas engine scenario.**

As currently understood, the deployment of biomass CHP on such a scale is unlikely, as it presents practical problems beyond the management of emissions. Availability of feedstock for fuel with an acceptable whole of life carbon impact (not to mention performance against other sustainability criteria) is a key constraint. Other issue arise in:

- Cost and emissions impact of transporting the biofuel to the power stations. This requires vehicle-based distribution as, unlike gas, biomass fuels tend to be solid and cannot be delivered via pipeline.
- Cost, siting requirements and impact on fuel quality of storage. Biomass fuel has a lower energy density than fossil fuels and tends to be degradable. Furthermore, without appropriate measures, on-site storage of solid biomass fuel can represent a fire risk, as has been demonstrated at existing biomass energy facilities in London (BBC News, 2012).

## 4.4 Conclusions

### 4.4.1 Use of UKIAM and importance of spatial factors

This study demonstrates the importance of spatial factors in modelling the impacts of future energy scenarios – specifically the relationship between emission sources and receptors of pollution, such as high population density areas.

UKIAM can supplement the use of energy scenario analysis and optimisation models by revealing the spatial aspects of changes in air pollutant emissions budgets from specific sources, such as those that may arise from emergent energy generation technologies like the introduction of CHP.

However, the assumptions about the exact size, location and emissions characteristics (e.g. stack height) of sources need to be made exogenously to energy scenario modelling tools, as they do not have this level of detail themselves. This role is thus limited to one-way analysis of output from such models: although the output of the UKIAM can be used as input for damage models to assess the health or environmental costs of predicted changes to energy infrastructure, the resultant costs cannot be represented in least-cost optimisation models such as the UK TIMES.

A further implication of this is that even more specific spatial studies than can be achieved with UKAIM may be needed for environmental assessment of combustion-based generation in complex city environments such as London, which have an increasing number of tall buildings. In these situations, the changes in urban morphology can be a key influence on both instantaneous and long-term average pollutant concentrations in small areas, in which high numbers of people may be exposed. This effect would likely be exacerbated by the growth of combustion emissions sources, such as CHP plant, in the urban environment. With such changes, current assumptions in regulatory modelling may cease to be adequate for assessing public health impacts of new buildings and energy developments.

### 4.4.2 Capability of energy projection models to describe delocalised CHP

The energy projection models considered here have no detailed spatial information on the location of electricity generation facilities. They can describe the carbon benefits gained from the introduction of delocalised generation using CHP and the changes to national emission budgets of the air pollutants each model covers. If, as in this case, the changes in generation include changes in location of air pollutant emissions, they will be unable to identify whether this represents a benefit or not in terms of the change in distribution of annual average concentrations. This is because they have no mechanism to assess the changes in exposure of populations or sensitive environmental locations to air pollutant concentrations.

The lack of spatial information also prevents such models assessing accurately the costs of distribution infrastructure for district heating: there is no information on parameters such as population density on which to base estimates of the size of network, the distance between heat consumers or the distances between generation facilities and consumers. This means that the models will include no clear influences to curtail the extent of heat network build. It also results in there being no information on the density of anchor loads to assess the size of generation facilities necessary.

## 4.5 Scope for further work

### 4.5.1 Use of hydrogen fuelling

This study is confined to exploration of combustion systems. The fuels and combustion systems considered in the above scenarios are ones currently in use for CHP systems. A CHP power and district heat generation system based on CCGT gas turbines appears to produce the greatest overall areas in which reductions of annual $NO_x$ exposure are observed. However, the future of the gas grid and composition of the fuel it transports are not certain. One option for the decarbonisation of heat under consideration is the replacement of natural gas, which consists mainly of methane, with hydrogen. If the hydrogen is sourced by a suitable low carbon means, this may offer an option of low carbon heat without the use of electricity or biomass combustion. Hydrogen turbines are commercially available and are technically an option for concentration. As hydrogen burns at a higher temperature than natural gas, hydrogen turbines will have different $NO_x$ emission factors than natural gas ones and further work would be required to assess the likely benefits for it displacing centralised electricity generation in this type of scenario.

An alternative scenario of providing hydrogen-fuelled district CHP using fuel cells in district energy generation centres is possible, as is a scenario of providing hydrogen-fuelled CHP through a fuel cells in individual installations. These would both provide energy without the $NO_x$ emissions from a hydrogen turbine, However, the way that material costs and efficiencies of hydrogen fuel cells vary with the scale of installation is likely to be different manner to the way that they vary for hydrogen turbines. The differences in this variation, and whether it changes between fuel cells being deployed in district energy centres and in individual buildings would appear to offer further insights into potential economic drivers for and against heat networks. This would especially apply to future energy scenarios with high levels of hydrogen use as an energy carrier.

### 4.5.2 Sensitivity to stack height

The work presented here suggests that the stack height of urban energy generation plant can have a significant impact on the maximum annual average concentration of $NO_x$ in areas affected by its emissions. Even when using relatively low pollution forms of energy generations such as CCGT plant, reducing its chimney and stack height may tip the balance between whether deployment of plant can deliver net air quality benefits. Similarly, as scenarios D1 and E1 suggest, even the impact of single plant with relatively high emissions can be mitigated to a great degree by choosing an appropriate stack height.

The exact height of stacks will depend on the plant type, as well as the population distribution and urban geography, as discussed in §4.3.3 and §4.3.4.

The influence of stack heights suggests that any decisions driven by planning legislation or aesthetic design to restrict chimney height in energy developments to minimise their visual impact can have a significant, potentially detrimental, effect on their environmental and public health impact. In such cases, additional air pollution abatement measures such as selective catalytic reduction systems to remove flue gas NOx may be appropriate.

### 4.5.3 Sensitivity of generation type

It would also appear that generation type can have a significant influence on annual average $NO_x$ concentrations. CCGT plant does, as expected, appear to have the lowest levels of $NO_x$ of the three types of plant considered. Biomass CHP plant has higher emissions

Gas engine plant has higher emissions of $NO_x$ per unit of energy delivered than either the CCGT or biomass plant considered. Even the deployment of a single large gas engine CHP plant appears to be able to lead to increases in $NO_x$ within London that are greater than those from the deployment of the full fleet of CCGT plant needed to produce the 17 TWh per year of energy derived from large CHP that the London Decentralised Energy Capacity Study identifies.

The probability of wide deployment of gas CHP plant in the >10 MWe range may be low, but the deployment of medium gas plant of several MWe output has been proposed in London (London Borough of Newham, 2012). The results of scenarios D and E may provide an indication of $NO_x$ emissions if these are to become widespread in areas of high heat demand where appropriate anchor loads exist and if remedial measures are not taken.

More assessment is needed of the potential for deploying and effectiveness of $NO_x$ abatement measures (e.g. selective catalytic reduction) in mitigating the air pollution impacts for such plant.

### 4.5.4 Impact of urban morphology

As discussed in section 4.1.6, the shape and layout of buildings in an urban area can radically alter the dispersion of air pollutants, especially if the stack height and therefore plume rise is small. On the scale of the 1km grid squares that this study uses, one would not expect this urban morphology to impact on the average annual $NO_x$ concentrations across the whole square. However, the ability of road canyons to channel pollutants and prevent dispersion, as well as the impact of building height in altering the exposure of people to individual source plumes will mean that any population weighted mean exposure figures calculated for highly built-up areas of London will be inherently more uncertain than for those calculated for the more suburban zones.

A more reliable assessment for the built-up areas might be derivable using a higher resolution fluid dynamic model, which includes urban morphological data from one of the growing number of datasets, such as UCL’s Virtual London, or the urban layout layers of Google Maps. This is likely to be possible for local studies of air quality impact, but it is unlikely to be feasible for a national level model.

### 4.5.5 Actual benefits - population weighted mean exposure

A comparison of the magnitude of $\Delta NO_x$ and the extent of the areas in which this is positive and negative can provide a first order assessment of whether each of the considered scenarios in this study provides air quality benefits. These would be proportionally accurate if the population density of London were uniform, which it is not. To assess the practical benefits of these changes in annual average $NO_x$ concentrations, one would need to examine the number of receptors in each of the areas and assess how they are affected by $NO_x$.

Comparing the spatial and temporal distribution of changes in air pollutant concentrations in relation to spatial and temporal changes of population density and location would allow the prediction of changes in population weighted mean exposure these air pollutants. This could provide a way of assessing immediate and long-term benefits to people and would allow the derivation of theoretical health benefits, using established methods. Current damage models assume the current distribution of population density in the UK, which may be acceptable for short time horizon assessments. On the longer horizon of 2050 energy and carbon projections, with potential influences such as depopulation of some rural areas, these may change.

Again, this capability is beyond the scope of the techno-economic optimisation models considered here. It is also partly beyond the scope of the 2050 Carbon calculator, which assumes current population distributions in defining the health impacts associated per unit mass of pollutant emitted.

# 5. Emissions from UK road transport

## 5.1 Introduction

Transport is the largest contributing sector to the UK's domestic greenhouse gas emissions, with road transport being the largest contributor to this (BEIS, 2018b). Light vehicles (cars and vans) dominate this sector, with cars alone producing the majority of road transport $CO_2$ (BEIS, 2018a). Road transport is also a major contributor to UK air pollutant emissions (DfT, 2018d), with ambient levels and exposure to $NO_x$ a frequent source of both media attention, concern about public health and failure of compliance with air quality regulations.

Road transport is also an area that is seeing significant changes in underlying technology, both through ongoing changes in approaches to emissions regulation and assessment as well as emissions control systems for vehicles. In addition to this, the UK light vehicle fleet has seen a significant degree of shift in the recent past, first with shifts away from petrol as a dominating fuel for the fleet and more recently with an increased use of electrical propulsion, through hybrid and electric vehicle powertrains, which are almost entirely based on battery technology. Both vehicle manufacturers (Volvo, 2017) and governments (Defra and DfT, 2017; MTES, 2017) have stated aims to reduce the contribution of internal combustion engines to propelling national vehicle fleets and there is the potential expansion of electrical powertrain options to include fuel cell vehicles.

In light of this, a credible capability to understand and model the long-term consequences of such shifts in transport technology will require an understanding of the relationship between changes in greenhouse gas and air quality pollutant emissions that these technologies will bring. It will also require an appreciation by the energy system modelling community of how representative current models are of these incoming technologies, the technical basis for any limitations that these models have in describing them and potential solutions for these.

Chapters 5 and 6 examine these issues, looking at the history of the UK vehicle fleet, its contribution to atmospheric emissions and the use of regulatory standards to address this. It uses the example of plug-in and non-plug-in hybrid electric vehicles as a case study of incoming technology that may be challenging to incorporate in current energy models and examines the technical basis and nature of these challenges.

## 5.2 Evolution of the UK vehicle fleet

### 5.2.1 Past trends in vehicle fuelling

*Uptake of diesel*

The UK vehicle fleet has undergone a significant shift in the past 25 years, driven by a combination of air quality and climate change objectives, as well as by petroleum refining economics. These have led to a dramatic increase in the proportion of diesel fuelled light vehicles, together with a smaller but still notable uptake of LPG (liquid petroleum gas) vehicles.

Diesel has long been the conventional fuel for heavy-duty vehicles and larger public service vehicles. However, until the early 1990s, the clear majority of the UK's light vehicle fleet has petrol engines, with diesel being used almost exclusively in heavy-duty and public service vehicles. This was partly due to public perception of diesel engines of the time having high levels of air pollutant emissions.

From the mid-1990s, diesel light vehicle uptake has grown steadily. This is particularly the case in the in the case of cars, where diesel vehicles have increased from 7.4% of licensed vehicles in 1994 to around 39% by the end of 2016 (DfT, 2017c) and annual diesel consumption by cars, taxis and light vans has overtaken petrol (DfT, 2017b).

The drivers behind this are both economic and climate driven. Diesel cars tend to have better powertrain efficiency than petrol vehicles (Craglia, Paoli et al., 2017), which translates into better fuel efficiency and their rise has occurred during a period when the price differential between petrol and diesel made the fuel costs of a diesel vehicle cheaper. Possible drivers behind this include the lower price of diesel fuel on fuel markets at the start of this process; lower UK fuel duty rates on diesel at a similar time; and the temporary additional fuel duty rebate in the early 2000s on ultra-low sulphur (<50 ppm) diesel. The last of these provided air quality benefits both through reducing the amount of $SO_x$ exhaust emissions and by enabling the use of the PM and $NO_x$ emissions aftertreatment technology to be adopted for incoming Euro standards, which was incompatible with higher fuel sulphur content.  A further financial incentive for diesel was the UK's vehicle excise duty structure, which is linked to vehicle $CO_2$ emissions and offers lower tax rates for lower carbon vehicles.

The UKs trend towards "dieselisation" of the car fleet is reflected across Europe, with industry estimating that, in 2015, 41.2% of cars across the EU run on diesel (ACEA, 2017b) and 44.4% of new cars in sold 2017 in the 15 states that were EU members in the year 2000 (EU-15) had diesel engines (ACEA, 2017a). Despite this, there are clear signs that diesel cars are currently on the wane, as the proportion of diesels in new car sales has fallen since its peak of 56.1% in 2011.

### *Stress on diesel production and shifts to alternative fuels*

The growth of the share of the diesel market has increased the demand for the fuel. Diesel fuel is usually manufactured using products of the petroleum refining process and consists largely of hydrocarbons with between 8 to 20 atoms per molecule, with smaller amounts of additives to enhance its performance and lubricate the engine. The range of temperatures it distils off lies between that of petrol and heavy fuel oil, leading to it often being referred to as a "middle distillate" from the refining process.

Diesel is not the only middle distillate fuel, and there are a few other widely used fuel types that share some of the range of compounds and distillation temperatures of diesel. These include marine diesel, aviation fuel and heating oils. Recent history has seen an increase in demand for the first two of these, as well as for diesel fuel for road vehicles. As crude oil contains characteristic ratios of hydrocarbons of specific molecular weights, a simple distillation process is constrained in the ratios of the different weight of fuel it can produce. If satisfied entirely through distillation, a high demand for middle distillate can lead to overproduction of petroleum products from the light and heavy fractions of the barrel. In the road fuel market, this can push down prices and drive usage away from diesel towards petrol and even lighter fuels.

A strong shift to petrol has not been seen in Europe, despite the increasing demand for diesel being met by the world market. Arguably, this has been prevented by an increasing global demand for petrol in North America, which has helped to balance global production. However, this situation has led to the plentiful availability of other, lighter fuels, which have not had a traditional place in the road fuel market.

### *LPG*

The best known of these alternative fuels is liquid petroleum gas (LPG). This consists primarily of propane and butane and, in common with petrol, requires a spark ignition engine to operate. An LPG conversion of a vehicle requires relatively simple changes to the engine and the addition of a pressurised fuel tank and supply line for the fuel itself. LPG has been marketed as a "clean" fuel on the grounds engines running on LPG produce lower emissions of particulate matter and often lower emissions of $NO_x$ than petrol or diesel engines (EEA, 2018). LPG is often found in light vehicles and is often found used in urban situations, where the public health benefits of its reduced emission might be expected to be greater, due to the greater population density.

LPG saw both increased uptake in vehicles and increased availability from the 1990s onwards as the result of both push and pull factors. Many European countries, including the UK, introduced tax incentives such as lower fuel duty to encourage its use. Simultaneously, as a relatively underused by-product of production of petrol and diesel, it was readily available at an attractive price. It remains a niche despite such factors and LPG vehicles account for slightly less than 1% of the UK parc.

Whist LPG offers reduced emissions, it is important to recognise that this is for a hot engine. An LPG vehicle performing a cold start will tend to do so by burning petrol, wait until the engine is hot enough to vaporise the LPG effectively and then switch fuelling over. Attempts to start burning LPG fuel when the engine is not warm can result in the vaporising fuel chilling the engine to the point where freezing can occur.

LPG vehicles tend to be more common in urban environments, which have high population densities, than petrol engines. As petrol engines tend to have high $NO_x$ emissions associated with cold starts, it is possible that this petrol-fuelled initial phase of an LPG engine's startup, combined with the high urban population density, may lead to LPG vehicles generating different levels of $NO_x$ than might be expected from the emission factors for their normal operation. This could be especially true for an LPG vehicle making short journeys, when the engine does not have enough time to heat up.

### 5.2.2 The introduction of electrification into the UK fleet

The decarbonisation of transport is one of the two key aims of vehicle manufacturer and public policies to phase out vehicles equipped only with internal combustion engines. At present, the only commercially available technology to do this is the introduction of partly or wholly electric powertrains into new vehicles. Increased market penetration of these appears to be inevitable between the time of writing and 2050.

There are three basic technologies available for electric vehicles: storage of electricity in a battery; generation of electricity by mechanical means, most usually provided by an engine or by capturing the vehicle's momentum via the wheels; and electrochemical generation of electricity through a fuel cell. There are many different methods of integrating these with each other into operable powertrain architecture and the relationship between any emissions and the vehicle's operation will depend on the exact method chosen.  These represents a great increase in variation of vehicle powertrain types on the road, with most electrified powertrains currently appearing in cars (DfT, 2016d; DfT, 2016b; DfT, 2016c).

Based on the manner that current energy models represent transport technologies, each of these could require a different approach, both relative to each other and to conventional vehicles, to describe their impacts on air pollution and include them in models. Current approaches to vehicle emission modelling base emissions on a variety of parameters, including distance travelled and time spent at different speeds. However, all of these operate on the assumption that the internal combustion engine powers the vehicle at all times and that it provides all the motive power to the vehicle at any time from a depleting energy store that can only be recharged from an external source. In the case of electric and hybrid power trains, neither of these assumptions is true, so this popular approach used models to predict vehicles' emissions is likely to be invalid for them.

*Battery electric vehicles*

The UK's battery electric vehicle (BEV) fleet underwent a significant change around the end of the 20th Century, which is still being played out. From the mid to late 20th Century, there was a small, but significant fleet of battery electric light goods vehicles, numbering in the low tens of thousands (DfT, 2016d). These were typified by the electric "milk float": a small, short range, lead-acid battery powered light goods vehicle commonly used for domestic delivery rounds by dairies. These declined rapidly during the 1990s, with the UK electric light goods fleet reaching its lowest level in 2011.

Since 2011, the number of electric light vehicles has grown, both for goods and passenger classes of vehicles. Unlike the earlier peak in electric light goods vehicles, data on vehicle models purchased show that these are based on the current, consumer-oriented electric powertrain technologies underpinning electric cars such as the Nissan Leaf and Renault Zoë. These tend to have different (typically lithium-ion) battery chemistries than the lead-acid systems of milk floats, with higher energy storage density, higher sustainable power output and more advanced power management systems than 20th Century electric vehicles (Miller, 2015; Mahmoudzadeh Andwari, Pesiridis et al., 2017). Taking into account the size of the UK electric vehicle fleet in 2016 and the growth of newly registered electric vehicles in 2017 [ref, ref], here are an estimated 50,000 BEVs currently on UK roads (DfT, 2016b; DfT, 2016c).

As battery electric vehicles have no internal combustion engines, $CO_2$ emissions from their operation therefore can be attributed entirely to the generation of electricity used to charge their battery, with their marginal impact being that of the additional generation of electricity that is required to run them. This is a fairly efficient process, with estimates of energy transfer efficiency from electricity grid to vehicle motion being much higher than for IC engines (Martins, Brito et al., 2013). Comparisons of efficiency of primary energy to vehicle motion are more complicated, as this depends on efficiency of grid electricity generation plant for BEVs and upstream processing and transport of fuel products for IC engine vehicles. However, the range of figures quoted suggest that an efficient BEV charging from an electricity grid supplied by high efficiency thermal generation plant, such as CCGT could convert energy from fuel supplied to the power station in to vehicle motion with similar or greater efficiency than fuel in the tank of in IC engine vehicle.

Battery electric vehicles are currently an evolving and increasing performance in several ways, due to improvements in battery efficiency and capacity. This leads to improvements in how efficiently and quickly batteries charge and discharge, higher ratios of energy density to battery weight and volume and greater amounts of energy storable per unit. Most importantly, the cost per unit of energy storage capacity also appears to be falling to the point where cost competitiveness of BEVs compares well with a sizable fraction of IC engine vehicles (Nykvist, Sprei et al., 2019). BEVs in a typical mid-range price bracket of USD 40,000 (roughly GBP 31,000 or EUR 35,000 at time of writing) with ranges of 150 – 250 km are now available (Shi, Pan et al., 2019), compared with rages of around 50 km of earlier production models. Realistic ranges for electric vehicles are up to around 400 km.

Typical ranges for most private car trips are under 100km, suggesting that a large proportion of car could be undertake with currently available BEVs, However, this is not the only factor for BEV use: access to suitable charging infrastructure is also necessary. Some estimates suggest that a sparsity of charging infrastructure increases the necessary range capability of a BEV significantly, in order for it to be able to travel suitably far between charges.(Shi, Pan et al., 2019)

This rapid fall in cost per km of range, increase in typical range of BEVs and increase in rate of charging reduces some of the functional difference between IC engine vehicles and BEVs and may drive more rapid consumer uptake of BEVs and an increase in the proportion of vehicle and passenger kilometres travelled on electric powertrains. Moreover, as the carbon intensity of BEV transport is linked to the carbon intensity of the electricity grid, a BEV fleet provides ongoing opportunities to decarbonise transport as electricity decarbonised, without a replacing vehicles in the fleet.

Battery electric vehicles contribute to particulate emissions through brake and tyre wear and the resuspension of particulates already in the environment. Having no internal combustion engine, they do not produce fuel combustion related emissions of $NO_x$, PM, organic compounds or the residual levels of sulphur oxides associated with current petrol and diesel fuels.

This is not to say that particulate emissions from electric vehicles are likely to be trivial to model and they highlight a challenge in transport-related air quality modelling that applies to all vehicles. That is, an appreciable proportion of particulate emissions are produced not by the propulsion system, but by the abrasion of vehicle components, such as brakes and tyres, and by resuspension by vehicles of existing particulates. 45% of $PM_{10}$ and 38% of $PM_{2.5}$ currently produced by UK road transport is estimated to come from brake and tyre wear; 23% of $PM_{10}$ and 19% of $PM_{2.5}$ is estimated to come from road abrasion(DfT, 2017a). If average vehicle exhaust emissions of particulates fall with increasingly effective aftertreatment technology and the adoption of alternative powertrains, the proportion of non-exhaust PM emissions will become an even more dominant factor in transport pollution modelling (AQEG, 2012).

Battery electric and hybrid vehicles both commonly employ regenerative braking. This transfers the vehicle’s momentum via the wheels and gearing to a generator that converts it to electrical energy to recharge the battery. This not only slows the vehicle down with minimum overall energy loss but does so in a manner that reduces the mechanical demand from the conventional, friction brakes. The source of particulates from brake wear is due to the abrasion of friction brake components when they operate, so increased use of regenerative braking might be expected to lead to lower non-exhaust vehicle emissions, particularly from brake and type wear.

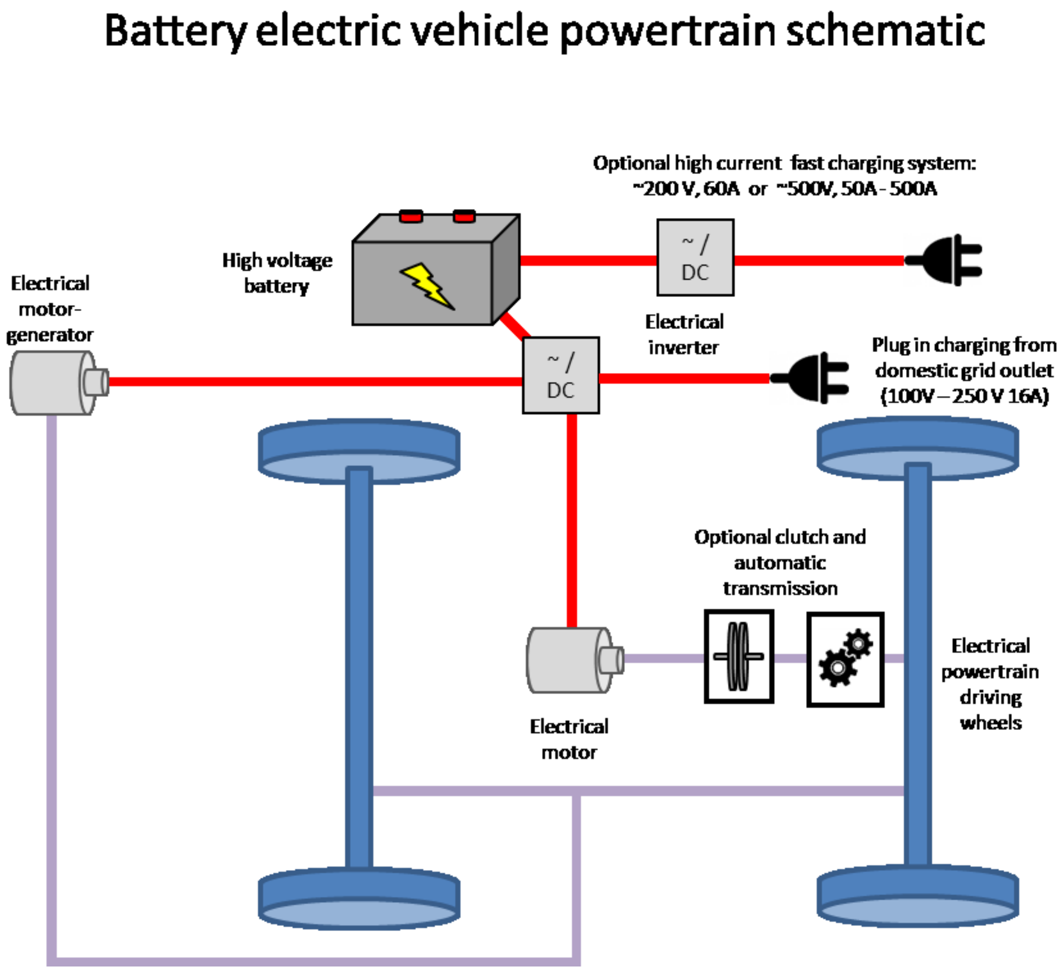

Figure 5.1 Battery electric vehicle schematic (electrical coupling in red; mechanical coupling in purple)

This may be difficult to verify at present. Data on non-exhaust emissions related to individual vehicle types is general is sparse, especially in relation to electrified powertrains.

Non-exhaust emissions occur every time a friction brake is applied, with the frequency and intensity of these applications being attributable to the drive cycle. Consequently, certain aspects of emission from brake and type wear may be able to be integrated into speed- or acceleration- based modelling. However, they are also vehicle specific in a way not likely to be linked as much to speed or acceleration. Vehicle weight, for example, is one such parameter already known to affect non-exhaust emissions (Timmers and Achten, 2016); the material composition of components is another known influence (Kukutschová and Filip, 2018). These relationships could hinder the integration of battery electric vehicle emissions in models that base emissions on speed, acceleration, engine size or even, as the latter case suggests, a vehicle's size of weight.

Emissions due to resuspension of ambient PM are, by contrast, determined by environmental factors, such as the physical characteristics of the road and even the weather, which can affect the ease of resuspension, through factors such as how wet the ground is, and the residence time of particulates in the air. Examples of electric vehicles are not included in this study, as the portable emissions monitoring system used to gather vehicle emissions data is configured to detect exhaust emissions, rather than ambient emissions.

Very few studies comparing the emission of electric vehicles with conventional or hybrid ones have been conducted to date. Those that have been undertaken, such as the 2016 study by Timmers and Achten, which includes resuspension, conclude that electric versions of common models of passenger cars provide little or no reduction in particulate emissions over the conventional models (Timmers and Achten, 2016). This is attributed almost entirely to the effect of the additional weight of the electric versions of the cars and is despite assumptions that regenerative component of braking generates no particulates. However, the study only focuses on particulates and does not include the elimination of $NO_x$ exhaust emissions from a shift to electric vehicles, so cannot be said to encompass the wider effects of light vehicle electrification on public health.

The above influences on the air quality pollutant emissions of electric vehicles appear likely to result in relationships between their operation and their air quality impact that are very different to those for a conventional internal combustion engined vehicle. For this reason, there may be challenges over including the air quality impacts of electric vehicles in current integrated assessment models that cover air pollution. This has implications for accurate prediction of the benefits of areas, such as London’s incoming Ultra Low Emissions Zone, where the air quality is likely to be influenced much more by the above factors, due to an early increase in the amount of electric vehicles, or vehicles running in electric only mode.

### *Fuel cell electric vehicles*

Fuel cell electric vehicles (FCEVs) are like battery electric vehicles in that they are powered entirely by an electrochemical power source. A fuel cell is very like a battery in that it relies on electrochemical changes between two stores of material, which depends on the flow of positive ions and electrical current between them. In a fuel cell, protons flow through a membrane between the two reactants and electrical current is routed through the powertrain to provide the energy to power the vehicle (Figure 5.2).  The key difference between them being that the electrochemical reactants in an electric vehicle’s battery are non-replaceable and are designed to be regenerated through recharging of the battery, whilst the reactants in a fuel cell vehicle are designed to be used and replaced.

Vehicle fuel cells commonly use hydrogen as a fuel as one set of reactants, although or low molecular mass organic compounds such as alcohols can also be used (NissanNews, 2016). Oxygen from the air is as the other reactant, so only one substance needs to be replaced when filling the fuel tank. The products of the fuel cell reaction are either water vapour, in the case of a hydrogen fuel cell, or water vapour and $CO_2$, in the case of a hydrocarbon fuelled system such as a solid oxide fuel cell, which are emitted as exhaust gases. Because no combustion occurs, there is no formation of combustion products, such as $NO_x$ or particulates in the exhaust and thus FCEVs’ exhaust emissions of air quality pollutants are zero.

$CO_2$ emissions from FCEVs may be direct or indirect, depending on the fuel cell used. A vehicle based on a methanol fuelled solid oxide cell system would have direct exhaust emission of $CO_2$. A hydrogen fuel cell vehicle would have indirect emissions associated with the carbon intensity of the hydrogen production. The majority of hydrogen supplied in the UK at the time of writing is produced from natural gas, via steam methane reforming (CCC, 2018). This process produces $CO_2$ emissions of around 285 g $CO_2$/kWh energy content. Hydrogen can, in theory, be mass produced with a lower level of $CO_2$ emissions from low carbon energy sources, such as via electrolysis from low carbon electricity or from the addition of CCS to the SMR process. However, the electricity generation capacity to provide mass market production via electrolysis for vehicle fuelling is far from in place. Proposals also exist to develop technologies for low carbon hydrogen production to using chemical cycling and high grade heat from nuclear (González Rodríguez, Brayner de Oliveira Lira et al., 2018) or concentrated solar sources heat (Vitart, Le Duigou et al., 2006), as well as via a range of other biochemical routes (USDOE, 2018). Such methods are currently only at the proposal or a very low technology readiness level, which precludes any quantitative analysis.

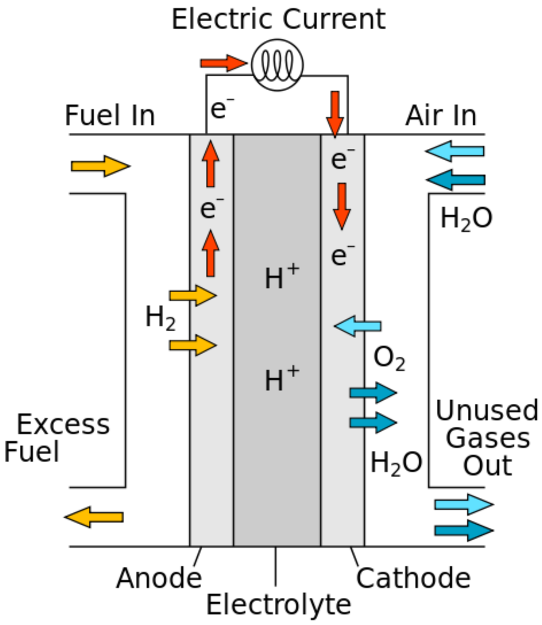

**Figure 5.2: Hydrogen fuel cell schematic. Source:(Dervisoglu, 2012)**

Hydrogen fuel cell powered buses have been available as production vehicles for some time, but fuel cell powered passenger cars are much less common. Some manufacturers have released production models of hydrogen fuel cell vehicles a very limited numbers, but UK market penetration is effectively zero, with the Department for Transport recording that there have been no fuel cell electric vehicles licensed in the UK between 2001 and 2016 (DfT, 2016c).

*Hybrid power trains*

Hybrid electric vehicles integrate multiple powertrains into the same vehicle and allow the sharing of power between them. Current hybrids on the market combine internal combustion engines and battery electric powertrains. In principle, other combinations such as battery storage and a fuel cell are also options (Das, Tan et al., 2017), with manufacturers such as Toyota beginning to address this market the UK and elsewhere with models such as the Mirai (Toyota, 2018), in advance of significant fuelling infrastructure. Hybrid vehicles have been available on the UK market since 1997, when the first models of Toyota Prius became available. The number of new hybrids registered in the UK has climbed steadily since, from a few hundred per year in the late 1990s to around 50,000 per year in 2016. Based on this growth rate and the number of current registered hybrids in 2016, there are likely to be around half a million hybrid cars on UK roads in 2018 (DfT, 2016b; DfT, 2016c).

An internal combustion / electric hybrid can deliver benefits, including the potential to offer improved efficiency, lower fuel consumption and reduced air pollutant emissions than a similar internal combustion engine vehicle, or to provide greater power than a similar internal combustion vehicle. Plug-in variants can also use electricity from large-scale electricity generation.

In terms of technology trajectories, electric-internal combustion hybrids can be seen as fulfilling several functions. In future light transport scenarios where fully electric powertrains are dominant, they may act as a transition technology to allow vehicles to take maximum advantage of electrical drives in advance of the roll out of significant distribution infrastructure for mass electrical charging or fuel cell reactant provision. In the interim, hybrids also help overcome the range limitations of most production vehicles which, with a few notable exceptions such as higher end Tesla models, tend to be capable of less than 250 km on a full charge. Thus, in future scenarios where electric light transport is still range-limited, such hybrids may have a longer-term role to play in applications where long distance road travel is required.

Hybrid vehicles are available in a variety of powertrain configurations, with their common trait being that they all use a combination of electric motor and internal combustion engine to provide propulsion. The two other major characteristics are the degree of how parallel the power train is and whether their batteries can be charged directly from the electricity grid.

Most hybrid power trains can drive the vehicle's wheels using both electric motors and the internal combustion (IC) engine simultaneously. This is referred to as parallel hybridisation. Parallel powertrain control algorithms tend to use the electric motor to provide motive power at very low road and IC engine speeds, when the torque from the electric motor is greatest and that from the IC engine is low. The also allow the electric motor to supplement the IC engine at higher speeds, often under situations when high power is needed. This allows the option for the IC engine in the vehicle to be sized somewhat smaller and with lower power for a hybrid than for the equivalent non-hybrid vehicle in the same class.

The alternative to parallel hybridisation is series hybridisation. In a vehicle operating in pure series hybrid mode, there is no mechanical coupling to the wheels at all and all motive power is provided via the electric powertrain. The IC engine serves purely as a generator to provide power directly to the wheel motors and to charge the battery. Such vehicles are often referred to as "range-extended" hybrids or electric vehicles and will, in principle, tend to rely largely on the battery over a short range, possibly supplemented by additional power from the generator, followed by greater reliance on the IC engine over the longer range in order to maintain an acceptable minimum state of battery charge. As all the IC engine needs to do is generate electricity, it provides the opportunity to optimise it to purpose by confining its operation to a narrower range of engine speeds than those for a parallel hybrid, essentially being those at which it can provide maximum torque, in order to maximise the efficiency of electricity generation.  As such, it is running the vehicle in manner similar to diesel electric railway locomotives. The overall efficiency and emissions of the vehicle should therefore be affected by factors such as engine efficiency, the efficiency of the charge / discharge cycle of the battery, the sizes of battery and engine and the algorithm for balancing power between the two.

In practice, however, virtually all production hybrids can allow varying degrees of parallel powertrain operation, with mechanical coupling of the IC engine to the wheels. This ranges from vehicles such as the Vauxhall / GM / Opel Ampera, which is largely a series hybrid, through vehicles such as the Volvo S60, which allow the car to be forced into a pure electric mode, through to mild hybrids, where a small electric motor is used to supplement the IC engine in situations of especially high power or torque demand. A more detailed analysis of hybrid powertrains is provided later in this section.

*Plug in hybrid vehicles*

A sub-class of hybrid vehicles allow direct charging of batteries from the electricity grid, in addition to charging via the IC engine. These are referred to as “plug-in” hybrid vehicles (PHEVs). PHEVs may be based around either parallel or series powertrains and, for reasons of practicality, the more series-oriented vehicles all tend to have plug in capability: if a vehicle is designed to operate on battery over the initial sections of any journey, it makes sense to be able to start a journey with a maximum state of charge in the battery whenever possible.

Charging a hybrid vehicle’s battery from its engine power or from regenerative braking can lead to more efficient use of fuel that the lack of this option. Nonetheless, it is less efficient in terms of $CO_2$ and air pollutant emissions than the option a plug-in hybrid offers of charging from the electricity grid. This is due to generating plant on the grid having lower average $CO_2$ and pollutant emissions per unit of energy produced than the hybrid’s power plant.

Plug-in hybrids have only become available in the UK around 2010, with few models on the market. The release of more models of PHEV has seen a rapid increase in registrations, from a few hundred per year around 2010 to 26,000 in 2016. Based on this rate, between 80,000 to 100,000 (about one fifth) of hybrid cars on UK roads in 2018 should be PHEVs (DfT, 2016b; DfT, 2016c).

As some plug-in hybrid can operate in a purely electric mode, it might be thought logical to consider them as electric vehicles with a supplementary internal combustion power train. This may be true for some vehicles, but it is a behaviour that is highly dependent on the powertrain management algorithms and is discussed in more detail in the next chapter.

## 5.3 Road transport emissions and legislation

### 5.3.1 Measuring vehicle performance: the role of test cycles

Vehicle test cycles exist to assess the performance of vehicles in a controlled and repeatable manner. Drive cycle based evidence of emissions performance is required for vehicle manufacturers to demonstrate that their new designs of vehicle meet standards and are eligible for sale in the markets they apply to.

Vehicle test driving cycles can be categorised into two types:

- **Transient cycles** involve many, frequent changes in engine power, engine load and representation of vehicle velocity. These are intended to provide an analogue of real-world driving conditions. They are based on a time profile of road speed or engine loading for a given vehicle, depending on whether the whole vehicle or just the engine is being tested.
- **Steady State Cycles** or “modal cycles” are designed to hold the engine loading, power or effective vehicle road speed at a steady value (a “mode”) for an extended period of time. These are well suited to situations where the engine, rather than the vehicle, is being tested and are used frequently in assessing compliance with heavy-duty standards. They are based on different timed stages, where the engine is held at a specific speed and load.

Both these types of drive cycles are highly formalised and are unlikely to be replicated by a driver on public roads. Their advantage is that they are well-suited to lab-based conditions and are easy to reproduce, thus forming the basis of a standard. Indeed, methodologies that require the use of engine dynamometers used to test the emissions directly from the engine exhaust at different engine different loadings and torque outputs are only achievable in the laboratory. At the time of writing, the most relevant drive cycles for demonstrating emissions compliance with regulation in the UK were those used for the Euro emissions standards.

*Euro standard light vehicle test cycles*

The New European Drive Cycle (NEDC) was used as the test cycle for assessing light vehicles' $CO_2$ emissions and compliance with Euro 5 and 6 air quality pollutant emission standards up to September 2017 and thus, at the time of writing, almost all light vehicles models will have had to demonstrate compliance with this standard. This is usually performed under controlled conditions with the test vehicle mounted on a chassis dynamometer: a "rolling road" testbed, where the vehicles tyres are in contact with a surface (often rotating drums) that can simulate the rolling resistance offered to the car by the road surface, its own inertia and, if necessary, a simulated gradient. The NEDC is an amalgamation of earlier urban and extra urban cycles, consisting of a cold start of the vehicle at between 20°C - 30°C, followed by four repetitions of the ECE 15 test cycle that simulates urban driving, then an instance of the Extra Urban Drive Cycle (EUDC), as shown in Figures 5.3, 5.4 and Table 5.1.

Despite being viewed as a transient drive cycle, the NEDC is based around a small number of steady state operating modes, with constant velocity being maintained between periods of smooth acceleration or deceleration and includes only a very small portion of the extra urban drive cycle at the highest road speeds normally permitted. It consequently bears little resemblance to a drive cycle that a vehicle may follow in a real-world journey (Williams and Carslaw, 2011), which would likely either have more frequent accelerations, corresponding to urban or minor extra-urban driving, or a more prolonged period of high-speed driving, corresponding to major road or motorways.

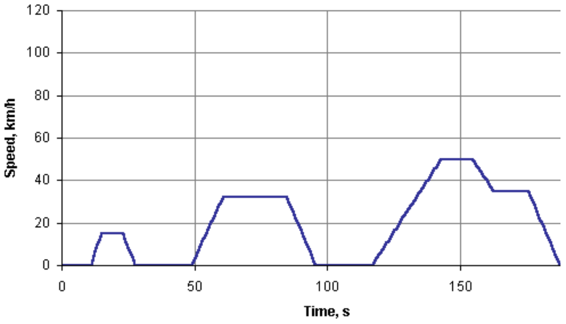

**Figure 5.3: NEDC 15 urban drive cycle. Source: (Dieselnet, 2019)**

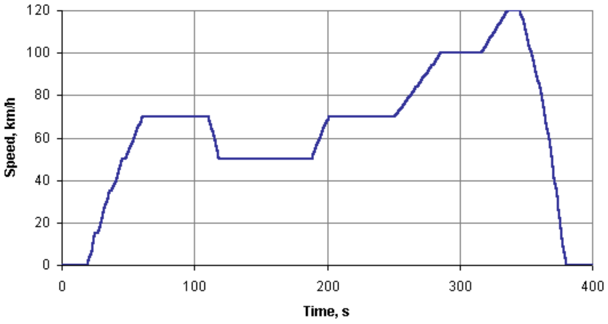

**Figure 5.4: NEDC Extra Urban Drive Cycle Source: (Dieselnet, 2019)**

| **Characteristics** | **Unit** | **ECE 15** | **EUDC** | **NEDC** |
|---|---|---|---|---|
| **Distance** | **km** | 0.9941 | 6.9549 | 10.9314 |
| **Total time** | **s** | 195 | 400 | 1180 |
| **Idle (standing) time** | **s** | 57 | 39 | 267 |
| **Average speed (incl. stops)** | **km/h** | 18.35 | 62.59 | 33.35 |
| **Average driving speed (excl. stops)** | **km/h** | 25.93 | 69.36 | 43.1 |
| **Maximum speed** | **km/h** | 50 | 120 | 120 |
| **Average acceleration** | **$m/s^2$** | 0.599 | 0.354 | 0.506 |
| **Maximum acceleration** | **$m/s^2$** | 1.042 | 0.833 | 1.042 |

**Table 5.1: Characteristics of the New European Drive Cycle for light vehicles. Source: (Dieselnet, 2019)**

The NEDC remained in use for assessing Euro 6 compliance until the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) was adapted for use as a replacement in late 2017. Development of the WLTP forms part of an initiative by the World Forum for Harmonization of Vehicle Regulations, a working party of the UNECE (UN Economic Commission for Europe), which aims to deliver benefits in in terms of safety, environmental protection and trade through common approaches to vehicle standards. Adaption of the WLTP required its extension to include extra high-speed parts of the cycle for testing European vehicles above 135 kph, as some EU countries have maximum motorway speed limits in excess of the originally proposed WLTP speeds (UNECE, 2014).

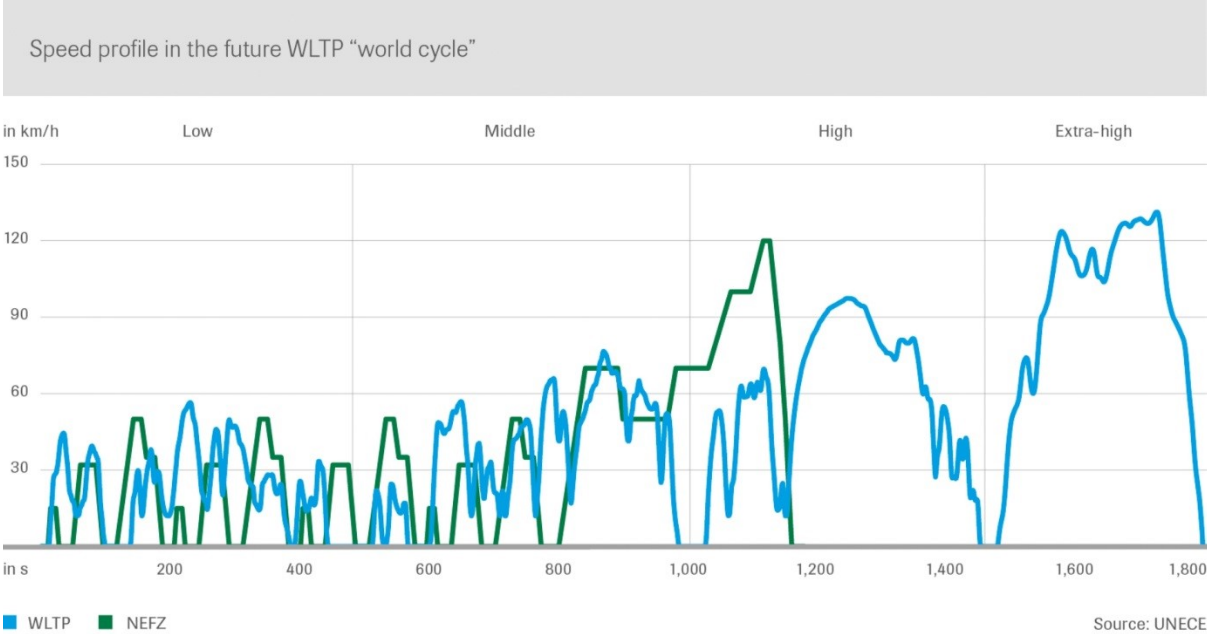

**Figure 5.5 WLTP drive cycle profile (blue) in comparison to the NEDC drive cycle (green). (VDA and UNECE, 2018)**

The WLTP is a much more transient drive cycle than the NEDC and should help in overcoming some of the shortcomings in light vehicle testing described in this study. A side-by-side comparison of the two cycles is presented in Figure 5.5. It incorporates much more frequent and faster changes in road speed and engine load, which goes some way to replicating the type of stop-start and rapid accelerations found in road driving conditions.

The WLTP also makes greater distinction between different types of light vehicles that focuses on the power to mass ratio. This is in recognition that the high power to mass ratio (and sometimes high mass) vehicles that typify high end cars in Europe are not representative of the potentially much larger fleet of low power, cheaper vehicles that are evolving in markets such as India and China, nor of many of the mid to low prices vehicles found in European markets. The WLTP approach is to provide different proposed drive cycles tailored to different vehicle types. This makes sense, as it offers a way of accommodating the fact that the more premium classes of vehicles are technically capable of higher road-legal speeds and greater accelerations then their lower end counterparts. Quite simply, higher end cars offer a different driving style that lower powered ones are incapable of and, as some drivers will choose to adopt this style, it needs to be accounted for in emissions testing.

In the longer term, the WLTP is also more future proof against new technology than the NEDC in that it includes defined provisions for testing hybrid and electric vehicles. These distinguish between plug-in hybrid vehicles, described by WLTP as “off-vehicle” chargeable hybrids and non-plug in hybrids that charge themselves off their engine or through regenerative braking systems. There are also provisions for testing vehicles with solely electric powertrains. These provisions cover air pollutant, $CO_2$ emissions and fuel consumption.

The inclusion of the full range of air pollutants for pure electric vehicles may seem counterintuitive, as a pure electric powertrain has no direct exhaust emissions. Nonetheless, it still has value: as reductions in particulate exhaust emissions improve, tyre and brake wear are increasingly significant contributors to ambient particulate matter emissions from road traffic. These are not capable of being addressed via the major emission reduction approaches taken by manufactures to date of fuel and engine efficiency improvements or exhaust gas aftertreatment. Since the inclusion of a test cycle for electric vehicles offers the opportunity to introduce specific standards for electric vehicles, it may also offer a method for incentivising measures to reduce non-exhaust emissions.

In the case of hybrid vehicles, the availability of a standardised process to assess emissions offers the opportunity to improve comparison of the behaviour and characteristics of hybrids and to develop more accurate descriptions of them. These can assist the refinement of technical and economic models, such as those discussed earlier in this study, to assess the benefits and impacts of the uptake of new technologies.

### *Euro standard heavy vehicle test cycles*

Heavy vehicle tests are usually performed only in engines, rather than the vehicles themselves. From Euro III to V standards, they have been based around:

- The European Transient Cycle (ETC), which simulates engine conditions over three regimes, corresponding to urban, rural and motorway driving.
- The European Stationary Cycle (ESC), which cycles the engine through a variety of loadings at speeds varying between 50% - 70% of the rated engine output.
- The European Load Response (ELR) tests, which measures smoke opacity from the exhaust by alternating between 10% and 100% engine loading under the speeds used by the ESC.

### *World harmonised heavy vehicle cycles*

For Euro VI standards, the above tests have now been replaced in Euro VI by the World Harmonized Stationary Cycle (WHSC) and World Harmonized Transient Cycle (WHTC). These have been developed by the United Nations Economic Commission for Europe

The World Harmonised Stationary Cycle (Table 5.2) is an engine dynamomenter based test cycle that takes an engine through a series of steady states (UNECE, 2010). It requires the engine to be at its normal operating temperature when started and measure emission from the engine at different combinations of 0%, 25%, 50%, 70% and 100% of engine loading and of 0%, 25%, 35%, 50% and 75% of the nominal maximum engine speed. Each of these is given a weighting factor, to achieve an overall score for the engine.

| World Harmonised Stationary Cycle | | | | |
|---|---|---|---|---|
| **Mode** | **Speed** | **Load** | **Weighting Factor** | **Mode Length** |
| | % | % | - | s |
| 0 | Motoring | - | 0.24 | - |
| 1 | 0 | 0 | 0.17/2 | 210 |
| 2 | 55 | 100 | 0.02 | 50 |
| 3 | 55 | 25 | 0.1 | 250 |
| 4 | 55 | 70 | 0.03 | 75 |
| 5 | 35 | 100 | 0.02 | 50 |
| 6 | 25 | 25 | 0.08 | 200 |
| 7 | 45 | 70 | 0.03 | 75 |
| 8 | 45 | 25 | 0.06 | 150 |
| 9 | 55 | 50 | 0.05 | 125 |
| 10 | 75 | 100 | 0.02 | 50 |
| 11 | 35 | 50 | 0.08 | 200 |
| 12 | 35 | 25 | 0.1 | 250 |
| 13 | 0 | 0 | 0.17/2 | 210 |
| Total | | | 1 | 1895 |

**Table 5.2: World Harmonised Stationary Cycle, as used for Euro VI. Source: IPC**

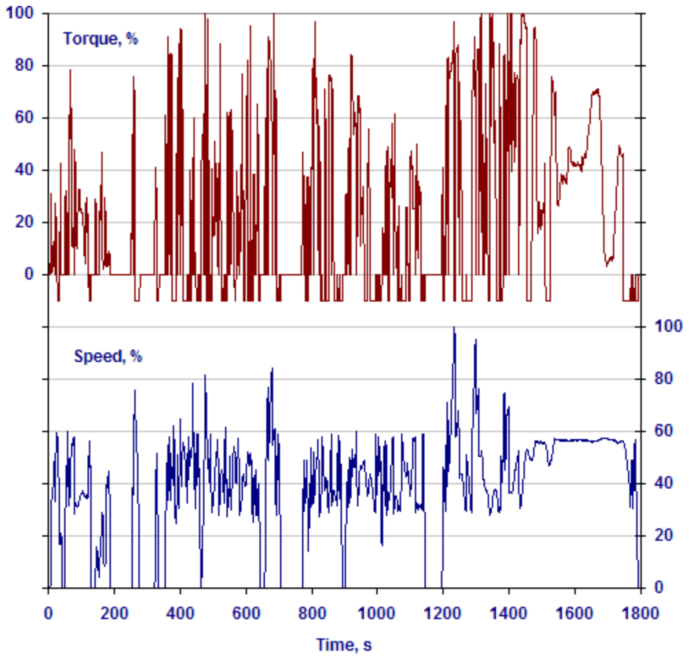

**Figure 5.6: World Harmonised Transient Cycle, as used for Euro VI. Source: ICCT**

The World Harmonised Transient Cycle (Figure 5.6) is also an engine dynamometer-based cycle but consists of much more rapid changes in engine speed and torque, in order to simulate some of the operation that might be demanded from the engine in real conditions. The WHTC requires engines to be subjected to cold and hot starts.

*Emissions compliance failures and real-world driving cycles*

Despite trends in the NEDC and the Worldwide Harmonized Cycles to try and replicate elements of on-road driving conditions, these drive cycles are still designed to be performed in laboratory conditions. This provides manufacturers with an incentive to optimise their vehicles' performance to perform under these conditions. A mounting volume of evidence has highlighted the discrepancy between the emissions and fuel economy performance of light vehicles undertaking drive cycles under lab conditions and their behaviour under in-service conditions on the road network (O'Driscoll, ApSimon et al., 2016). These suggest that, out on the road, cars compliant with Euro 5 and 6 standards may produce up to several times the average level of pollutants that they do under test conditions.

This discrepancy is not new and has been seen in earlier Euro standards (Kageson, 1998; EC, 2015). Partly this has been accredited to behavioural response by vehicle manufacturers to standards: if one has to meet a standard based on drive cycles in the laboratory, one will optimise vehicles to meet them, rather than drive cycles in the real-world. This approach is often referred to as "cycle beating" is widespread. However it is also partly inevitable, due to the greater range of operating conditions that vehicles are subjected to on the road than in the controlled conditions used for emissions compliance testing and due to the fact that the efficacy of emissions reduction systems decreases over time (Chen and Borken-Kleefeld, 2016).

A key moment in this debate occurred in 2015, when it was disclosed that the software managing the engine and emission abatement systems on some of Volkswagen's diesel vehicle models were designed to operate as a "defeat device" to vehicle emissions tests. Defeat devices are defined in the EU as "any element of design which senses temperature, vehicle speed, engine speed (RPM), transmission gear, manifold vacuum or any other parameter for the purpose of activating, modulating, delaying or deactivating the operation of any part of the emission control system, that reduces the effectiveness of the emission control system under conditions which may reasonably be expected to be encountered in normal vehicle operation and use" (EC, 2007b). Vehicles installed with defeat devices are recognised by many jurisdictions, including the EU and the US, as ineligible for emissions certification or sale.

The US Environmental Protection found that the affected Volkswagen diesel vehicles would only operate the engine and emission control systems in full compliance of emission standards when certain combinations of operational parameters were met. These include vehicle speed, steering wheel position, barometric pressure and engine operation duration (USEPA, 2015). These combinations are unlikely to occur it the real world but are characteristic to emissions testing drive-cycle conditions. When these conditions were not detected, the engine and emissions control systems operated such that vehicles did not comply with emission standards, with $NO_x$ emissions observed as between 10 to 40 times the limits of EPA compliance. The use of this approach also resulted in the vehicles meeting required emission performance when being assessed for Euro emission standards compliance, but potentially falling dramatically short of them when being driven (EC, 2015).

Volkswagen admitted to these practices and the use of various forms of defeat device has since been identified in other vehicle manufacturers' diesel models. Consequently, this series of revelations is often referred to as "Dieselgate" by the media.

### *Real-world driving cycles*

The use of defeat devices, as well as wider evidence of poor real-world operational compliance of light vehicles with air pollutant emission standards has precipitated moves to introduce real drive cycles (RDCs) into vehicle emissions assessment.  Their first appearance in EU legislation is in the most recent revision of the European Union's standard for light vehicle emissions testing (Euro 6d). This appears intended to discourage manufacturers from taking Volkswagen's approach and to facilitate assessment of the efficacy of vehicle standards in reducing air pollution. RDCs offer the advantage of real-world evidence for verifying the performance of a vehicle against its theoretical capabilities and understanding how well emissions abatement technologies hold up in the field. They also allow the introduction of additional factors that influence vehicle performance, such as:

- Vehicle loading and gradient of roads, which is likely to affects engine loading under acceleration;
- Ambient temperature and altitude, which is likely to affects catalyst and engine operation;
- Weather conditions, which is likely to affect driving style and power load on the vehicle from use of air conditioning or heating.

The variability of conditions under RDCs means that they will be hard to replicate. For this reason, the Euro 6d revision aims to incorporate RDCs as an assessment method complementing, but not replacing, laboratory-based drive cycles for assessing particle number and gaseous emissions from new vehicles.

Until recently, RDCs would have been burdensome to implement, due to the onerous measures needed to fit appropriate instrumentation to the vehicle being tested. The exhaust gas capture, detection and analysis equipment that forms the basis of a functional Portable (vehicle) Emissions Measurement Systems (PEMS) was both expensive and often required substantial modification to the vehicle to fit. The more recent development of lighter PEMS, which are easier to mount on the vehicle and remove, have made the prospect of routine RDC testing feasible. Nonetheless, the PEMS likely to be used for these assessments are still complex assemblies that bring together, exhaust mass flow meters, advanced gas analysers, environmental monitoring, Global Positioning System (GPS) and data collection from a vehicle's on-board telemetry and sensor system.

### 5.3.2 Greenhouse gas emission trends and legislation

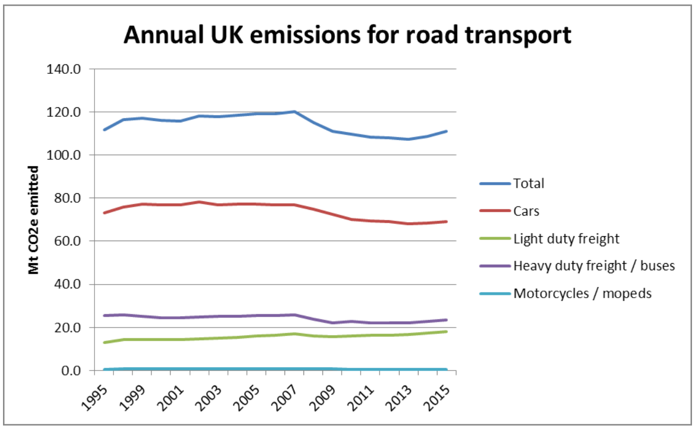

**Figure 5.7: Annual UK emissions for road transport. Source: (NAEI, 2019)**

The UK Greenhouse Gas Inventory, which is used for national level reporting to the United Nations Framework Convention on Climate change, highlights that carbon dioxide from domestic transport is a major component of the UK's annual greenhouse gas emissions.

In 2017, it accounted for 27% (126 $MtCO_2e$) of national total greenhouse gas emissions. 114 $MtCO_2e$ of this arises from road transport. In comparison, the remainder of rail transport that is not already electrified and domestic aviation each contribute 1.5 $MtCO_2e$ – 2.0 $MtCO_2e$ of direct emissions respectively (BEIS, 2019).

*Light-duty vehicles*

In 2017, 69.1 $MtCO_2e$ of UK road transport greenhouse gas emissions came from cars (BEIS, 2019). This is calculated in two ways: firstly, a bottom up methodology is used that estimates greenhouse gas emissions using road traffic modelling data and drive cycle related emission factors. Then this is normalised against total road fuel consumption data, which is calculated from duty receipts of the actual amount of fuel sold. This second step provides a low uncertainty (around ±2%) estimate of direct $CO_2$ emissions for the overall transport sector, based on real-world data of physical fuel purchases and the assumption that, on the basis that hoarding does not appear to be taking place, the amounts of fuel bought across a year are the same as the amounts combusted (Brown, Broomfield et al., 2018). The former process is used to estimate figures for non-$CO_2$ emissions as $CH_4$ and $N_2O$, that depend on engine and exhaust gas aftertreatment characteristics. These should have a greater margin of error than the $CO_2$ emissions, as they are based on vehicles' emissions performance in test cycles which, for the reasons presented below, are known to differ from on-road emissions performance.

Car emissions are still lower in both absolute terms and as a proportion of transport emissions since its peak of 76.9 $MtCO_2e$ in 2002, despite an increase in the number of cars that are currently registered and paying road taxed (i.e. eligible to be driven on the road). There are many factors that affect this, but two of the possible influences are:

- A small but gradual fall in the annual distance people travel in England as a passenger or as a driver by car and in the number of car journeys taken per person per year (DfT, 2018b).

- Reductions seen in estimated $CO_2$ emissions per kilometre for vehicles, driven either by changes in vehicle standards or shifts towards diesel.

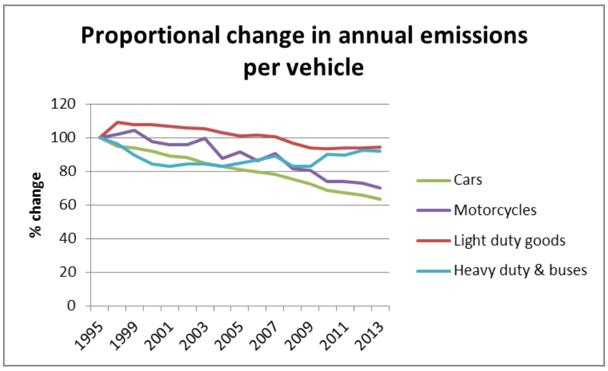

**Figure 5.8: Proportional Change in annual emissions per UK road vehicle. Source (BEIS, 2018a; DfT, 2018e)**

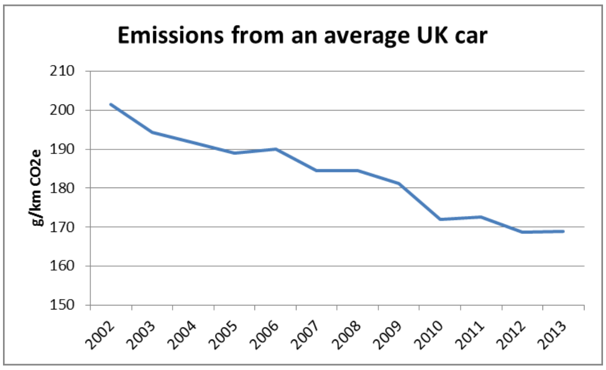

**Figure 5.9: Annual CO2 Emissions from an average UK car. Source (BEIS, 2018a; DfT, 2018b; DfT, 2018e)**

The UK's National Transport Survey suggests that the first of these two phenomena has been partly driven by modal shift. The fall in distance travelled by car has occurred while the number of rail journeys has risen sharply, as has the number of bus journeys in the London area. Further possibilities may include a reduced need to travel for certain purposes, such as types of shopping, because of an increase in the amount of online ordering and delivery services.

The reasons behind the fall in of $CO_2$ emissions per kilometre and the validity of these figures are much less clear. Based on fuel sale, car numbers and average distances driven, average $CO_2$ emissions per km appear to have fallen by around 15% between 2002 and 2016 (BEIS, 2018a; DfT, 2018b; DfT, 2018e).

In principle, newer cars should have lower emissions, as emission targets have been set for vendors of light vehicles into the EU market for two decades. These started in 1998, in the form of a non-binding emissions reduction target, agreed with the ACEA (European Automobile Manufacturers Association) (EC, 1999), which aimed for fleet-average emissions of 140 g/km $CO_2$ by 2008. The JAMA (Japanese Automobile Manufacturers Association) and KAMA (Korean Automobile

Manufacturers Association), followed suite with agreements targeting the same average emissions by 2009. Whilst these agreements were instrumental in reducing vehicle $CO_2$ emissions, manufacturers still fell short of their targets (EC, 2007a).

Since 2009, EU legislation has set mandatory standards for light vehicles, when Regulation EC 443/2009 was introduced requiring the fleet average emissions of new cars across all manufacturers to be no more than 130 g/km $CO_2$ by 2015 (EC, 2009). Compliance with these standards were on a "fleet average" basis across all new cars sold by all manufacturers in the EU that year. This allowed significant variation of $CO_2$ emissions between individual vehicle models and between individual manufacturers' overall fleets. The subsequent amendment to this Regulation, sets targets of 95 g/km $CO_2$ of all cars by 2021, applies to the average emissions of all new cars sold by each manufacturer (EC, 2014).

Financial incentives for the public to try and purchase lower carbon new cars are one possibility. These exist in the form of UK Vehicle Excise Duty, which increases the annual tax for road usage on light vehicles in line with increasing $CO_2$ emissions per km. Additionally, Regulation EC 443/2009 limits the average $CO_2$ emissions per km for a manufacture's output of vehicles.

Compliance with these pieces of legislation is based on car fuel efficiency and $CO_2$ emissions data measurements for new vehicles under pre-defined driving test cycles described in section 5.3.1, which take place in lab conditions. The weight of recent evidence in this and other studies, suggests that this data underestimates real-world fuel consumption. Cars on the road are subject to variable influences that are not experienced under controlled test cycle conditions and which influence their fuel consumption and emissions performance. These include factors such as the environment (wind, terrain, road surface, temperature etc.); the driving style of the driver; the loading and number of occupants and; configuration of optional aspects of the vehicle such as tyre pressure. For now, evidence of the scale and variance of the discrepancy between test and on-road data for is still largely through the observation of on-road emissions in recently manufactured vehicles (O'Driscoll, Stettler et al., 2018). The level of discrepancy and its variance for the overall car fleet still uncertain and this is likely to impede the ability to assess the impact of this legislation and the ability of emission trajectory models and other forecasting tools to describe the future (or current) impacts of cars.

One contributor to any fall in car $CO_2$ emissions may be the increase in the proportion of diesel vehicles in the UK car fleet that has been seen over the past two decades. This is potentially easier to gauge from evidence, as diesel vehicles typically have lower $CO_2$ emissions than equivalent sized engine petrol vehicles and the numbers of engine types in use are documented in vehicle licencing data. In 2002, the UK car fleet was about 15% diesel engine with the rest overwhelmingly petrol engine. By 2016, this had changed to almost 40% diesel cars and 59% petrol vehicles (DfT, 2018e), representing a 24% proportional shift towards diesel. A recent study of car models available in the UK during in recent years (covering Euro 5 and 6 standards) suggests that petrol cars have $CO_2$ emissions per km of between 13% - 65% greater than diesel engine vehicles in the same size class, with the difference increasing with vehicle size and engine displacement (O'Driscoll, Stettler et al., 2018).Given the composition of the UK car fleet, it estimated that petrol vehicles emit 23% more g $CO_2$ / km than diesel vehicles in urban drive cycles and 6% more in motorway drive cycles.

Road usage statistics for 2017 (DfT, 2018c) suggest that around 51% of the distance travelled in England was on rural A class roads or on motorways, which represent the high speeds and low engine loadings that equate to motorway driving in the O’Driscoll and Stettler study. This would imply that a shift to diesel might result in an overall fall of 12.7% g $CO_2$ per km per vehicle in average usage. Given this the 25% shift towards diesel cars could conceivably account for around a 3% decrease of overall car $CO_2$ emissions or about one quarter of the estimated fall for the fleet average.

### *Heavy-duty vehicles*

Whist both EU and national legislation aims to curtail and improve the greenhouse gas emissions from light-duty vehicles in the UK, there is none in place with the explicit aim of limiting limit $CO_2$ emissions from either heavy goods vehicles or buses and coaches.

UK Vehicle Excise Duty rates for large passenger vehicles is related to the number of seats, but it varies for heavy goods vehicles (HGVs) with their maximum authorised mass (MAM) permitted when loaded. If a vehicle is to be used exclusively for low mass loads, the MAM can be reduced below the normal level for that model and its Excise Duty is reduced accordingly. In addition to Vehicle Excise Duty (VED), another potential influence on vehicle $CO_2$ emission is the Road User Levy (RUL). In theory, it is a tax on road surface wear and tear and, like VED, depends on the vehicle's weight. Unlike VED, which applies only to UK registered vehicles, the Road user Levy applies to all heavy-duty vehicles using UK roads, whatever its country of registration.

A vehicle's weight influences its fuel economy and its $CO_2$ emissions per km, so it is possible that VED and RUL play a role in curbing the use of excessively heavy or oversized vehicles. However, there is not clear evidence of this.

Regardless of tax rates, the amount of fuel a vehicle needs is a significant long term operational cost in the goods transport sector, and therefore of economic importance. Measures to reduce fuel consumption, without incurring greater cost increases elsewhere (such as in purchase or maintenance costs), are therefore likely to be an attractive. The lack of observed $CO_2$ reduction in this sector may therefore be an indication that manufacturers have already exhausted competitively costed options to this end under the current market drivers or that there are market barriers to the introduction of emerging technologies to deliver future $CO_2$ reductions.

### 5.3.3 Air quality emission trends

Road vehicles are a major source of air pollutants in the UK and are thought to be responsible for around one third of $NO_x$ emissions and about 8% of $PM_{10}$ emissions by weight. Both of these have been on a significant downward trend since 1990, with road transport $NO_x$ emissions in 2016 being about 22% and road transport exhaust $PM_{10}$ exhaust emissions around 26% of their 1990 levels, respectively.

A primary contributor to these trends has been the phased introduction of increasingly stringent vehicle emission standards over this period. These are agreed at European level and are implemented as EU Regulations, which take direct effect in all EU member states without national laws having to be passed to being them into force and apply to states participating in the European single market. As European vehicle manufacturers tend to produce a single design for the overall European market, European vehicle emissions Regulations also have significant influence on European states outside the single market: Ukraine, for example, generally introduces requirements for imported light vehicles to meet a specific European emission standard around three to four years after it enters into force in the EU.

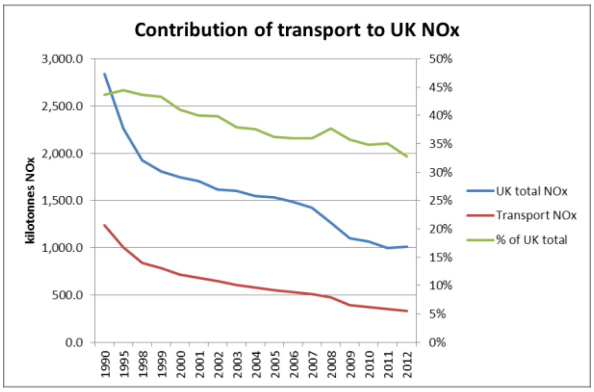

**Figure 5.10: Contribution of transport to UK NOx (NAEI, 2019)**

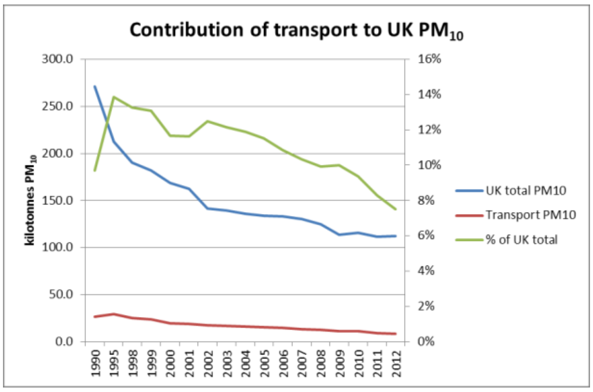

**Figure 5.11: Contribution of transport to UK $PM_{10}$ (NAEI, 2019)**

Since 1992, six successive rounds of standards have stipulated the maximum permitted limits of emissions of carbon monoxide, hydrocarbons, $NO_x$ and particulate matter, in vehicle exhaust emissions as described in Tables 5.3 – 5.5.

The implementing legislation sets dates by which all new vehicles receiving type approvals ("Date (TA)") and new vehicles sold ("Date (NV)") must conform to the limit values in the standards. Usually, these two dates are a year apart.

**Euro emission standards for petrol cars (spark ignition, Class M)**

| **Standard** | **Type Approval** | **New Vehicles** | **CO** | **Total HC** | **Non-$CH_4$ HC** | **$NO_x$** | **HC+ $NO_x$** | **$PM_{10}$** | **Particle Number** |
|---|---|---|---|---|---|---|---|---|---|
| | | | **g/km** | **mg/km** | **mg/km** | **mg/ km** | **mg/ km** | **mg/ km** | **per km** |
| Euro 1 | Jul 1992 | Jan 1993 | 2.72 | | | | 970 | | |
| Euro 2 | Jan 1996 | Jan 1997 | 2.2 | | | | 500 | | |
| Euro 3 | Jan 2000 | Jan 2001 | 2.3 | 200 | | 150 | | | |
| Euro 4 | Jan 2005 | Jan 2006 | 1 | 100 | | 80 | | | |
| Euro 5 | Sep 2009 | Jan 2011 | 1 | 100 | 68 | 60 | | 5 | |
| Euro 5b | Sep 2011 | Jan 2013 | 1 | 100 | 68 | 60 | | 4.5 | |
| Euro 6 | Sep 2014 | Sep 2015 | 1 | 100 | 68 | 60 | | 4.5 | 6.0 x $10^{12}$ |
| Euro 6c | Sep 2017 | Sep 2018 | 1 | 100 | 68 | 60 | | 4.5 | 6.0 x $10^{11}$ |
| Euro 6d | Jan 2020 | Jan 2021 | 1 | 100 | 68 | 60 | | 4.5 | 6.0 x $10^{11}$ |

Notes: Particle number limits for petrol vehicles apply to direct injection vehicles only.
Euro 6d temporary standards are due to be introduced for new vehicle types from Sept 2017 and new production vehicles from Sept 2019.

**Table 5.3: Euro emission standards for petrol cars**

These standards often conform to the introduction of new technologies in vehicles. Euro 1, for example, heralded the use of catalytic convertors to petrol engines to reduce CO emissions in light vehicles, Euro III encouraged uptake of diesel oxidative catalysts (DOCs), Euro 5 and V drove the introduction of diesel particulate filters (DPFs) on diesel vehicles and Euro IV and V and 6 saw the introduction of NOx reduction technology such as selective catalytic reduction on diesel vehicles.

| **Euro emission standards for diesel cars (compression ignition, Class M)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Standard** | **Date (TA)** | **Date (NV)** | **CO** | **HC** | **NO$_x$** | **HC+ NO$_x$** | **PM$_{10}$** | **Particle Number** |
| | | | **g/km** | **g/km** | **g/km** | **g/km** | **g/km** | **per km** |
| Euro 1 | Jul 1992 | Jan 1993 | 2.72 | | | 0.97 | 0.14 | |
| Euro 2 | Jan 1996 | Jan 1997 | 2.2 | | | 0.7 | 0.08 | |
| Euro 3 | Jan 2000 | Jan 2001 | 0.64 | | 0.5 | 0.56 | 0.05 | |
| Euro 4 | Jan 2005 | Jan 2006 | 0.5 | | 0.25 | 0.3 | 0.025 | |
| Euro 5 | Sep 2009 | Jan 2011 | 0.5 | | 0.18 | 0.23 | 0.005 | |
| Euro 5b | Sep 2011 | Jan 2013 | 0.5 | | 0.18 | 0.23 | 0.005 | 6.0 x $10^{11}$ |
| Euro 6 | Sep 2014 | Sep 2015 | 0.5 | | 0.08 | 0.17 | 0.005 | 6.0 x $10^{11}$ |
| Euro 6c | Sep 2017 | Sep 2018 | 0.5 | | 0.08 | 0.17 | 0.005 | 6.0 x $10^{11}$ |
| Euro 6d | Jan 2020 | Jan 2021 | 0.5 | | 0.08 | 0.17 | 0.005 | 6.0 x $10^{11}$ |

**Table 5.4 : Euro emission standards for diesel cars**

| **Euro emission standards for heavy-duty diesel vehicles** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Standard** | **Date (TA)** | **Date (NV)** | **CO** | **HC** | **$NO_x$** | **$PM_{10}$** | **Particle Number** | **Smoke** |
| | | | **g/kWh** | **g/kWh** | **g/kWh** | **g/kWh** | **per kWh** | **per $m^{-3}$** |
| Euro I | Jan 1992 | Jan 1993 | 4.5 | 1.1 | 8 | 0.612 (≤ 85 kW) | | |
| | | | 4.5 | 1.1 | 8 | 0.36 (> 85 kW) | | |
| Euro II | Jan 1996 | Jan 1997 | 4 | 1.1 | 7 | 0.25 | | |
| | Jan 1998 | Jan 1999 | 4 | 1.1 | 7 | 0.15 | | |
| Euro III | Oct 1999 | Oct 2000 [1] | 1.5 | 0.25 | 2 | 0.02 | | 0.15 |
| | Jan 2000 | Jan 2001 | 2.1 | 0.66 | 5 | 0.10 | | 0.8 |
| Euro IV | Jan 2005 | Jan 2006 | 1.5 | 0.46 | 3.5 | 0.02 | | 0.5 |
| Euro V | Jan 2008 | Jan 2008 | 1.5 | 0.46 | 2 | 0.02 | | 0.5 |
| Euro VI[2] | Jan 2013 | Jan 2014 | 1.5 | 0.13 | 0.4 | 0.01 | $8.0\times10^{11}$ | |

**Table 5.5 : Euro emission standards for heavy-duty diesel vehicles**

Manufacturers have used different strategies to meet these standards, which are not necessarily those based on incoming technologies and their approach affects affected subsequent standards. For example, when Euro IV and V were introduced, it was widely expected that these would require most new heavy vehicles to have DPFs fitted, which would drastically reduce the mass and number

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[1] For Enhanced Environmental Vehicles only. An EEV is a low emission passenger vehicle of weight > 3.5 tonnes. The standard lies between the levels of Euro V and Euro VI

[2] Euro VI also includes a 10 ppm limit of exhaust pipe $NH_3$ emission.

of particles released. In contrast, some manufacturers took the approach of tuning their engines for a high combustion temperature, which also had the effect of reducing the mass of particulates but increasing the amount of $NO_x$ produced, which was then removed by a selective catalytic reduction stage. This system proved less expensive to fit than a DPF, but was not as effective as a DPF at removing the high number of very small particulates (<2 µm diameter) from the exhaust gases, which are thought to have proportionally greater health impacts than the coarser particulate fraction. This was a driver for the inclusion of a particle number standard in later revisions to the legislation.

Euro standards can take several years to agree and are often updated via sub-gradations to reflect emerging evidence on the health impacts of air pollution or changes in technology that have substantial implications for emissions and which the vehicle standards of the day are unable to address. The Euro 6 standards have undergone the following evolution:

- Euro 5b for diesel engines and Euro 6 for GDI petrol engines introduced particle numbers emission limits in response to concern about the impacts of fine particles;
- Euro 6c responded to the introduction of biofuels into the mainstream European market by requiring that vehicles still comply with emission limits when the maximum permitted levels of biofuels (5% ethanol in petrol and 10% methyl esters in diesel) in EN fuel standards are included in the blend;
- Euro 6d introduces new requirements for the use of real-world driving cycles and the world harmonised test cycle in response to evidence of manufacturers designing vehicles that perform substantially better under test conditions than in the real-world.

Euro 6 has been subject to further revisions in order to accommodate new evidence on the efficacy of technology and the health effects of pollution. The increasing evidence base on the negative health impacts of fine ($PM_{2.5}$) particles emerged in the wake of the original agreement of the Euro 6 standard and, to this end, the Euro 6c revisions decrease the permitted number of particles by and order of magnitude. Furthermore, evidence that vehicle manufacturers' optimisation of their vehicles to perform far better under test conditions than in the real-world and, indeed, to configure some of their emissions control technology to operate only under test conditions has led to the inclusion of emissions under real-world conditions for new vehicles for the Euro 6d revision.

### 5.3.4 Comparison of vehicle $CO_2$ targets and Euro vehicle standards

The key difference between limits on vehicle $CO_2$ emissions and air quality pollutant emissions in Europe are the basis on which they are applied. As described above, $CO_2$ targets currently apply to a manufacturers' production of new vehicles sold across an entire year and the distribution across this is at the manufacturer's discretion. There is no specific limit on how much $CO_2$ a particular model of vehicle may emit as long as the overall year's production is compliant. Incentives for consumers to purchase lower $CO_2$ emission vehicles may be delivered by other means, such as the UK's $CO_2$ linked road tax bands, as well as the implicit link to the cost long term fuel consumption.

In theory, this could place limitation on sales of the number of higher fuel consumption models a manufacturer might be able to sell in a year, which may affect a manufacturer's strategy for production. However, as individual vehicles cannot fail specific $CO_2$ targets, there has been no obvious deployment of defeat devices in test cycles in the manner that has been observed for air quality emissions. Instead, a key question to the effectiveness of $CO_2$ targets is how closely the measured emission in test cycles matches real-world performance of vehicles. Until very recently, most vehicle test cycles consisted of sequential sections of steady state operating, which limited acceleration and therefore engine load within sections. It is only with the advent of the WLTP cycle that a continuously variable cycle has been introduced.

Air quality pollutant emission limits, in comparison are applied on a per-vehicle basis for all vehicles in the same class and engine type: all must meet the requirements for that class, regardless of weight or engine size.

### 5.3.5 Comparison of Euro and ambient air quality standards

The Air Quality Directive sets limits on pollutants that are also covered to a degree by the Euro vehicle emission standards. The way individual pollutants are measured has implications for how they might safeguard health impacts.

Euro vehicle standards differ from annual air quality standards in that they define average emissions over a relatively short drive cycle. In comparison, air quality standards define either limit values on annual average concentrations of pollutants, which they may not rise above, along with higher shorter-term averages, on the scale of hours, which are permitted to be exceeded a limited number of annual times.

*Nitrogen oxides*

Both the Air Quality directive and Euro standards cover emissions of oxidised nitrogen. The Air Quality directive sets limits for $NO_2$ concentration and does not address NO emissions, whilst the Euro vehicle standards limit aggregate emissions of both NO and $NO_2$ and treats neither separately. In terms of assessing contribution to a national emissions budget, both these approaches should produce similar results as NO emitted as a primary pollutant will oxidise in the atmosphere to form $NO_2$ as a secondary substance. The difference between the two standards comes to the fore when short-term speciation of nitrogen oxides at the point of emission is considered. $NO_2$ is the more damaging of the two oxides to human health and a higher concentration of it as a primary emission in exhaust or flue will imply that emissions in close proximity to the source are more damaging to human health than emissions with a larger fraction of the less toxic NO, which will not yet have had time to undergo atmospheric oxidation.

If source characteristics change, the Air Quality Directive places a maximum limit on average hourly $NO_2$ concentrations, which should be able to guard against frequent large build-up of $NO_2$ on the scale of an hour over reasonably large areas. In comparison, the Euro vehicle standards have no safeguard against any rise in the $NO_2$ fraction in the $NO_x$ component of vehicle emissions. Such a rise has been observed in recent years, driven by the introduction of oxidative catalysts in diesel vehicles compliant with Euro III and IV standards. These are non-selective catalysts that are effective at oxidising nitrogen-based compounds to $NO_2$, in addition to undertaking their intended role of converting the carbon-based compounds to $CO_2$. The result is an observed increase in the concentration of $NO_2$ in exhaust gases and in close proximity to major roads than would have been the case has oxidative catalysts not been deployed (Carslaw, Murrells et al., 2016).

This outcome is now being addressed to an extent by the solution of selective catalytic reduction in later Euro standards, as a means to lower $NO_x$ emission in general. This is a technology that uses a reduced nitrogen compound and catalyst to provide reaction pathways capable of reducing both NO and $NO_2$ to molecular nitrogen. Despite this being a very common approach to meeting such standards, it is in no way obligatory and the use of alternative $NO_x$ reduction technologies is still permitted. Consequently, there remains no direct way within vehicle emission legislation to address directly the amounts of primary $NO_2$ being emitted.

*Particulate matter*

Prior to 2011, the primary metric of both Euro standards and ambient air quality standards for particulate matter was the mass of $PM_{10}$, which encompasses all particulate matter of under 10 µm aerodynamic diameter. This included the fine fraction of particles of <2.5 µm in size ($PM_{2.5}$), which are thought to be the more damaging to human health than the coarser fraction of diameters between 2-10 µm.

Efficient filtering or oxidation and condensation of volatile products of this coarse fraction by exhaust aftertreatment can still lead to situations in which a vehicle produces a low overall mass of particulates, but a high number of small, low mass particles. The health impact of such fine particulates would be expected to be proportionately much greater per unit mass than that of particulate emissions is therefore a key factor to account for when considering their health impact and setting appropriate metrics on which to base regulation.

Evidence suggests that, unlike the coarser fractions of particulate matter that tend to be associated with diesel engines, fine (<2.5 µm diameter) and ultrafine (<0.1 µm diameter) particulates are produced from both diesel and gasoline vehicles (Karjalainen, Pirjola et al., 2014). In the former case, the introduction of diesel particulate filters has resulted in a much lower reduction of the finer fractions of particles from diesel exhausts than of more coarse particles and methods are being sought to drive reduction on the remaining ultrafine fraction. The situation is different in the case of petrol vehicles, which had been characterised as having much lower particulate emissions than diesel. In recent years, convincing evidence has emerged of increasing levels of $PM_{2.5}$ emission in the petrol fleet, attributable to greater use of gasoline direct injection (GDI) engines (Bonandrini, Di Gioia et al., 2012). This same evidence suggests that the number of fine particles produced by a GDI petrol vehicle can be an order of magnitude greater than an equivalent diesel vehicle

Ambient air quality legislation and vehicle legislation have approached the fine particulate issue in different ways. From the 1st January 2015, air quality legislation (Directive 2008/50/EC) introduced a 25 $\mu g\ m^{-3}$ limit on the maximum permissible average annual concentration by mass of $PM_{2.5}$ particulates. This is further underpinned by additional requirements to reduce population exposure to $PM_{2.5}$. These take the form of three-year rolling average $PM_{2.5}$ concentration limits of 20 $\mu g\ m^{-3}$, known as “average exposure indicators” (AEIs), which are applied in selected areas of high population density and apply to urban background measurements. This AEI limit must be met from the 2013-15 three-year period and thereafter. There is a further requirement to reduce the AEI with the aim of achieving an AEI of 18 $\mu g\ m^{-3}$ by 2020.

Euro vehicle standards, by comparison, take the approach of placing an absolute limit on the number of particles produced by a vehicle per kilometre. These have been introduced in phases for different classes of vehicles since 2011, with the final set due to enter into force in 2018. By this time, both petrol and diesel light vehicles will be limited to $8 \times 10^{11}$ particles of any diameter per km, in addition to the particulate mass limits.

Particle number limits may have an advantage over mass limits of $PM_{2.5}$, in that they could be more robust against future changes in the size spectrum emitted. However, meaningful enforcement and benefits of particle number limits are only possible to realise if a high enough proportion of particles that have health impacts are detectable. This may be a challenge with current technology. Evidence suggests (Rai and Kumar, 2018) that particle enumeration with current equipment becomes less reliable as the size of particles falls. This would suggest that without equipment capable of enumerating particles regardless of size fraction, there will be an unavoidable uncertainty in quantifying the potential health impacts from particulates in an exhaust emission sample.

Should reliable particle number measurement become available, this may change matters, as any increase in average size would lead to coarser fraction particles being emitted and fewer ultrafine ones, which may be expected to have a lower overall threat to health. Any decrease in size may result in more ultrafine particles being emitted and a downward shift in the size distribution of particles, with many smaller ones being emitted. Whilst this could be more damaging to health, vehicles would still have to comply the overall particle number limit and one would expect to see a notable decrease in the mass of particulates they produced. In comparison, particle mass limits in such a situation may permit the emission of an even greater number of ultrafine particles whilst still complying with regulation.

### 5.3.6 Application of emissions standards to new technologies

The Euro air quality and the EU vehicle $CO_2$ emission standards have evolved in an environment where internal combustion engines were virtually the only type of road vehicle powertrain in use. The introduction of hybrid IC electric vehicles has changed this. It has removed the need for the IC engine to be in operation whenever the vehicle is being propelled and has introduced the possibility of different powertrains operating at different times in a drive cycle.

In theory, the electric part of the powertrain could propel the vehicle at any time that there is enough charge in the battery to do so. However, if the battery is depleted, then it is unlikely that the electric powertrain will be used at all. This raises the likelihood that a vehicle's engine will not operate in the same way on the same part of a laboratory-controlled test cycle in successive test cycle runs. Its exact behaviour in any one run may depend on factors such as battery charge and powertrain architecture. If this is the case, individual test cycle runs may be much less representative of a hybrid vehicle's compliance with emission standards than of a conventional vehicle with only an IC engine. It may also result in even greater divergence between hybrid vehicles' performance in test cycles in comparison to their real-world performance than is currently seen in IC engine vehicles.

This would break a previously reliable relationship between the drive cycle characteristics and power demand from the engine, which underpins the principle of using standard test drive cycles to assess vehicle performance. It is also a principle that underpins assumptions about vehicle emissions in mathematical models used to predict air pollution, fuel consumption and $CO_2$ emissions from transport.

Measurements of how emissions from hybrid vehicles vary in real-world driving situations should allow a better understanding of how applicable current emissions test procedures are to hybrids and should give an indication of the capabilities and limitations of current environmental and energy models to describe them.

# 6. Modelling hybrid vehicle emissions

## 6.1 Overview

This section examines the $CO_2$ and $NO_x$ emissions performance of commonly available production cars with hybrid internal combustion / electric powertrains against conventionally internal combustion engine ones. This choice is based on the availability of easily comparable measurements for these type of vehicles, taken with portable emissions monitoring systems, which were not available for vehicles with other powertrains. It discusses evidence on how accurately emissions models describe hybrid and conventional vehicles and analyses evidence on whether there is a greater challenge in describing hybrid vehicles in air pollution and energy trajectory models than conventional, internal combustion vehicles. Conclusions are drawn on the implications this has for energy technology trajectory modelling.

Internal combustion engine vehicles have higher $NO_x$ emissions under load when compared with cruising, due to the increased rate of fuel combustion needed to meet the increased power demand. This results in greater $NO_x$ emissions from high duty drive cycles, with their frequent sharp changes in velocity and significant acceleration, than from lower duty drive cycles, in which vehicles spend extended periods at the same velocity. If the combustion engine is hybridised with an electric powertrain, it becomes possible to substitute some of the power from the engine under acceleration with power from the electric motor, decreasing the rate of fuel demand from the engine and thus the peak $NO_x$ emissions when acceleration.

The introduction of hybrid vehicles is presented as one approach to addressing the global trends of introducing increasingly ambitious limits on the emissions of air pollutants from road transport and of the drive to decarbonise the energy sector. Hybrid vehicles offer the potential to use hydrocarbon fuels more efficiently and, in the case of plug-in hybrids, to allow transport to take advantage of any decarbonisation of the electricity supply from electricity grids. Cars represent the majority of light transport vehicles in the UK and they produce the largest share of $CO_2$ and air pollutant emissions in the UK transport sector(DfT, 2018d). They are also the vehicle type for which production models with hybrid powertrains have been available for the longest time, with the first hybrid cars appearing in the mid-1990s. They therefore represent the most mature available example of hybrid powertrain technology.

The alternative approach to hybridisation for reducing emissions from cars relies on manufacturers of internal combustion engine vehicles continuing to implement measures to reduce engine fuel consumption and improve the efficacy of exhaust gas aftertreatment. These are verified under controlled test conditions but, as has been discussed earlier, the results are not necessarily replicable in the real-world and there is recent evidence of poor practice by manufacturers in meeting these standards. Furthermore, emission standards only apply to the internal combustion aspect of the powertrain, which results in identical requirements being demanded of both hybrid and non-hybrid vehicles, based on whether the vehicle runs on a compression (diesel-like) or spark (petrol-like) ignition system.

The technology developments in exhaust emissions monitoring technology that allow real-world drive cycle testing are compatible with both hybrid and non-hybrid vehicles. Data from these tests allows direct comparison of the emissions performance of the two types of vehicles. Comparison of this data with the results of vehicle emissions modelling software run against the same drive cycles allows the assessment of how the real-world performance compares with the expected performance of vehicles meeting the same emission standards.

## 6.2 Hybrid powertrains considered

### 6.2.1 Principles of hybridisation

A hybridised vehicle is defined as one that can draw simultaneously on multiple energy sources for propulsion. To date, all production hybrids have relied on the combination of an internal combustion (IC) engine and an electric motor. The degree of hybridisation ranges from "mild" hybrids, where the electric part of the power train assists the IC engine, but cannot propel the vehicle on its own, to "full" hybrids, capable of operating solely on either electric or IC power or on a combination of both. "Mild" hybridisation can provide operational advantages by either boosting maximum power or by allowing a smaller IC engine to be fitted in order to reduce fuel consumption. Full hybridisation allows a wider range of capabilities, including that of being able to operate as a zero emissions (electric) vehicle. In this study, only full hybrid vehicles were tested (Ford, 2018).

There are many ways to configure a full hybrid powertrain and the way that the power from its motors couple to the wheels. The basic hybrid architectures are:

- Series hybrids, where the wheels are driven entirely by electric motors and the IC engine provides power to the wheels indirectly by driving electrical generators to power the motors or charge the battery. Series-only production hybrid vehicles include range extended electrically driven cars, such as the BMW i3 and the TfL's new Routemaster buses.
- Parallel hybrids, which can couple the IC engine to the wheels mechanically at the same time as power is being provided to them from the electric motor.
- Vehicles that can route power from the IC engine via both a parallel and a serial path and which can normally vary the proportion in which this is done, are referred to as "power split" hybrids. These account for most production hybrids and there are multiple approaches on how to configure a power split hybrid powertrain.

Schematics of series and parallel powertrains are shown in Figures 6.1 and 6.2, with mechanical power couplings in mauve and electrical couplings in red.

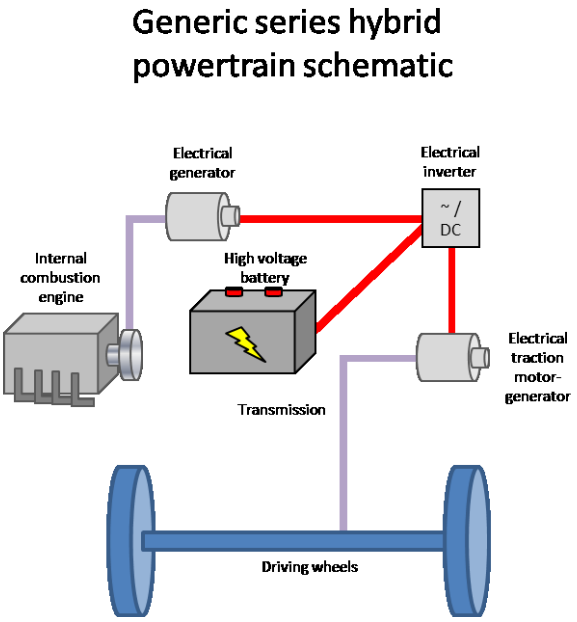


Figure 6.1: Series hybrid powertrain

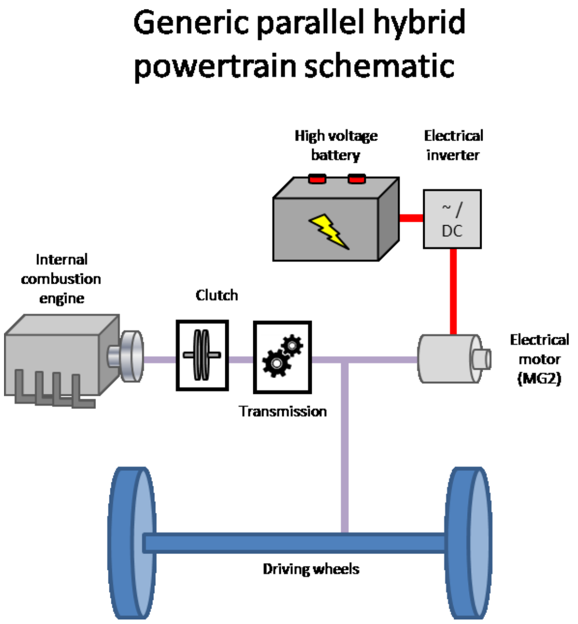


Figure 6.2: Parallel hybrid powertrain

The powertrain approaches taken in this study are as follows:

### 6.2.2 Power split series-parallel hybrid

Cars 1 and 2 considered in this study are based on a split power hybrid powertrain (Fig. 6.3), of a type originally developed by Toyota. A similar approach is used by Ford in some of its hybrids. It has also been used under license in several other manufacturers' hybrids. This integrates an IC petrol engine and two electric motor-generators, mechanically. In the cases above, all three of them permanently mechanically coupled through a single planetary gear set, which delivers torque through reduction gears to the wheels. One motor-generator (MG2 in the schematic) is the electric traction motor, used to propel the car and to charge the battery during regenerative braking. The other motor-generator (MG1) is a starter motor for the IC engine and converts the IC engine's mechanical output to electrical power, both charging the battery and powering the electric traction motor through the series path of the powertrain (Pangaribuan and Purwadi, 2013; Toyota, 2019).

They key differentiators in this approach over other hybrid varieties has been the development of a system that allows power coupling through series and parallel paths in the powertrain simultaneously and in continuously variable ratios. This is enabled by the planetary gear set, which also allows continuously variable gearing ratios to deliver torque to the wheels. The result is a highly flexible system that allows smooth, highly granular energy transfers to take place in all directions across the power plants and energy storage.

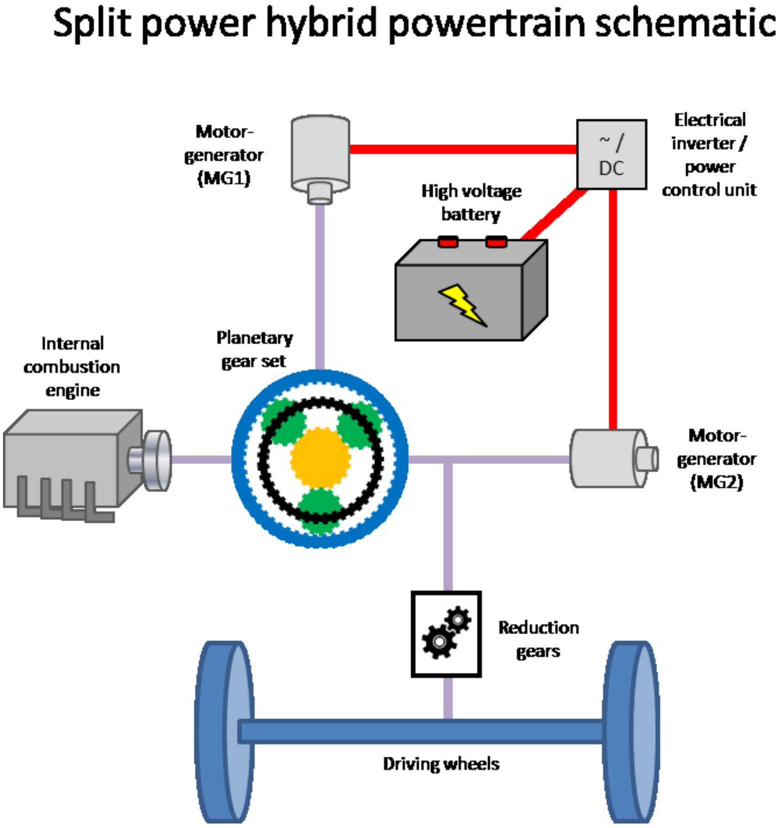


Figure 6.3: Split power hybrid powertrain

This allows, for example, management of the amount of engine power being used to generate electricity (whether for electric propulsion or for battery charging) by MG1 that is independent from the amount of power the electric traction motor MG2 is using. In versions to date, the three main driving modes are:

- Electric propulsion only, used mainly for acceleration from rest and low speeds, as well as low speed propulsion.
- "Cruise" mode, over most of the drive cycle, where engine power is simultaneously coupled to the wheels both mechanically and electrically through MG1 and MG2 in a series path, without recharging the battery. The power distribution between the two paths is varied, with the aim of maximising overall efficiency.
- Rapid acceleration, where the power coupling of cruise mode is used along with the battery providing additional power to MG2.

In addition to these modes the battery can charge by converting the vehicle's momentum to electricity via MG2 (regenerative braking) or by using the engine and MG1.

In theory, the powertrain could also operate in a pure series-hybrid mode, coupling the engine via MG1 to MG2, with no mechanical coupling to the wheels. However, the power control algorithms used by Toyota for power management do not currently use this option and it is not clear whether this would provide acceptable power or energy efficiency for normal road driving.

### 6.2.3 Parallel hybrid

Car 3 is based on a full parallel hybrid system that employs a double clutch system to mechanically couple the engine, a single motor-generator and the driving wheels. Depending on the configuration of the clutches, the electric motor can propel the car on its own, provide an additional boost to the IC engine or charge the battery, either from the engine or by regenerative braking from the wheels. Unlike the split power hybrid architecture, it is incapable of charging the battery from the engine whilst simultaneously providing electric propulsion: the motor-generator can generate or consume electricity, but not do both at the same time. This means that when using the IC engine to propel the car, it must turn at the speed determined by the wheels and the discretely geared transmission. This scenario is likely to result in engine speed and load that have suboptimal efficiency, both for propulsion and battery charging. This parallel architecture may have different energy efficiency than the split power architecture, which offers both an additional series path of power to charge the battery and continuously variable gearing differential.

Literature from the developer of this powertrain, stresses that it is aimed at boosting performance rather than improving environmental impact, but it does note that it allows the acceleration of a larger engine car with a smaller sized engine than would be used in a conventional vehicle. In this case the decrease in size appears to be slightly below 10%, given that Car 3 has a 3.5 litre engine in comparison with the 3.7 litre engine of the non-hybrid version of the same model.

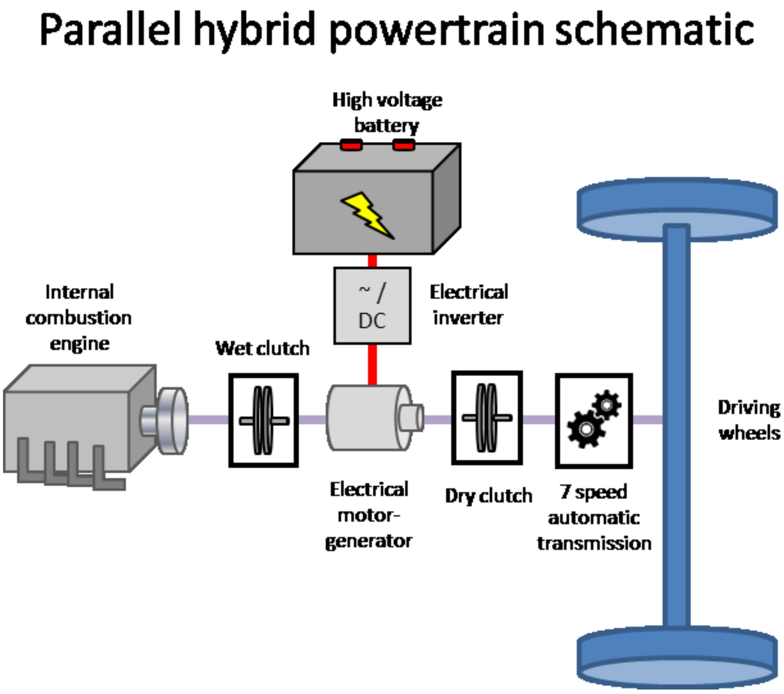


Figure 6.4: Parallel hybrid powertrain

### 6.2.4 “Through the road” (TTR) parallel hybrid

Cars 4 and 5 are based on a variation of a conventional parallel hybrid powertrain where there is no direct coupling between the engine and electric motor driven parts of the powertrain. This architecture implements two entirely separate powertrains: one internal combustion and one electric in the same vehicle, without any power transmission between them within the car itself. The electric powertrain charges itself from the motion of and can drive a separate set of wheels to those driven by the engine. The two systems are still mechanically coupled when all four wheels are in contact with the road, but this coupling is only through the road surface. Charging of the battery in the electric component of the powertrain increases apparent rolling resistance to the IC engine, whilst power assist from the electric motor does the opposite.

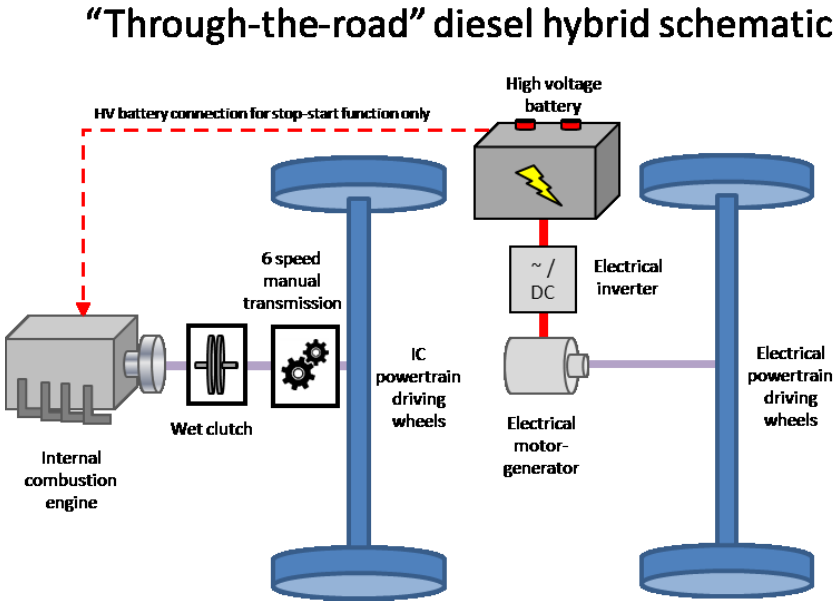


Figure 6.5: Through-the-road parallel hybrid powertrain

This system may have practical advantages in terms of increasing traction, as there are 4 powered wheels on the road surface. However, it introduces an additional limitation over all other hybrid powertrains considered here, in that the battery can only be charged whilst the car is in motion and cannot receive power from the engine when the vehicle is stationary. This may mean that a considerable amount of energy from the engine remains unused. Peugeot literature suggests that the powertrain attempts to mitigate this through an aggressive stop-start strategy. As higher $NO_x$ emissions are associated with the start-up of IC engines than with their uninterrupted operation, it is possible that whilst this approach may indeed limit $CO_2$ emissions, it may do so at the cost of increased $NO_x$ emissions.

### 6.2.5 Plug-in hybrid

Car 6 is the only plug-in hybrid electric vehicle (PHEV) system considered in this study, for which emissions data was available. This allows the battery to be charged from just from the internal combustion engine and from regenerative braking, but also from an external electricity supply. This offers the potential to have the maximum contribution for each journey from the electric powertrain, if a charging source is available and used.

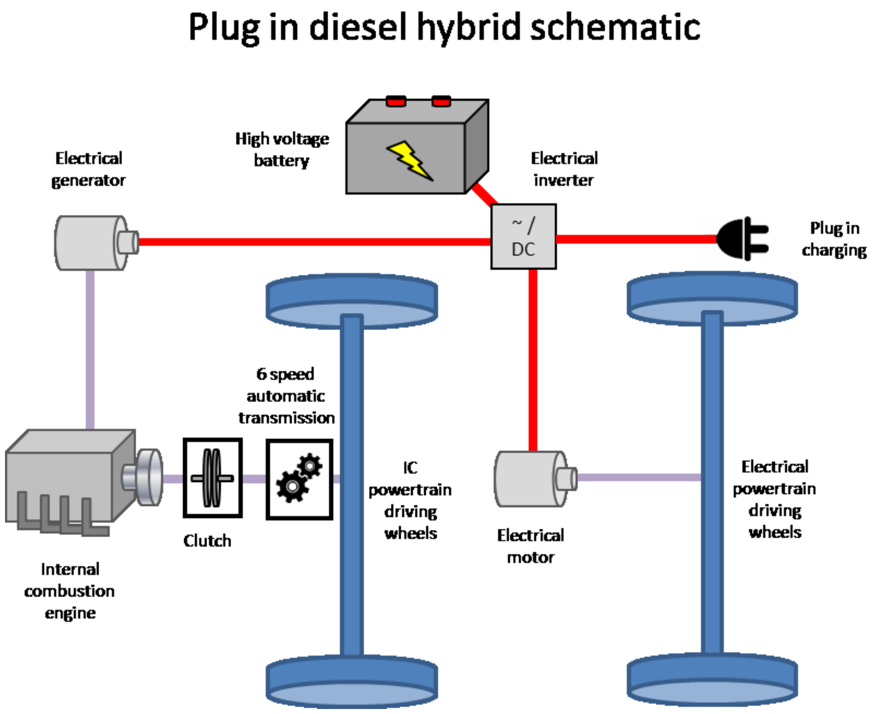


Figure 6.6: Plug-in parallel hybrid powertrain

The specific powertrain used by Car 6 resembles a “through the road” hybrid system, in that the diesel IC and electrical parts of the powertrain drive different sets of wheels. The key difference is that there is also direct coupling between the diesel engine and the battery via a motor-generator that is used to charge the main battery and as a starter motor for the IC engine. This allows charging of the battery from the engine and regenerative braking, although the regeneration energy is captured by the generator from the slowing of the IC part of the powertrain, rather than through the electric motor.

The powertrain allows the vehicle to be propelled solely by the electric part of the powertrain as a "pure electric" vehicle, solely by the IC engine to conserve battery, or by a combination of both. When being driven using only the IC engine, the battery can still charge through the generator. The separation of generator and propulsion motor also allows the IC engine to power the vehicle's electric motor in a series-hybrid manner. This is not equivalent to a full series powertrain, as there is insufficient power to propel the car on its own in this manner. However, it does allow the electric motor to offer supplementary power and traction to the IC powertrain, with the latter delivering a form of 4-wheel drive capability.

## 6.3 Methodology

### 6.3.1 Emissions Analytics PEMS data

Emissions Analytics (EA) is a company that specialises in obtaining real-world measurements of air pollutant emissions and vehicle operation through a lightweight portable emissions monitoring system (PEMS) that can be fitted quickly to a vehicle's tailpipe without the need to modify the vehicle. Currently, the PEMS equipment is configured to sample emissions for $CO_2$, CO, NO, $NO_2$ and total hydrocarbons, using a Sensors Inc. SEMTEC LDV PEMS unit. This is a gas analyser, sample control system and exhaust flow rate meter in a single package, with integral environmental and GPS sensors. Particulates are measured by a Pegasor Mi2 coronal discharge sensor, which can measure particulate mass, surface area and number. In the EA methodology, this is configured to measure total particle mass. The system provides a 1 hz monitoring rate of emissions, location, altitude, air temperature, pressure, humidity and is supplemented by engine data obtained through the vehicle's own on-board telemetry system (O'Driscoll, Stettler et al., 2018).

The result is a system that can be deployed across a very wide range of vehicles to provide a high temporal resolution description of in-service operation. The datasets can be very large and, although discontinuities can occur as the result of transient issues with the sensors, the information yielded is usually both continuous and self-consistent in the equipment used across vehicles.

EA has tested a selection of several hundred Euro 5 and 6 petrol and diesel cars on a limited number of standardised routes in the UK and Germany to provide insight into the vehicles' real driving emissions (RDE) on public roads. These routes include the full range of road types and driving styles proposed for RDE testing to complement controlled condition testing for Euro emission standards. These cover urban, rural and high speed routes, as covered by the RDE recommendations of the Worldwide Harmonized Light Vehicles Test Procedure, as well as the extra-high speed section recommended for testing of vehicles in Europe and other regions with significant distances of highway with high speed limits.

The two main UK-based routes covered urban roads and high-speed sections within greater London and area the surrounding area and the German route was in central Baden-Württemberg. However, EA has not had the opportunity to test most of the vehicles at more than one point in the year, so the data does not account for the full range of seasonal environmental variables included in RDE proposals for the Euro 6d standard.

It should be noted that, at the time of writing, commencement of measurements using a standardised methodology for real-world drive cycle measurements had not yet begun and EA results represent the best data resource available on in service measurement of recent vehicles. Given that Euro 6d will only apply to new vehicles it is likely that EA data will be the only real-world measurements available for some of the older Euro 5 vehicles tested. Furthermore, as real-world conditions driving are inherently variable, individual real-world tests are likely to be unrepeatable and it may be that consistent results for an individual model may only arise possible by comparing behaviour across sets of many, similar, real-world test cycles.

For this study, $CO_2$ and total $NO_x$ (i.e. NO + $NO_2$) were used, along with speed data. GPS data is used to identify the routes covered and allows the identification of road type and terrain, as discussed in this study. For commercial and privacy reasons, actual GPS data is not presented here.

### 6.3.2 iMOVE and COPERT

Predictive modelling of emissions from vehicles in this study has been based on emission factors generated by the COPERT model (**Co**mputer **P**rogramme to calculate **E**missions from **R**oad **T**ransport).

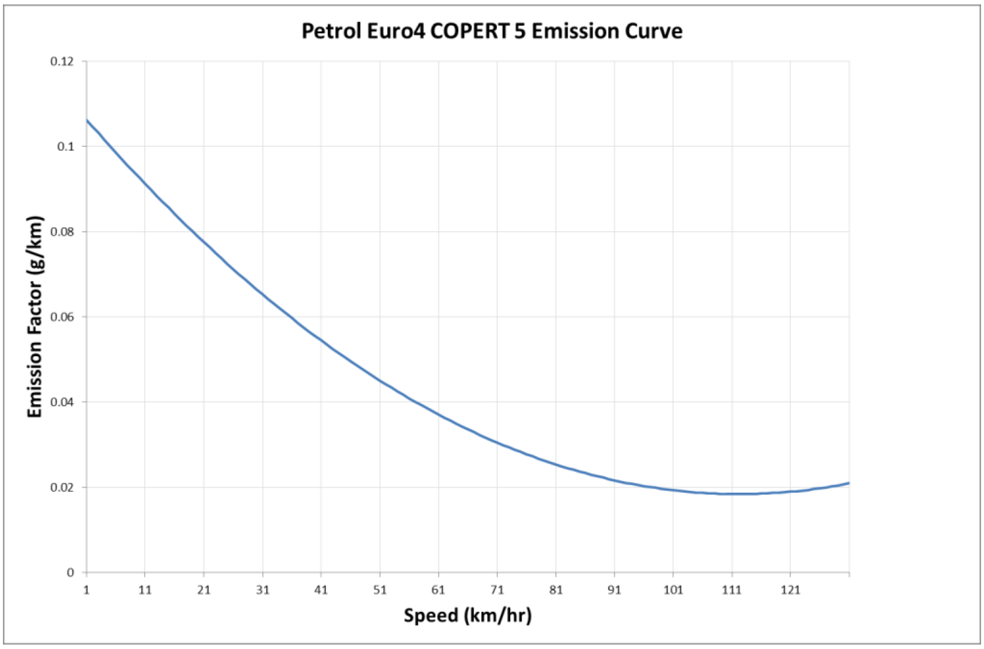


**Figure 6.7: COPERT 5 Speed / $NO_x$ relationship for a Euro 4 Petrol car (Source: T. Oxley)**

COPERT is a tool developed by Emisia, with its scientific development managed by the European Commission's Joint Research Centre. It is intended to provide a standard tool for estimating road transport emissions for reporting in national emissions inventories (Emisia, 2019b). COPERT emission factors are speed dependent functions, defining curves that represent instantaneous emissions in terms of g / km of pollutant as a function of instantaneous speed (Emisia, 2019a). An example of the curve of the function for $NO_x$ emission factors for Euro 4 petrol cars is shown in Figure 6.7.

The UK's inventory of air pollution emissions from road vehicles, used in the National Atmospheric Emissions Inventory, is calculated using COPERT emissions estimation software and UK road traffic data of vehicle types and speeds on different sections of road.

For this study, emission factors based on the predictions of COPERT version 5 for Euro 5 and 6 vehicles for 2015. These form the basis for emissions calculation of iMOVE, a software tool developed at Imperial College London to generate aggregate emission factors and time dependent emission profiles of $NO_x$, primary $NO_2$, $PM_{10}$, $CO_2$, $N_2O$, tyre & brake wear, for theoretical fleets of vehicles (Valiantis and Oxley, 2019).

iMOVE input uses a time series of vehicle speed in one second intervals and fleet composition that is disaggregated by vehicle class (car, light-duty goods vehicle, etc.), engine type by size and fuelling and nominal compliance with Euro standard. The composition can be based on real-world transport statistics and as such may be used in estimating the actual impact of sections of the transport fleet. Alternatively, as in this study, it can be used to describe a fleet consisting of a single vehicle to estimate the expected performance of a car on a particular drive cycle, based on commonly used modelling assumptions.

iMOVE outputs a time series of emissions for the fleet in terms of g/s of pollutant emitted. This is the same format as the data collected by Emissions Analytics PEMS system.

Previous analysis of $NO_x$ and $CO_2$ emissions of Euro 5 and 6 vehicles has been undertaken using EA datasets (O'Driscoll, ApSimon et al., 2016). These have examined average emissions for petrol and diesel vehicles for four classes of vehicle engine size (<1.4 litres, 1.4-1.55 litres, 1.55-2.0 litres and >2 litres) for urban and motorway section of the test route. All but two of the vehicles considered used non-hybrid powertrains. The conclusions were that many of the considered vehicles, especially those with diesel engines, showed emissions markedly higher than COPERT 5 predicts.

### 6.3.3 Modelling

Modelling was undertaken by the author for eight vehicles from Emissions Analytics' datasets. The aim was to provide consideration of the behaviour of hybrids at a more detailed level than drive cycle or road type averages, to examine how the vehicles' behaviour within the drive cycles varied between powertrain and hybridisation types and to consider how these compared to COPERT emissions predictions, based on the real-world velocity traces.

The vehicles chosen were all cars: three petrol hybrids, three diesel hybrids (one of which was a plug in hybrid) and two diesel non-hybrids. The characteristics of these are:

| Vehicle | Engine Size (litres) | Fuel | Hybrid powertrain | Euro standard |
|---|---|---|---|---|
| **Car 1** | 1.8 | Petrol | Full power split | 5 |
| **Car 2** | 1.8 | Petrol | Full power split | 6 |
| **Car 3** | 3.5 | Petrol | Full parallel | 5 |
| **Car 4** | 2.0 | Diesel | Full parallel TTR | 5 |
| **Car 5** | 2.0 | Diesel | Full parallel TTR | 5 |
| **Car 6** | 2.4 | Diesel | Full parallel plug in | 5 |
| **Car 7** | 2.2 | Diesel | None (IC Diesel) | 6 |
| **Car 8** | 2.0 | Diesel | None (IC Diesel) | 6 |

**Table 6.1: Vehicles used for PEMS datasets.**

The speed profiles against time for each of these vehicles were extracted from the EA data and these were used in iMOVE to generate profiles of emissions for $NO_x$, $CO_2$ and primary $NO_2$ against time for Euro 5 and 6 vehicles of equivalent engine size and fuel type, using COPERT 5 emission factors. Each pollutant was then compared for each vehicle to their real-world emissions, as measured by EA.

The data were disaggregated into sections of different driving style, usually characterised by the road type or the impacts of congestion. Examples of these are provided in Figure 6.8. Conventional driving is defined as driving with low (<90 kph) average speeds and / or an aggressive drive cycle with frequent accelerations and decelerations. Motorway driving is defined as those sections of the drive cycle at which the vehicle consistently averaged 90 kph or over for an extended period, with little or no acceleration or deceleration. This approach differs from the World Light-duty Test Cycle definitions of motorway driving, which sets a higher average speed threshold for what is considered to be a European-style motorway. Whilst it is non-standard, it is representative of real-world driving in EA's data on motorway class roads: grade separated, multi-lane dual carriageway with a speed limit of at least 110 km/h.

The most popularly used route in this study's sample, used in whole by five of the vehicles (Cars 1,4,6,7 and 8) and in part by one (Car 5), involves covering the same set of roads around London and southeast England once in each direction. This facilitates comparison in vehicle behaviour and leads to some of the vehicles being subject to identical sections of terrain twice. Urban terrain on this route is relatively flat with gradients of roughly 0.5% - 1%. Extra-urban terrain varies from this to gradients of around 4%-5% on the main carriageways and up to 11% on structures such as slip roads and exit ramps.

Car 2 follows a different route in Germany but completes it twice. The second lap commences around 7200 s into the drive cycle. About half of this route, including the high-speed sections, are similar in terrain to the urban routes around London, about one quarter of around 1%-5% gradient, whilst another quarter frequently included gradients of between 5%-10%.

Only Car 3 followed a non-repeating route. The characteristics of this resulted in motorway sections having similar terrain to that encountered by Cars 1,4,6,7 and 8: usual gradients of 0.5%-1% with maximum gradients of around 5%. The final extra urban section was much more level, with gradients rarely exceeding 0.5%.

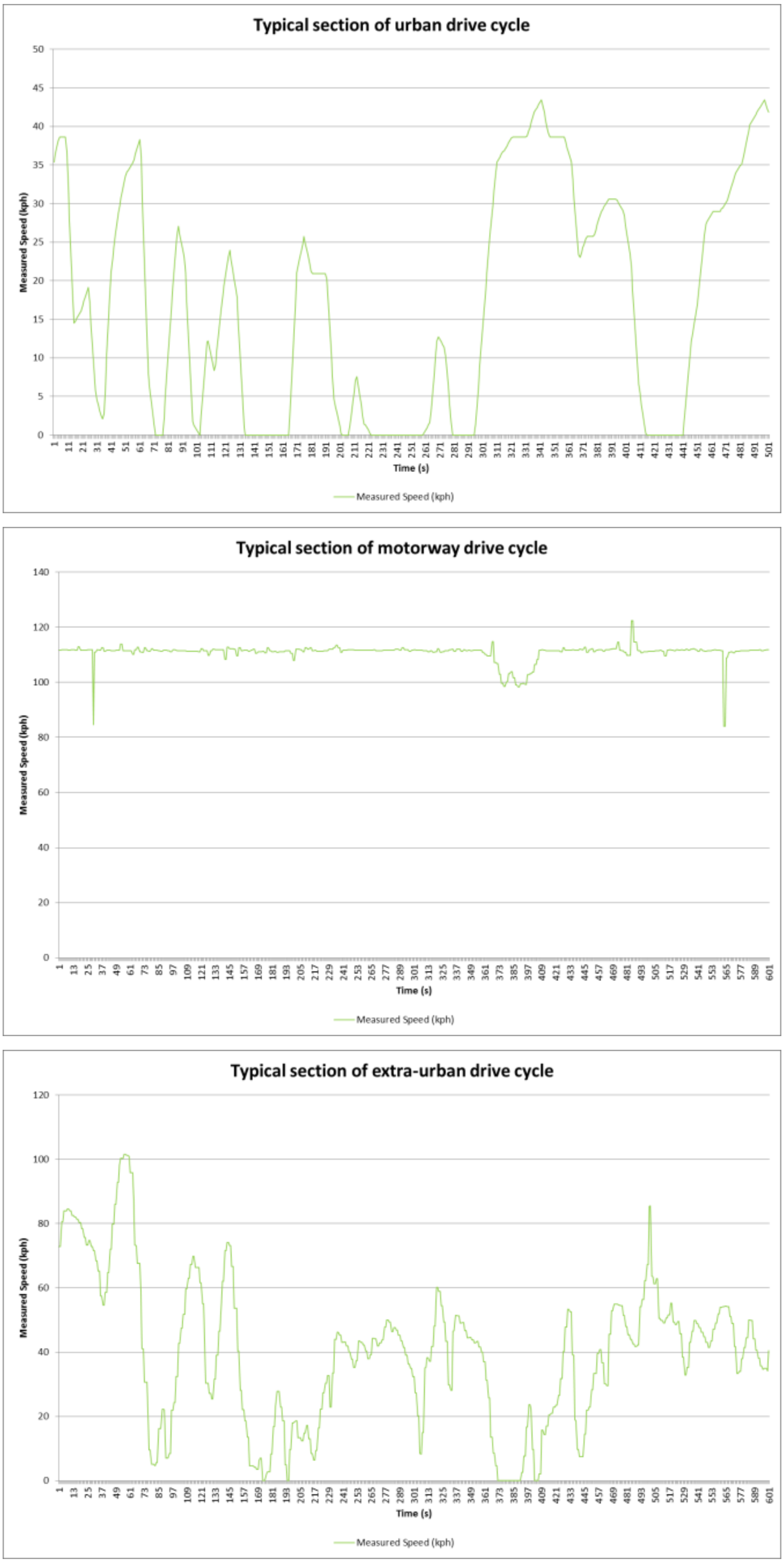


**Figure 6.8 Characteristic examples of drive cycle sections**

Where drive cycles consisted of an out and return portion of the same route, with a short stop during the middle of the motorway portion, this stop was included in the motorway drive cycle.

Conventional driving was further sub-categorised into urban and extra-urban driving, with extra-urban driving being defined by being those non-motorway sections of the drive cycle in which the typical urban speed limit of 50 kph is regularly exceeded. These can be characterised by accelerations at speeds or duration not found in urban driving and at a frequency not found in motorway driving. The result is a drive cycle that may demand more overall power than an urban cycle and that will certainly demand power at different combinations of gear ratios and engine loads than urban driving.

The PEMs systems used by Emissions Analytics record emissions by mass per unit time (g/s). These were converted to mass per unit distance data based on trip average and average of individual sections of the drive cycle.

### 6.3.4 Presentation of emissions graphs

*Emissions per km with time*

The petrol fuelled vehicles considered were two 1.8 l engine power split hybrids (cars 1 and 2) and one 3.4 l engine fully mechanically coupled parallel hybrid (car 3).

Due to the nature of measurement in terms of emission per unit distance, emissions are highly variable from vehicles that are near stationary and, in theory, may be infinite per km when a vehicle is at rest and the engine is still running. In a real-world situation, emissions per unit distance at very low average speeds are arbitrary and are affected by whether the car is truly stationary for the entire section, as opposed to making slow and sporadic manoeuvres; whether or not the vehicle is able to operate on a purely electric powertrain if such manoeuvres are taking place; and whether the vehicle is configured to operate a “stop-start” system that switches off the engine when it is truly stationary. For this reason some of the section averages for emissions appear off the scale of the graphs.

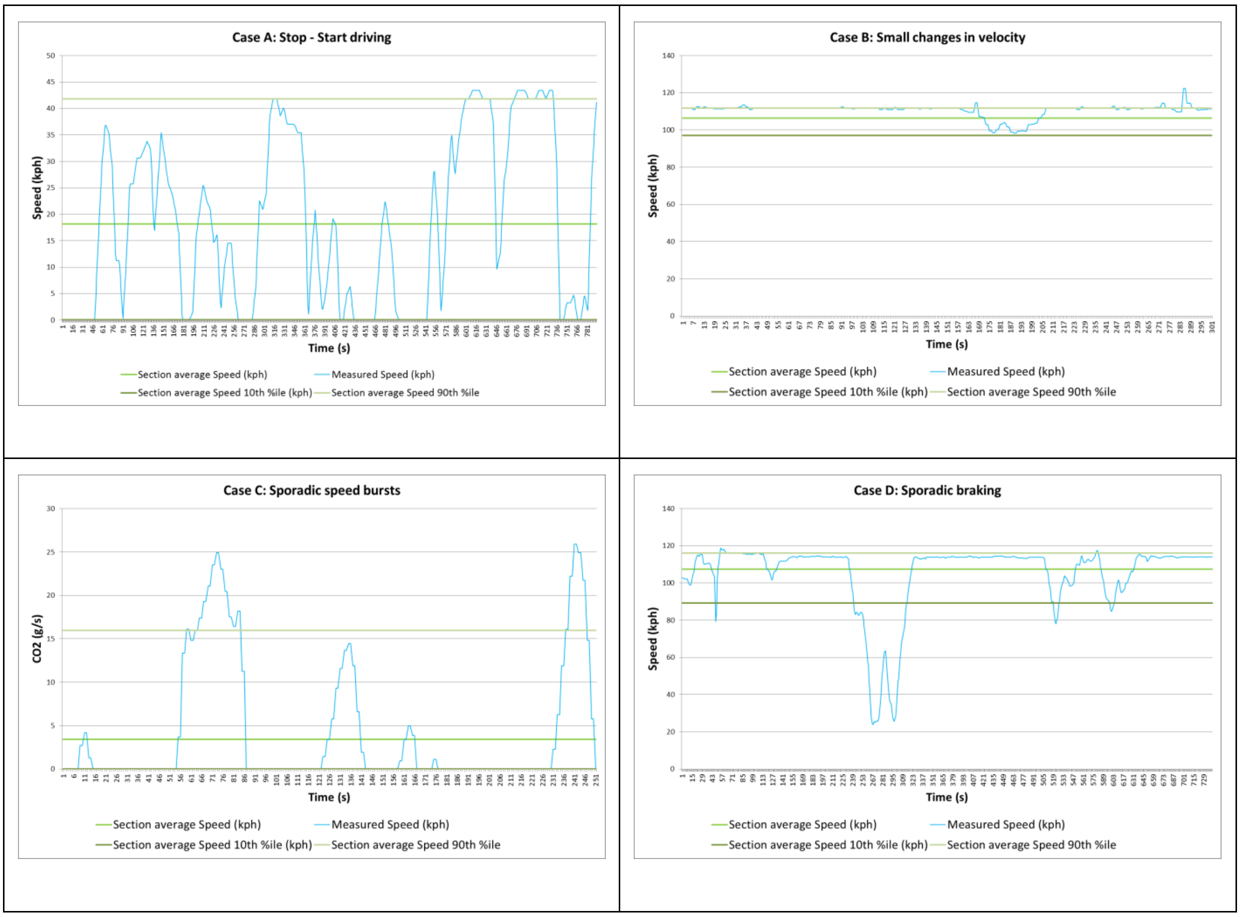


**Figure 6.9: Examples of driving styles**

Although EA's speed data measurement at a rate of 1 hz was used as source data, the complete speed vs time traces cannot be presented here due to their commercially sensitive nature. Instead, average speeds for each section are provided, accompanied by 10th and 90th percentile values for the speed measurements. These give an indication of both the intensity of the drive cycle section (how much the speed varies around the mean) and the asymmetry of the distribution of speed maxima and minima around the mean, as shown in Figure 6.9. A wide 10th – 90th percentile range, with a very low 10th percentile and 90th percentile of around twice the average speed is likely indicative of frequent and intense acceleration and braking, with sudden stops and starts; a low 10th – 90th percentile range indicates less aggressive changes in speed, or at least relatively small changes in relation to the average cruising velocity for the section. An average speed that is much closer to the 90th percentile than the tenth indicates a section with generally constant velocity, interrupted by sporadic braking, whilst one with an average close to the 10th suggests a section with low average velocity and sporadic but short bursts of speed.

*Rate of emissions with time*

Average $NO_x$ and $CO_2$ emission rates in g/s with time are presented for each drive cycle section. All $NO_x$ plots for diesel engine vehicles are shown to the same scale, although this is not practical for the petrol engine vehicles, due to the greater degree of variation in emission levels. As with emissions per unit distance plots, the average speed and 10th – 90th percentile ranges are used to illustrate speed and drive cycle intensity for each section of each route.

The first standard deviation above the mean is provided as a measure of distribution of the measurements. Only the positive standard deviation is plotted, as the wide range of speeds in many parts of the drive cycle often results in the first standard deviation below the mean being negative.

The plots demonstrate that, as with rates per unit distance, rates of $NO_x$ and $CO_2$ emission per unit time of individual vehicles can vary greatly between similar sections of the drive cycle on similar types of road. This is counter to the fundamental assumptions of modelling in COPERT, as well as common software packages used for assessing air pollution impact, which assume a dependable relationship of vehicle engine sourced emissions with speed (Ricardo-AEA, 2014; Emisia, 2019a). Furthermore, differences in the rate of $NO_x$ and $CO_2$ emissions are seen varying between similar sections of a vehicle's drive cycle in different manners, with increased emission rates of one not always coincident with increases in emission rates for the other.

Cold start emissions

Cold start emissions are included on the plots with time for both g/km, g/s and cumulative emissions. The reason for this is to demonstrate the magnitude of these with respect to normal operation and the difference that a cold start can make to the overall emissions for a journey of an IC engine vehicle.

## 6.4 Results

### 6.4.1 Car 1

**Car 1 (Petrol power split hybrid) 1.8 litre Euro 5**

| Drive cycle | Average speed (km/h) | Section length (km) | Average $NO_x$ Emissions (mg/km) | Average $CO_2$ Emissions (g/km) |
|---|---|---|---|---|
| **Cold start emissions (before emissions control starts working)** | 10.1 | 0.26 | 1258.2 | 691.1 |
| **Urban** | 18.3 | 4.03 | 16.8 | 166.6 |
| **Motorway** | 92.5 | 47.5 | 7.2 | 165.7 |
| **Urban** | 22.8 | 23.3 | 2.6 | 115.1 |
| **OVERALL (Excluding cold start)** | 42.1 | 75.1 | 6.1 | 149.3 |

**Table 6.2:** Drive cycle average section emissions per km for Car 1.

Car 1 exhibited cold start emissions before its engine and emission control catalyst were at normal operational conditions. $NO_x$ emissions per km during this period around 2 orders of magnitude greater than peak $NO_x$ in any drive cycle sections with normal operation conditions, even accounting for the relatively low speed. The highest emissions for both $NO_x$ and $CO_2$ were seen for around 200 s, before they fell. These still remained relatively high relative to the majority of the drive cycle for the first 1000 s. The initial high emissions appear to be typical of a conventional cold start, with a rapid improvement in engine performance as it approaches normal operating conditions within the first 200 s, leading to a rapid fall in both $NO_x$ and $CO_2$.

The initial cold start is be followed by a more gradual fall in $CO_2$ emission in the first urban section, together with a proportionally greater reduction in $NO_x$. Following this, the $NO_x$ emissions per km are higher on the motorway section than the subsequent urban section.

Car 1 follows a fairly low speed drive cycle in non-motorway sections, with speeds rarely exceeding 40 kph. Peaks align with acceleration across the drive cycle and emissions are low, with non-urban sections typically peaking at around 2 g/s – 3 g/s $CO_2$ with occasional peaks of 5 g/s – 6g/s $CO_2$. Both pre-motorway urban and motorway sections exhibit very frequent peaks of roughly 0.25 – 0.5 mg/s $NO_x$, followed by almost as frequent, but much smaller peaks in the post-motorway section.

When average rates of emissions are considered, a higher average rate of $NO_x$ production (80 µg/s) occurs during the pre-motorway urban sections, up to 1000s into the drive cycle, than it does afterwards (17 µg/s), although the rate at which $NO_x$ is produced is still much higher in motorway sections (180 µg/s) . Both the pre-motorway urban and the motorway sections exhibit very frequent peaks of roughly 0.25 – 0.5 mg/s $NO_x$, which leads the observed standard deviation of 320 µg/s and 350 µg/s $NO_x$ respectively. This followed by almost as frequent, but much smaller peaks during the subsequent urban section with an average standard deviation of 60 µg/s $NO_x$.

The proportional change in $CO_2$ emissions in the urban sections before and after the motorway driving is much lower than that of the $NO_x$ rate, suggesting that the majority of the cold start effects of engine fuel efficiency have abated by 200 s into the drive cycle, but that $NO_x$ abatement measures are not yet fully effective: potentially the emissions control system has not yet reached optimal operating temperature.

Analysis of cumulative emissions against time for Car 1 and comparison to the emission predictions of iMOVE, using COPERT 5 emission curves, demonstrates that over most of the journey the rate of $NO_x$ production is considerably lower than might be expected of a conventional Euro 5 petrol vehicle of similar engine size. $NO_x$ is produced at a considerably greater rate on the high-speed motorway section than the lower speed one.

Whilst cold start emissions are not normally included in conventional testing procedures, they are presented on the cumulative emission to highlight the fact that they produce around half the total trip $NO_x$ for Car 1. Although the hybrid system appears to be effective in minimising $NO_x$ emissions in normal operation in comparison to predictions against conventional vehicles, it does not appear to be capable of reducing cold start emissions: regardless of when a hybrid vehicle switches from purely electric drive to using its engine, the first time it does so in its journey will result in a cold engine start. According to DfT transport statistics, the 75 km trip length of Car 1's drive cycle is considerably longer than the current average car trip in Great Britain, where only around 6% of all car trips are over 40 km in length (DfT, 2016a). This high contribution of cold start $NO_x$ in a relatively long journey suggests that in scenarios with high adoption of hybrids, cold start emissions may potentially be a greater proportional contributor to the remaining contribution of cars to the UK's $NO_x$ emissions budget.

Closer scrutiny of Car 1's drive cycle reveals that during the second urban section, Car 1 covers an identical 6.85 km section of route twice, which allows for exact comparison of performance over the same route. The same type of drive cycle is followed in both sections, with similar frequencies and rates of acceleration, similar average speeds of 24.3 kph for the first lap and 22.8 kph for the second lap and almost identical 90th percentile speeds of 41.8 kph. Despite this similarity, the $NO_x$ emissions fall considerably between the first and second lap from 4.9 mg/km and 33.1 µg/s to 1.4 mg/km and 8.6 µg/s.

$NO_x$ peaks are synchronised with acceleration and those on the first lap are in the order of two to three times greater than those on the second lap. $CO_2$ emissions are seen to follow a similar pattern.

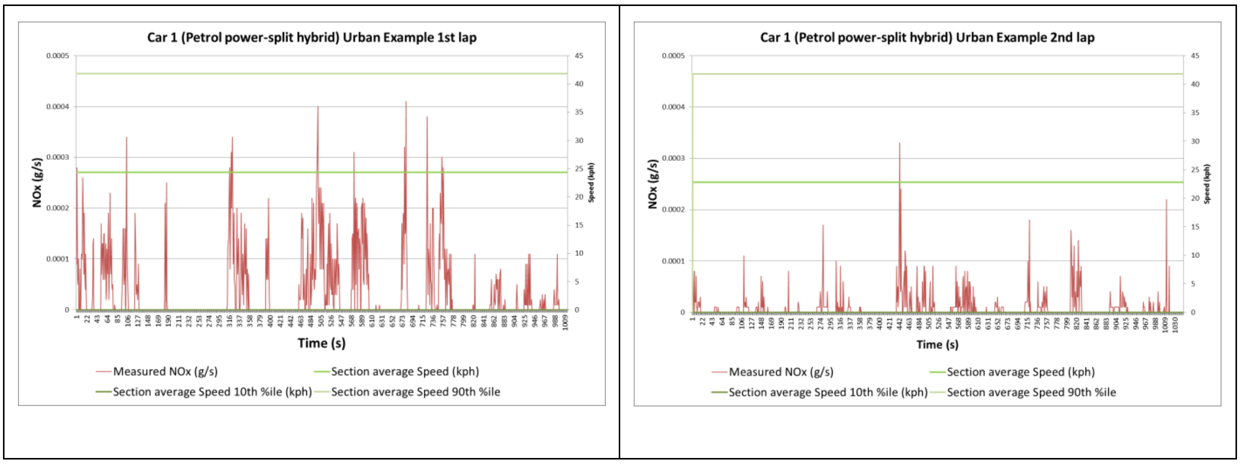


**Figure 6.10 Comparison of $NO_x$ peak frequency and maximum for identical urban sections of Car 1**

A plausible cause for this fall in intensity of $NO_x$ peaks over time would be a growing contribution to peak power demand by the electric part of the powertrain, as the drive cycle progresses. $NO_x$ emissions increase with engine load and the use of electrical power to reduce peak engine demand can reduce peak $NO_x$ emissions. An increase in electrical contribution could arise if the battery was in a relatively low state of charge at the beginning of the drive cycle and was gradually recharged from the engine and regenerative braking, increasing the amount of peak reduction. This would explain the shifts in $NO_x$ seen both between first and second urban sections in general and the former and latter laps examples from the second urban section.

Car 1's behaviour is a key comparator with Car 2, as both share the same basic powertrain architecture. Nonetheless, Car 1 performs as if its battery is increasing its charge state along its route, whilst Car 2 behaves as if it is decreasing charge state. Plausible causes for this include differences in the power control algorithms of the vehicles or the intensity of the drive cycle. In terms of drive cycle intensity, Car 2 is subject to higher frequencies of acceleration than Car 1 which occur, for some sections of the drive cycle, across greater speed ranges than Car 1. The power demand on the engine is therefore likely to be greater for Car 2, which would likely correspond to a higher demand for power assistance from electric motor. If this power is delivered at a rate faster than the battery can charge, the battery would discharge to a point at which power assist would be unavailable. The lower duty drive cycle followed by Car 1 would be more likely to result in lower demand for power assistance and may offer greater opportunity for the battery to recharge.

Understanding the actual variation in battery state of charge, the degree to which battery depletion affects emissions and the relevance of these effects to Cars 1, 3 and 6 would require real-world monitoring of the electrical side of the powertrain during real-world PEMs tested drive cycles. The Emissions Analytics tests did not include this instrumentation at the time of testing and this prevents any clearer conclusions to be drawn over the fact that these vehicles emissions vary in a manner that is unlikely to be observed in non-hybrid vehicles.

### 6.4.2 Car 2

**Car 2 (Petrol power split hybrid) 1.8 litre Euro 6**

| Drive cycle | Average speed (km/h) | Section length (km) | Average $NO_x$ Emissions (mg/km) | Average $CO_2$ Emissions (g/km) |
|---|---|---|---|---|
| **Urban** | 39.1 | 4.8 | 0.55 | 45.5 |
| **Extra urban** | 74.8 | 25.8 | 0.71 | 105.9 |
| **Motorway** | 124.2 | 16.6 | 0.25 | 206.2 |
| **Urban** | 4.9 | 0.62 | 3.12 | 249.1 |
| **Extra Urban*** | 48.8 | 28.5 | 7.13 | 112.3 |
| **Motorway** | 99.5 | 22.6 | 0.53 | 114.4 |
| **Urban** | 29.9 | 7.00 | 18.55 | 96.0 |
| **Stationary** | 0 | 0.008 | 0 | 0 |
| **Urban** | 29.3 | 4.73 | 0.39 | 41.4 |
| **Extra Urban** | 74.1 | 26.2 | 1.13 | 101.6 |
| **Motorway** | 101.4 | 16.2 | 2.39 | 142.7 |
| **Urban** | 10.7 | 1.91 | 55.92 | 168.3 |
| **Extra Urban*** | 52.93 | 27.8 | 48.81 | 127.0 |
| **Motorway** | 99.5 | 22.8 | 1.00 | 106.2 |
| **Urban** | 26.3 | 6.0 | 56.21 | 87.9 |
| **OVERALL** | 55.6 | 205.6 | 10.7 | 118.0 |

**Table 6.3: Drive cycle average section emissions per km for Car 2 (* denotes high duty cycle)**

Car 2’s drive cycle consists of two laps of the same route, the first lap running up to about 6300 s and the second running from about 7000 s in to the drive cycle. Overall, Car 2 tends to maintain low levels of $NO_x$ emissions of below 20 mg / km on most sections of the drive cycle. There are clear, very notable exceptions of greater $NO_x$ emissions per km on the second lap of its route, which increase by up to a factor of 5 in comparison to the same sections on the first lap. This is highly noticeable in the sections after 9000 s into the drive cycle. The differences occur despite maintaining similar speeds and, in the case of the final section of each lap, having a marginally lower duty drive cycle on the second lap than the first.

The increases in average $NO_x$ per km are not reflected in the $CO_2$ emissions, which show proportionally much smaller changes. The changes in $CO_2$ averages are not always reflected in those for $NO_x$. A small increase in $CO_2$ is seen in the corresponding sections between 4500 s - 6200 s in the first lap and 10080 s – 11800 s, where $NO_x$ emissions per km increase by a factor of around 5; $CO_2$ emissions decrease in the final lap between the first and second laps, whereas $NO_x$ emissions per km increase by a factor of around 2.5.

Car 2 tends to emit $NO_x$ in the pattern of much sparser peaks of $NO_x$ under acceleration than Car 1, but these peaks tend to be higher in the case of Car 2. In the early part of the drive cycle, these are relatively sparse and reach maximum values of around 10 mg/s $NO_x$, as can be seen in the low average value and standard deviations of $NO_x$ emission rate, but these increases in frequency after around 9000s into the drive cycle and reach peaks of 50 – 60 mg/s $NO_x$, driving an increase in the average and standard deviation of $NO_x$.

Car 2, has the same 1.8 litre size engine and hybrid architecture as Car 1 and produce similar peak $CO_2$ emissions over similar sections of drive cycle (up to 500 s, between 5200 s and 6200 s and after 12700 s) of between 4 g/s and 6 g/s $CO_2$. There are no comparable sections in Car 1’s drive cycle for the high duty cycle extra-urban drive sections seen in car 2’s sections between 2760 s – 4710 s and 10000 s – 11890s, but it is notable that, whilst the frequency of $CO_2$ peaks appears to be the same, the maximum emissions rate of these peaks are somewhat higher. The earlier peaks typically occur between 5 g/s – 9 g/s $CO_2$ and the later ones between 6 g/s – 14 g/s $CO_2$.

The normal motorway sections, of around 110-120 kph produce similar looking traces, with Car 2's emissions centred around 4 g/s $CO_2$ and Car 1's around 5 g/s $CO_2$ and. However, the very high-speed section of 150 kph that Car 2 undertakes between 1650 s – 2200 s produces typically around 9 g/s $CO_2$ and peaks of up to 15 g/s $CO_2$: a much greater proportional increase in $CO_2$ emissions than speed.

The discontinuities in Car 2's emissions behaviour also is clear when cumulative emissions are considered. The gradient of $NO_x$ emissions increases sharply in some of the final sections of the drive cycle. Overall, the cumulative (and thus trip average) emissions of $NO_x$ are still much less than are predicted by iMOVE's COPERT 5 based predictions, but the amount of $NO_x$ emitted after 10000 s into the drive cycle is larger than iMOVE would predict, whilst it is a small fraction of iMOVE's predictions in other sections. $CO_2$ emissions are much closer to iMOVE predictions, with overall performance across the drive cycle being slightly less than predictions, mainly due to very low $CO_2$ emissions in the low speed sections of the drive cycle up to the 10000 s point.

| **Lap 1** | **Cumulative $NO_x$ (g) at start** | **Cumulative $NO_x$ (g) at finish** | **Total $NO_x$ (g)** | **Cumulative $CO_2$ (g) at start** | **Cumulative $CO_2$ (g) at finish** | **Total $CO_2$ (g)** |
|---|---|---|---|---|---|---|
| **2nd Extra Urban** | 0.02694 | 0.23034 | 0.2034 | 6506 | 9712 | 3206 |
| **Final Urban** | 0.24236 | 0.37201 | 0.12965 | 12291 | 12964 | 673 |
| **Lap 2** | | | | | | |
| **2nd Extra Urban** | 0.17776 | 1.53175 | 1.35399 | 5491.413 | 9015.393 | 3524 |
| **Final Urban** | 1.55722 | 1.89139 | 0.33417 | 11431.666 | 11953.859 | 522 |

**Table 6.4: Comparison of differences between Car 2 key drive cycle sections in each lap.**

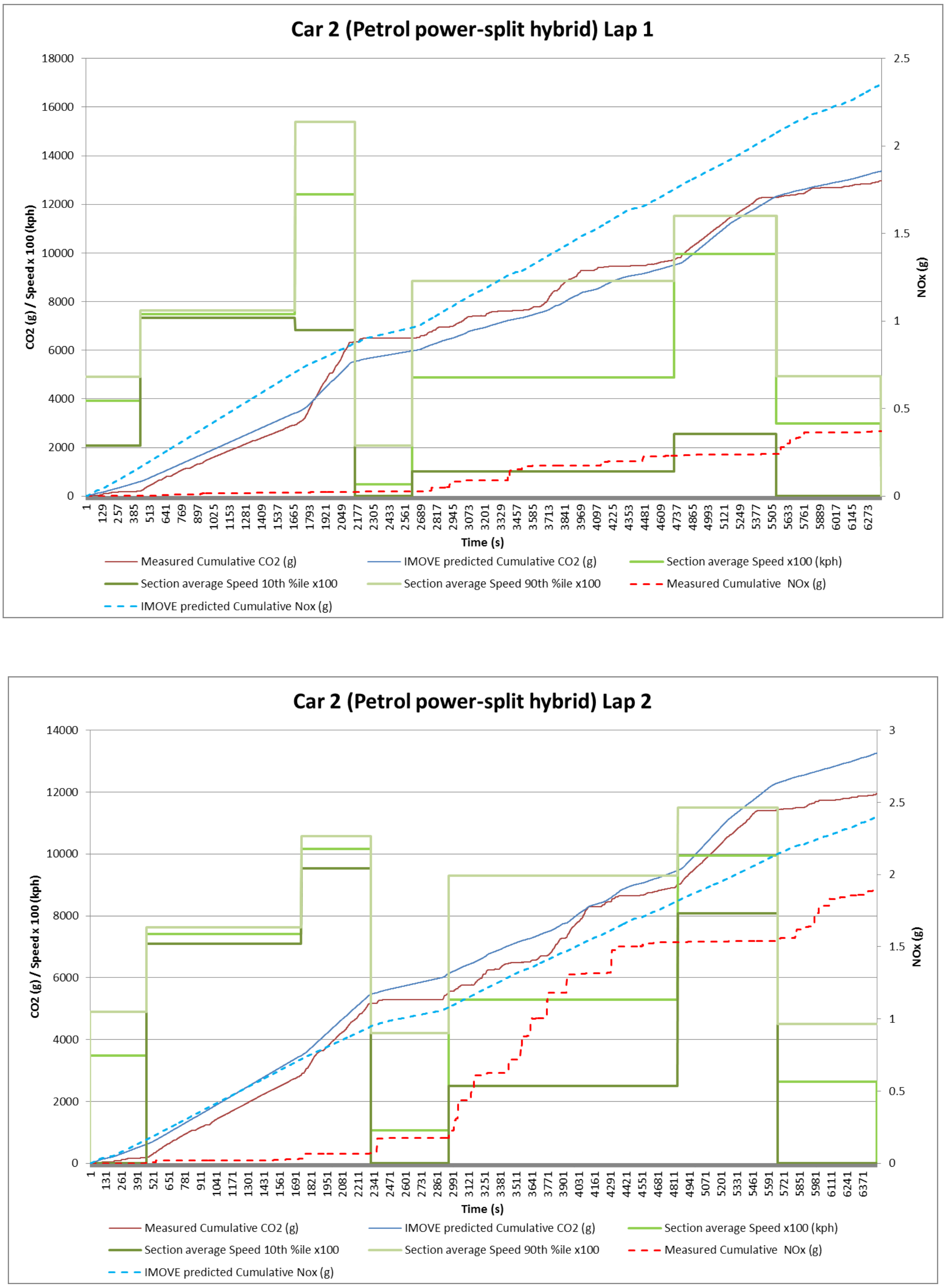


**Figure 6.11 Cumulative emissions of the two laps of Car 2's drive cycle.**

Comparing the two laps of Car 2's drive cycle shows a much steeper increase in cumulative $NO_x$ emissions on the second lap than on the first. The major differences show most clearly in the second extra urban sections (starting at around 2600s on Lap 1 and 2900s on Lap2) and the final urban section (5100 s on Lap 1; 5650 s on Lap 2). These are matched by smaller, synchronised increases in $CO_2$ emission, and thus fuel consumption.

The roads covered in the same section for each lap are identical and do not differ greatly for corresponding sections, as can be seen from the speed data, average speeds and variability in speeds. Yet, the overall $NO_x$ emissions of the second extra-urban section of road are around 0.20 g $NO_x$ for the first lap and 1.35 g $NO_x$ for the second lap; for the last urban section, they are 0.13 g for the first lap and 0.33g for the second lap. This is an increase of 6.7 on the extra-urban section and 2.5 for the urban one.

The emissions per second graphs in figure 6.23 also show a significant increase in average emissions over the two sections above on the second lap. Average $NO_x$ emissions on the extra urban section rise from 96.7 µg/s to 718 µg/s and on the last urban section of each lap from 154 µg/s to 614 µg/s. In both cases, the standard deviation of the $NO_x$ values is a smaller proportion of the mean level of emissions than the first lap. Despite this reduction of the proportional difference between mean and standard deviation, the peak $NO_x$ values seen in these sections of the second lap, which reach around 60 mg/s $NO_x$ at times, are considerably higher than the 20 mg/s $NO_x$ peak values seen on the first lap.

An increase in frequency and maximum value of the $CO_2$ peaks is also seen in the second lap, despite the relatively small change in average $CO_2$ emissions in these sections.

The difference suggests that factors beyond speed, acceleration and driving environment are able to have a significant impact on the $NO_x$ emissions of a hybrid vehicle of this design. These factors may also appear to only be weakly linked to fuel consumption, as the increase in $NO_x$ emissions does not seem to be matched by a corresponding increase in average $CO_2$ emissions, but is coincident with a moderate increase in the standard deviation.

A possible influence on the increase in $NO_x$ emissions could be an increase in engine load on the second lap. This could arise if the state of charge of the battery decreases during the drive cycle sufficiently for the power controller to reduce the maximum level of power assistance that the electric side of the powertrain will provide to the engine. This load could be increased further if the power controller draws on the electrical motor when driving to also recharge the battery whilst propelling the car, supplying power to the wheels and the batter charging generator simultaneously.

Figure 6.12: $NO_x$ and $CO_2$ profiles for Car 2 on an identical extra urban section of each drive cycle lap.

An alternative, but related, influence could be if the slightly increased average speed and power intensity of the drive cycle in the sections in the second lap exceeds the overall capacity of the electric side of the powertrain to deliver assistance. Such a change in pattern could explain an increase in the greater frequency and maximum value with which $NO_x$ peaks occur in these high emission sections of drive cycle. However, it would not explain why higher rates of $NO_x$ emission are not seen in Lap 1 on sections of road with a significantly higher speed and drive cycle intensity in Lap 1 than in Lap 2, such as that covered between 1700 s – 2100 s and 8800 s -9300 s in the drive cycle.

It is unclear whether either of these suggested influences or a combination of both are driving the increase in $NO_x$ emissions. The $NO_x$ increase is very large, suggesting that marginal effects on engine operation are not the dominant cause. Understanding these causes would likely be assisted by further real-world drive cycle testing with additional monitoring of state of charge of the battery and power flows to and from the motor-generators.

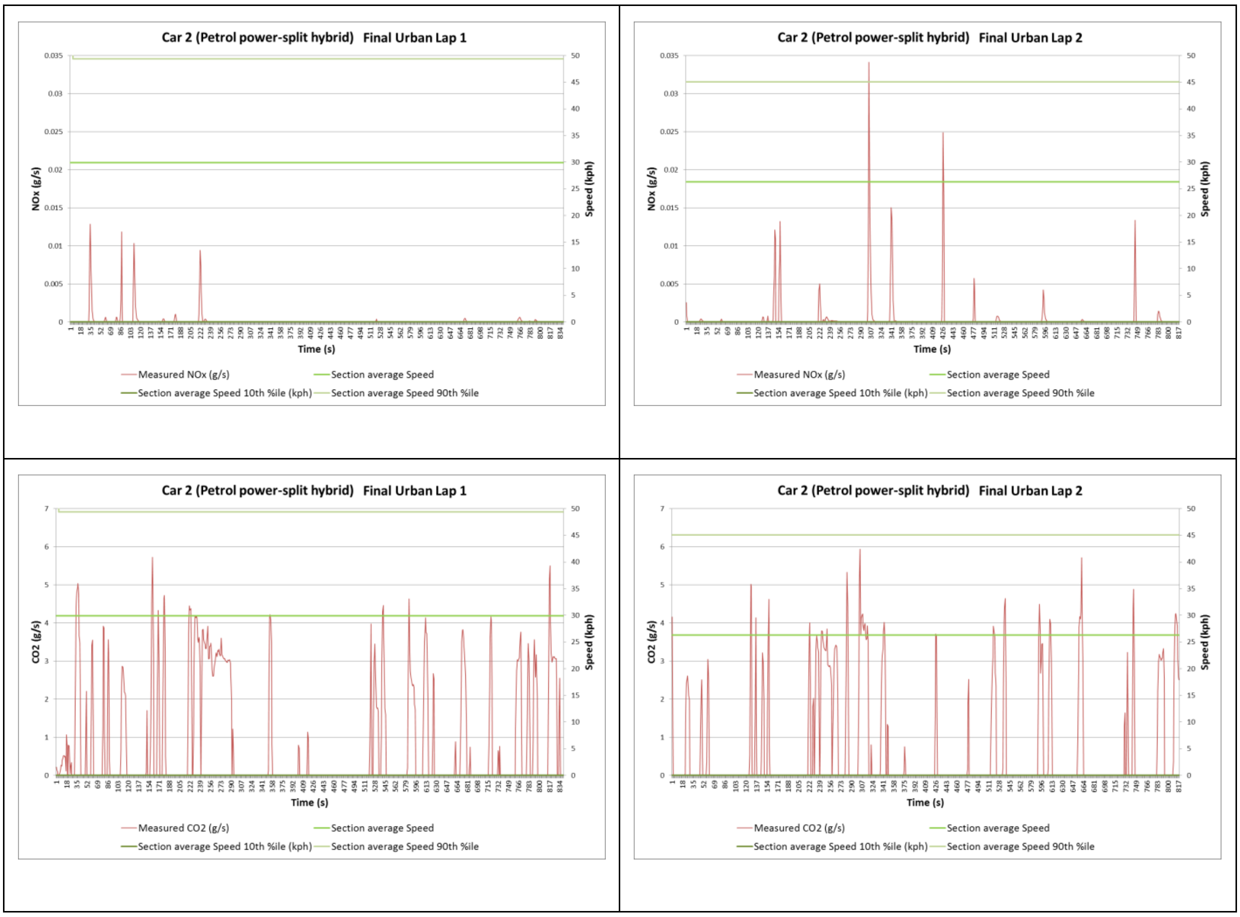


**Figure 6.13: $NO_x$ and $CO_2$ profiles for Car 2 on an identical urban section of each drive cycle lap.**

Predicting when such changes in behaviour might occur would require a more in-depth understanding of the power control algorithms of Car 2. Despite this, some inferences can be drawn from the fact that the car does not seem to be producing high frequency, high amplitude $NO_x$ peaks during motorway sections and that all the clusters of $NO_x$ peaks appear after high speed sections of the drive cycle, either in urban or extra urban sections. This can be seen in the detailed emission traces of the final urban section of the first lap (Figure 6.23, top left) where the car has just completed a motorway section. Here, a dense cluster of high $NO_x$ peaks occurs just after the car transitions to an urban style of driving, which lasts for about a quarter of that section. This is masked by the graphs displaying section average $NO_x$ levels, but it can be seen in the detailed excerpt from the emission measurements presented here. Again, this would be consistent with the vehicle drawing on, but not recharging the battery during high speed driving sections and then drawing on engine power to propel the car and allow charging of the battery whilst driving on slower sections.

If this is the case, it implies that emissions from Car 2's powertrain depends heavily on the state of charge of the battery, as well as factors such as speed and acceleration.

### 6.4.3 Car 3

**Car 3 (Petrol parallel hybrid) 3.5 litre Euro 5**

| **Drive cycle** | **Average speed (km/h)** | **Section length (km)** | **Average $NO_x$ Emissions (mg/km)** | **Average $CO_2$ Emissions (g/km)** |
|---|---|---|---|---|
| **Stationary** | 2.0 | 0.15 | 0 | 333.3 |
| **Cold start emissions (before emissions control starts working)** | 30.1 | 0.84 | 266.7 | 333.7 |
| **Urban¤** | 32.0 | 0.21 | 3.0 | 558.2 |
| **Urban** | 45.1 | 11.0 | 7.0 | 207.1 |
| **Extra Urban** | 79.6 | 11.8 | 2.6 | 138.3 |
| **Motorway** | 106.5 | 52.4 | 3.7 | 159.4 |
| **Extra urban*** | 48.08 | 12.5 | 18.2 | 154.0 |
| **Urban (congestion)** | 3.4 | 0.32 | 0.3 | 84.2 |
| **Extra urban** | 34.2 | 3.33 | 3.2 | 206.0 |
| **OVERALL (Excluding cold start)** | 63.83 | 92.6 | 8.3 | 165.8 |
| **¤Not statistically significant – too few data points.** | | | *** denotes high duty cycle** | |

**Table 6.5:** Drive cycle average section emissions per km for Car 3.

Car 3, like Car 1, exhibits cold start emissions, which are included in the plots below. Like Car 1, these are at least two orders of magnitude greater than normal running emissions and persist for between 100 s -200 s. Unlike Car 1, the $NO_x$ emissions fall and stabilise before the $CO_2$ emissions do. Once these have decreased, $NO_x$ emissions are around 3 mg / km with the notable exception of an extra high duty section of drive cycle between 3600 s – 4900 s where $NO_x$ emissions per km increase by a factor of around 6 to 18.2 g / km.

$CO_2$ emissions are less variable with speed and duty cycle then $NO_x$ emissions and, after stabilising, vary between 100 – 200 g / km, with no increase in emissions between 3600 s – 4900 s to correspond with the increase in $NO_x$ emissions.

When the rate of $NO_x$ emissions is considered, the remaining petrol hybrid (car 3) also has much sparser, more intense $NO_x$ peaks than Car 1, with extremely low levels of emissions between these. Mostly these peaks vary between 1 – 4 mg/s $NO_x$, but occasionally reach 10- 20 mg/s $NO_x$. Where these occur, they coincide well with sharp, extended accelerations with changes in velocity of over 40 kph, but there are some parts of the drive cycle where such accelerations occur without any appreciable $NO_x$ increases. These can be seen between about 600 s – 700 s, and 4200s – 4800s into the drive cycle.

Cumulative emissions plots for Car 3's drive cycle show that the cold start emission are again a significant contributor to $NO_x$ emissions, accounting for around one quarter of the total $NO_x$ from the trip. Like Car 1's drive cycle, Car 3's falls into the longest 5% of car trips taken annually in the UK. Were this a trip to be closer in length to the current UK average, the overall amount of $NO_x$ emitted during the cold start would be the same and the contribution of cold start $NO_x$ to overall trip emissions would be even greater.

$NO_x$ emissions appear to be significantly lower for most of the drive cycle than iMOVE would predict, with the overall gradient of the $NO_x$ emission trace being notably lower than that the iMOVE predicted one. However, that there are a number of points where $NO_x$ emission is considerably greater than the predicted case, corresponding to the intense extended accelerations. Furthermore, the overall gradient of the $NO_x$ trace in higher speed sections is greater than that of the low speed sections which, between 750 s – 1250 s and 4600 s – 4900 s appear almost flat. If cold start emissions are discounted, the overall emission of $NO_x$ across the drive cycle are roughly one third of those that iMOVE would predict.

$CO_2$ emissions performance matches iMOVE predictions much more closely, with similar rates of $CO_2$ emission as predicted occurring on lower speed sections and greater rates of prediction occurring on higher speed sections. Car 3 finishes this drive cycle having emitted around 15% more $CO_2$ than iMOVE predicts.

Overall, Car 3 has a highly varied drive cycle, but exhibits greater consistency in emissions between similar sections of drive cycle than Car 1, Car 2 or Car 6. A key point made in the manufacturer's literature on the characteristics of the hybrid is that the powertrain is configured with a bias to using the electrical part of the powertrain to boost the peak acceleration of the vehicle, rather than to mitigate the engine load during acceleration. This would appear to imply that the battery is used in a more limited manner to reduce load and emissions at speeds and accelerations where the engine is able to produce adequate power. The electrical side of the powertrain should therefore be used much more to provide additional power at speeds or accelerations where the engine is inefficient (e.g. accelerating from rest) or where the power demand exceeds the engine output (e.g. high acceleration at any speed).

This is consistent with the observed behaviour of the average vehicle emission varying much more in the pattern of a conventional internal combustion engine vehicle than a power spilt hybrid. A notably aspect of this is that there is no mechanical reason for a parallel hybrid vehicle to be constrained to this strategy, which draws attention to the significant role that powertrain management software must play in hybrid vehicles' emissions. In principle, a change in software version in a service, or even a user-initiated switch in powertrain management mode can change the behaviour of a hybrid vehicle significantly. Whilst the influence also applies to modern conventionally engine vehicles, which often come with different driving modes, the scope for change in emission levels and their distribution throughout the drive cycle (and thus their geographical location) is greater for hybrids.

### 6.4.4 Car 4

**Car 4 (Diesel parallel TTR hybrid) 2.0 litre Euro 5**

| Drive cycle | Average speed (km/h) | Section length (km) | Average $NO_x$ Emissions (mg/km) | Average $CO_2$ Emissions (g/km) |
|---|---|---|---|---|
| **Stationary** | 0 | 0 | 0 | 0 |
| **Urban** | 22.3 | 4.12 | 918.2 | 174.6 |
| **Stationary** | 3.0 | 0.05 | 2983 | 447.4 |
| **Motorway** | 98 | 49.3 | 618.8 | 149.8 |
| **Urban** | 29.4 | 3.82 | 205.4 | 48.8 |
| **Stationary** | 0.007 | 0.004 | 2908 | 874.4 |
| **Urban** | 3.7 | 0.076 | 700.0 | 178.6 |
| **Urban** | 26.7 | 11.2 | 829.3 | 150.2 |
| **OVERALL** | 51.0 | 68.6 | 649.5 | 146.0 |

**Table 6.6: Drive cycle average section emissions per km for Car 4.**

Car 4 shows significantly greater consistency between drive cycle sections than the petrol hybrids (Cars 1,2, and 3) or the plug-in diesel hybrid (Car 6). This is in terms of similarity of $NO_x$ and $CO_2$ emissions between similar drive cycle sections, but also in similarity in how $NO_x$ and $CO_2$ emissions increases and decreases across the various drive cycle sections: these mirror each other much more closely than in the other hybrid vehicles considered here.

When emission traces are studied, Car 4 produces higher and more frequent instances of $NO_x$ peaks than the conventional diesels. These peaks are between 30 mg/s – 50 mg/s $NO_x$ in non-motorway and 50 mg/s – 200 mg/s $NO_x$ in motorway conditions. The peaks before the motorway section are of roughly the same range of $NO_x$ production and of frequency of occurrence as those after.

The first and final urban sections of the drive cycle have very similar mean and 90% ranges for speeds, matched with means and standard deviations of rate of $NO_x$ emissions of around 6 mg per second and 16 milligrams per second respectively. Means and standard variations of rate of $CO_2$ are likewise similar, at around 1.1 g/s and 2.7 g/s respectively. Car 4 has non-motorway $CO_2$ peaks of between 5 g/s – 10 g/s but tends to emit less than 4 g/s $CO_2$ for most of the non-motorway drive cycle. Motorway emissions are roughly 5 g/s $CO_2$, with peaks between 10 g/s – 20g/s $CO_2$. $CO_2$ emissions also fall to zero when in motion for extended durations, such as between 3025 s and 3089s.

There is one exception. Car 4's second section of urban cycle has very similar average speeds and 90% intervals to the first and last, indicating a similar drive cycle in terms of speed and duty cycle. The lowest rates of $NO_x$ emission within this section covers relatively flat terrain (average gradients of -0.4 % to 4%). However, the rate of $NO_x$ emission is around one third of the other two urban sections, with much lower standard deviation.

Changes in the rate of $CO_2$ emissions follow a similar pattern, as do changes in $NO_x$ and $CO_2$ emissions per kilometre. In the instantaneous emissions data for this section, $NO_x$ peaks are considerably lower than the first and final urban sections. This shows a clear, but brief deviation from the overall trend for this powertrain for relatively speed and acceleration dependent $NO_x$ emissions.

One possible explanation for this brief anomaly in Car 4's behaviour is that the battery could have been in low state of charge at the start of the drive cycle with the engine providing most of the energy for the car's propulsion, then recharged during the motorway section. This is enough energy to the battery for the electric part of the powertrain to then play a significant role immediately afterwards in limiting engine load, after which the powertrain management returns to its more usual behaviour.

Car 4's cumulative emissions reflect the replicability of emissions behaviour across similar sections of drive cycle and the appreciable level of increased rate of emissions with increases speed. Comparison with iMOVE COPERT 5 predictions suggests it matches the expected behaviour of a conventional Euro 5 IC diesel. Motorway driving leads to $NO_x$ emissions very similar to those predicted to iMOVE. Whereas there is some variation between real-world and predicted $NO_x$ in specific parts the non-motorway sections, overall emission for these sections are also very similar. Non-motorway $CO_2$ emissions are very similar to those predicted for a conventional Euro 5 diesel, although Car 4 produces about 50% more $CO_2$ on the motorway sections than would be predicted for a conventional diesel of this Euro class.

### 6.4.5 Car 5

**Car 5 (Diesel parallel TTR hybrid) 2.0 litre Euro 5**

| Drive cycle | Average speed (km/h) | Section length (km) | Average $NO_x$ Emissions (mg/km) | Average $CO_2$ Emissions (g/km) |
|---|---|---|---|---|
| **Urban** | 37.2 | 16.9 | 1082 | 158.2 |
| **Motorway** | 107.5 | 51.2 | 996.1 | 169.6 |
| **Extra Urban** | 50.214 | 6.86 | 1169 | 154.1 |
| **Motorway** | 91.6 | 15.4 | 1030 | 167.3 |
| **Urban** | 18.1 | 4.73 | 567.6 | 104.7 |
| **OVERALL** | 47.9 | 95.0 | 1008 | 162.8 |

**Table 6.7:** Drive cycle average section emissions per km for Car 5.

Car 5 shares the same hybrid powertrain architecture as Car 4 and, like Car 4, it shows significantly greater consistency between drive cycle sections than the petrol hybrids (Cars 1,2, and 3) or the plug-in diesel hybrid (Car 6). It also exhibits the same similarity of $NO_x$ and $CO_2$ emissions between similar drive cycle sections and between changes in rates of emission of the two pollutants.

The changes in average speed of the two urban sections has a marked effect on $NO_x$ which falls by about 45% in terms of g/km and 60% in terms of rate of emission for a 50% reduction in speed.

Car 5 produces peaks of 60 mg/s – 100 mg/s $NO_x$ in non-motorway conditions in drive cycle sections before the motorway and around 20 mg/s – 55mg/s $NO_x$ after the motorway, with peaks of around 50mg/s – 175 mg/s $NO_x$ occurring on the motorway. The higher peaks in the former appear to be linked to the more intense drive cycle, as shown by the greater difference in mean and first standard deviation. The frequency, as well as the intensity of $NO_x$ peaks falls after the motorway sections.

Car 5 has more frequent and higher $CO_2$ peaks than Car 4 on the non-motorway and motorway sections, rising to peaks of about 10 g/s $CO_2$ in non-motorway conditions and around 14 g/s $CO_2$ in motorway conditions. It is also notable that between 4500 s and 5000s into Car 5's drive cycle the frequency and height of the peaks falls for a while to less than 4 g/s $CO_2$ compared to earlier non-motorway performance.

Cumulative emission graphs highlight the lack of major discontinuities in the rates of emission within the drive cycle sections and between similar sections. Car 5 produces lower overall emissions of $CO_2$ and $NO_x$ than the COPERT 5 based iMOVE predictions suggest, with real-world $NO_x$ and $CO_2$ emission both being around 60% of those predicted. This improved performance is present for the whole drive cycle: the proportional difference in gradients of real and predicted curves for both substances appears to be constant across all sections.

Like Car 4, the mean and standard deviations of emissions change very much more in proportion to changes of speed than those of the other hybrids considered here. This suggests that the “through-the-road” hybrid powertrain behaves more like a conventionally engine car than power split or parallel plug-in variants and that, whilst the exact average relationship may vary, the use of current speed-dependent emission factors may match TTR hybrids more closely than the other hybrid architectures considered here.

### 6.4.6 Car 6

**Car 6 (Diesel plug in parallel hybrid) 2.5 litre Euro 5**

| Drive cycle | Average speed (km/h) | Section length (km) | Average $NO_x$ Emissions (mg/km) | Average $CO_2$ Emissions (g/km) |
|---|---|---|---|---|
| **Urban** | 21.9 | 25.2 | 103.2 | 25.3 |
| **Extra Urban** | 58.9 | 3.27 | 490.5 | 74.7 |
| **Motorway** | 99.9 | 43.0 | 611.3 | 148.5 |
| **Urban** | 37.0 | 9.21 | 472.1 | 101.6 |
| **OVERALL** | 42.7 | 80.7 | 434.1 | 102.0 |

**Table 6.8:** Drive cycle average section emissions per km for Car 6.

Car 6's drive cycle displays two very different sets for characteristics. Up to around 4100 s into its drive cycle it shows consistently low average $NO_x$ emissions per km. This is followed by a sharp increase by a factor of around 4 for average emissions before and after its high speed section, despite the speeds and terrain of these sections being similar, with an even higher average emission per km for the high speed motorway section.

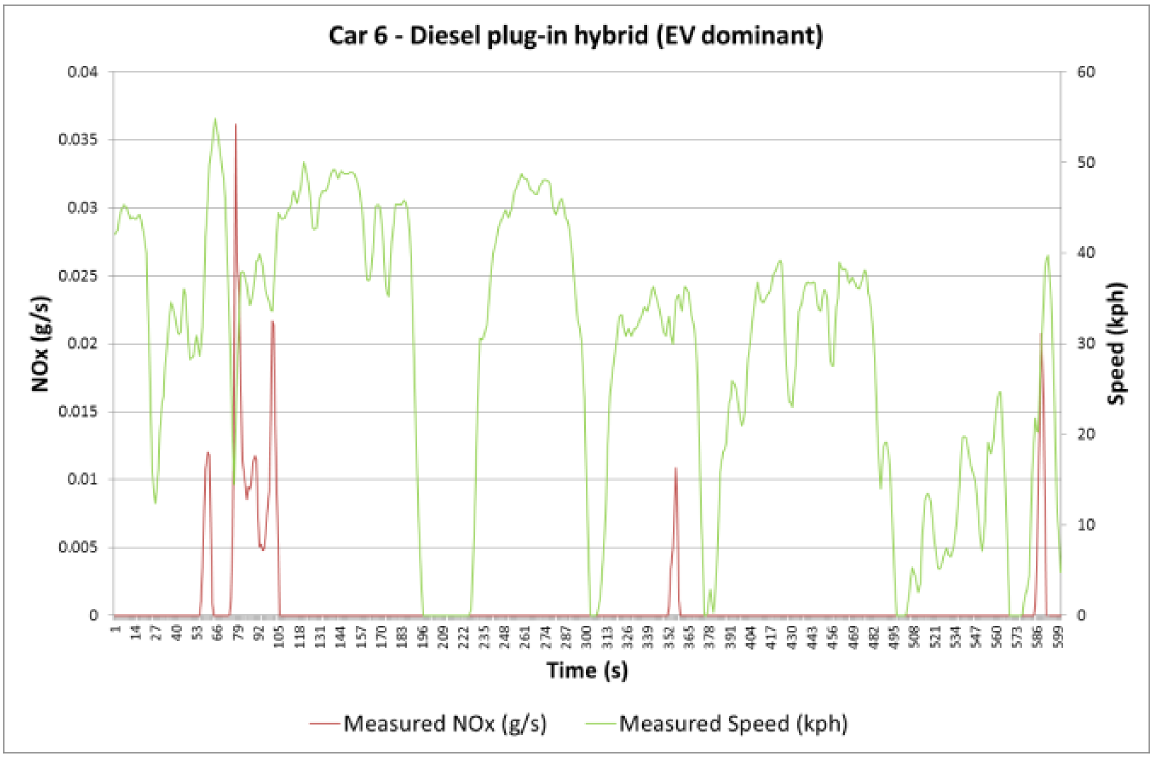
Rates of $NO_x$ emissions in the first section of non-motorway driving remain mostly zero, interspersed by a small number of peaks of between 10 mg/s and 40mg /s $NO_x$. This leads to the very low average and standard deviation for $NO_x$ emissions in this section respectively of around 1 mg/s and 4mg/s. The most likely explanation for this would be if the vehicle is using the electric part of the powertrain for a large proportion of its motive power and is using the battery, rather than the engine to provide this.

The frequency of peaks increases significantly once motorway driving commences and reaches around 80 mg/s – 200 mg/s $NO_x$. Following the motorway section of driving, the $NO_x$ peak frequency remains high, with peaks around 25 mg/s – 50 mg/s $NO_x$. If assumptions about an earlier dependency on electric power is correct, this change in behaviour may be explained by the battery becoming depleted and the control systems switching to the engine as the main source of power.

A high dependency on the electric side of the powertrain is also consistent with the extended period of near zero $CO_2$ emissions during the first 4100 s, interrupted by only a few peaks of up to 8 g/s $CO_2$ up to the motorway section, when emissions then rise to roughly 5 g/s with peaks of up to 16 g/s. Following this, the second non-motorway section of the drive cycle is much more like that of Car 1, with peaks of up to 16 g/s and typical emissions of around 4 g/s.

Car 6 is a clearer case of a hybrid vehicle changing between an operating regime dominated by electric propulsion and one relying much more on engine power. The drive cycle starts with a period of very low, but non-zero average $NO_x$ emissions of 0.6 mg/s. This arises from an extended period of operation with zero emissions, which would be consistent with the vehicle operating using the purely electric side of the powertrain. For the purposed of this study, this behaviour is therefore termed “EV” (electric vehicle) dominant. Zero emission propulsion is interspersed with some very short periods of what appears to be regular engine operation, with $NO_x$ peaks appearing very briefly that generally reach around 0.1-0.2 g/s and $CO_2$ peaks following the shape and timing of the $NO_x$ emission trace. This detail is not visible in the average figures of section speed and emissions data, so limited excerpts of this part of the drive cycle are shown in Figure 6.44.

This EV dominant behaviour occurs within the first of two urban sections of drive cycle, with frequent acceleration and deceleration between rest and 50 kph. There appears to be no reliable relationship between either the emissions and the vehicle’s acceleration or speed, as can be seen in the excerpts of the urban drive cycle in Figure 6.46. When emissions are occurring, peaks appear to coincide with acceleration, but there is no clear speed or acceleration pattern of when emissions will occur during this part of the drive cycle and when they will be zero.



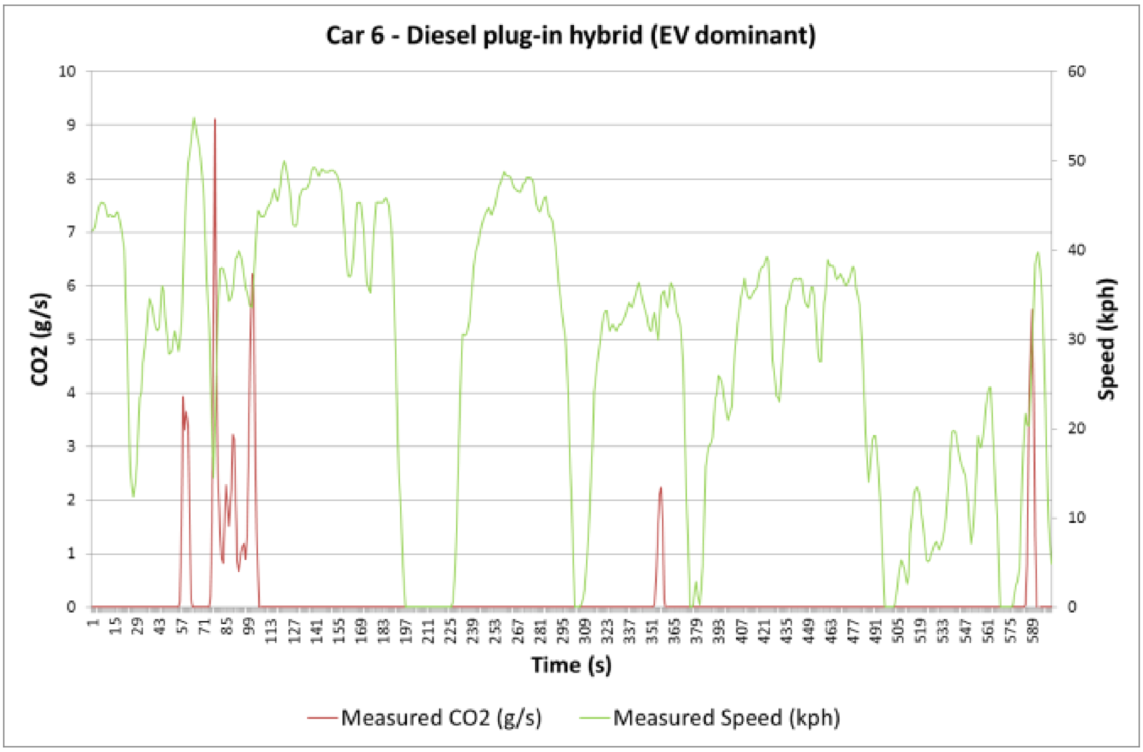
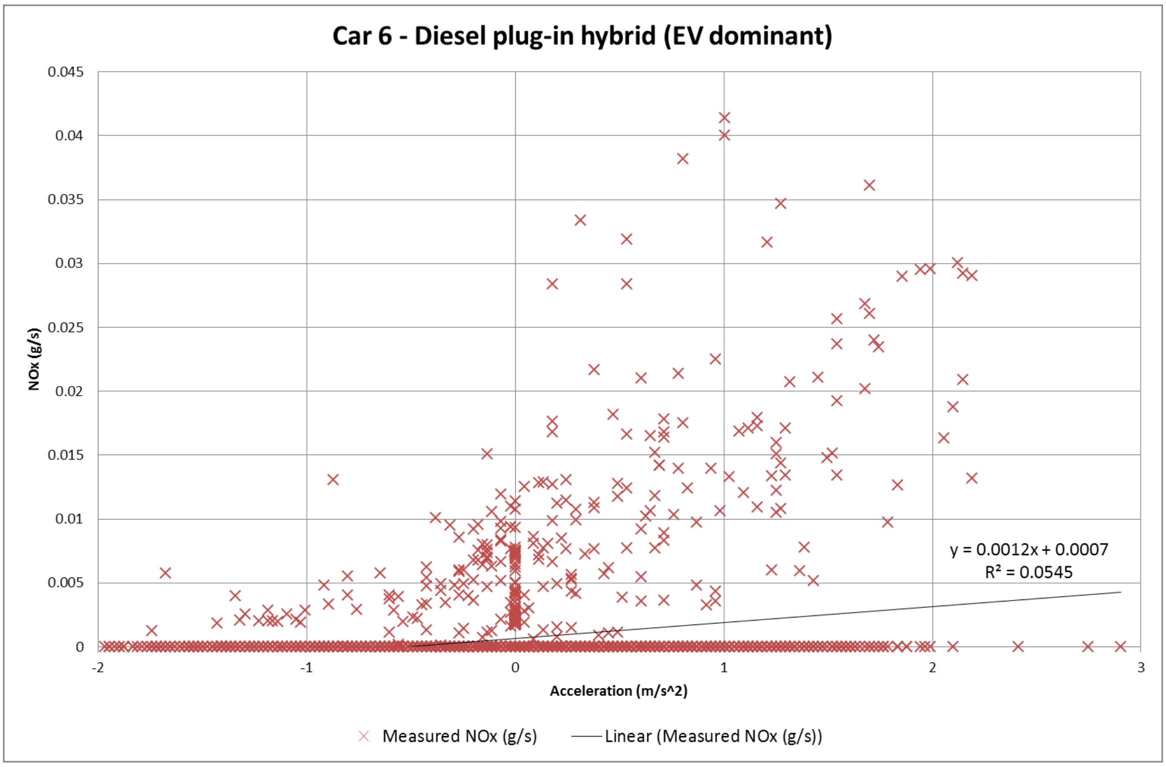


**Figure 6.14: Emissions from Car 6 in EV dominant mode.**



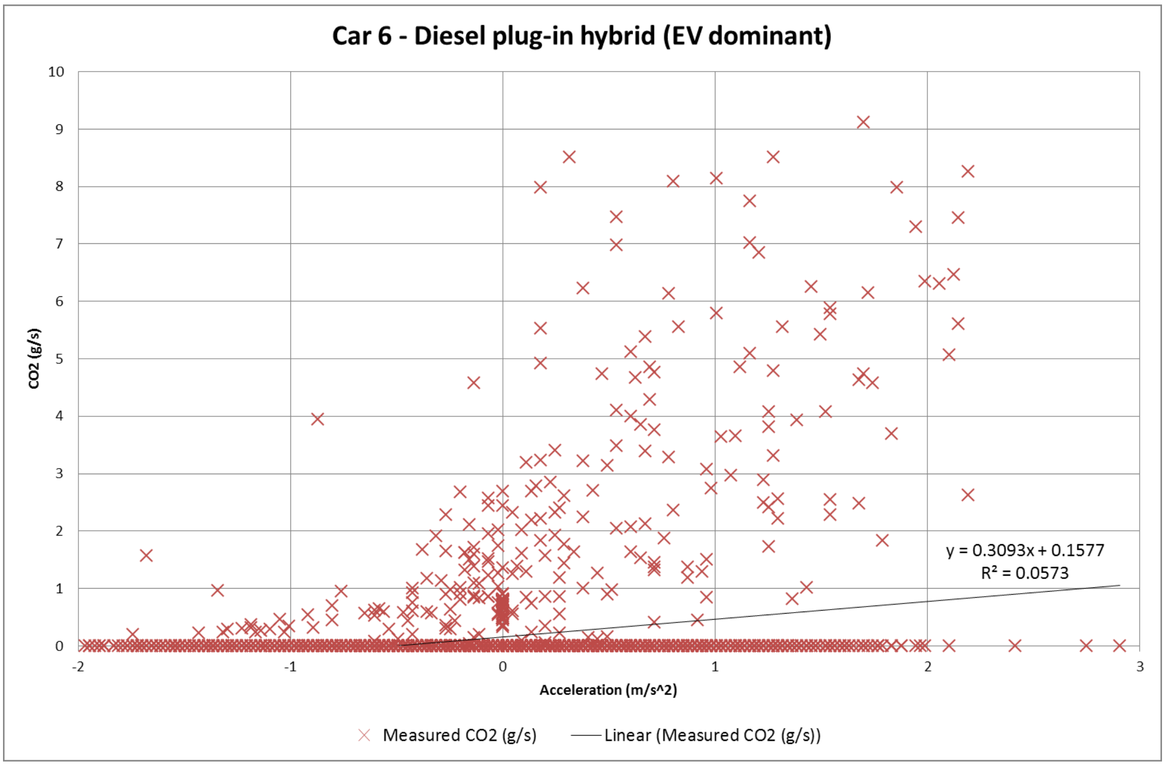


**Figure 6.15: Emissions vs. acceleration for Car 6 in EV dominant mode.**

Plots of $NO_x$ and $CO_2$ emissions against acceleration, as an indication of high-power demand from propulsion are shown in Figure 6.15. There appears to be two distinct domains: those where measurements shown have zero emissions, which appear to cover almost all the range of acceleration and deceleration, and a smaller number that have positive emission. The zero emissions points are likely indicative of acceleration purely on electric power. The positive emission measurements imply that the engine is providing at least some component of the propulsion and appear to have generally positive correlation with acceleration, but the degree of this correlation appears to be low. However, for the overall set of measurements in this sample of EV dominant behaviour, including zero emission points, there appears to be even lower correlation of speed with emissions, with $R^2 \approx 0.05$ for both $NO_x$ and $CO_2$. This suggests that the factors affecting when emissions take place in this mode of operation in an urban environment are not related closely to acceleration.

When car 6 accelerates to motorway speeds, $NO_x$ and $CO_2$ emissions occur with very few interruptions and at the higher rate than previously, with the engine appearing to be in continuous operation. Most $NO_x$ peaks are around 40 mg/s, about twice the most frequent values of peaks in the EV dominant part of the cycles, although the highest peak is 200 mg/s, compared with 0.35 g/s in the EV dominant section.

This suggests that most power for vehicle operation is being drawn mainly from the internal combustion engine and this section is labelled “IC Dominant.” Short excerpts of the IC dominated motorway drive cycle and the subsequent IC dominated urban cycles, are shown in Figure 6.16.

The section of driving after the motorway is of a similar speed range and variance to that before the motorway. Yet, comparison of emissions traces show that although the height of $NO_x$ peaks is roughly similar to those in the pre-motorway section, the frequency of these peaks is still higher after the motorway section than before: more peaks are seen in the 160 or so seconds in the excerpt from the post-motorway cycle than in the 600 or so seconds of the seconds of the pre-motorway excerpt.

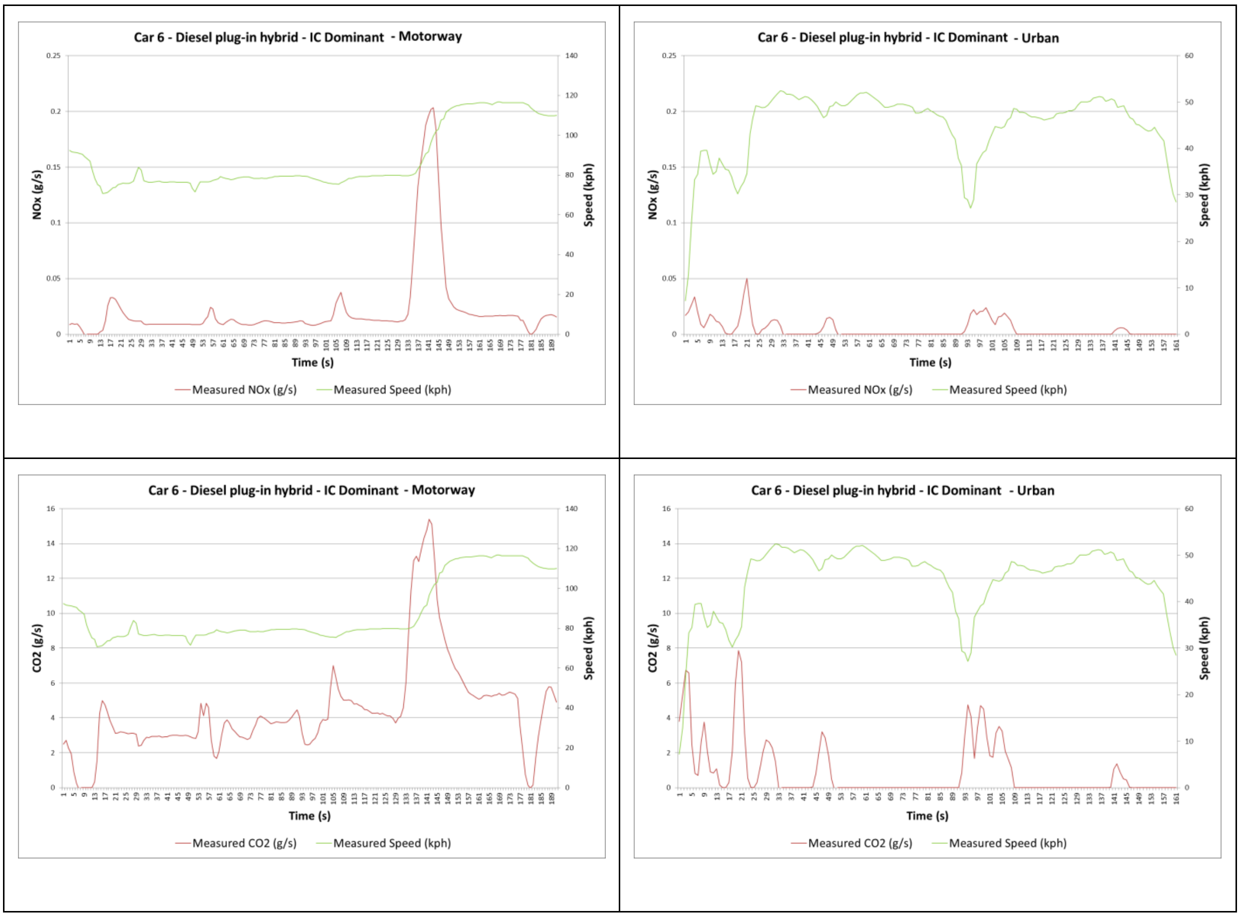


**Figure 6.16: Excerpts of Car 6 IC dominated motorway drive cycle and IC dominated urban cycles**

Comparison of graphs of emissions against acceleration for the two sections in Figure 6.17 demonstrate two highly differentiated behaviours. In the motorway section of IC dominated drive cycle, there are no discernible points corresponding to acceleration without emissions. Most of the emission measurements taken during the motorway section driving form a lobe of points, with the maximum observed emissions for a given level of acceleration increasing steeply with acceleration up to around 1 m/s$^2$. However, at higher acceleration, lower emissions are seen again that are more comparable with the subsequent IC dominated urban section of cycle.

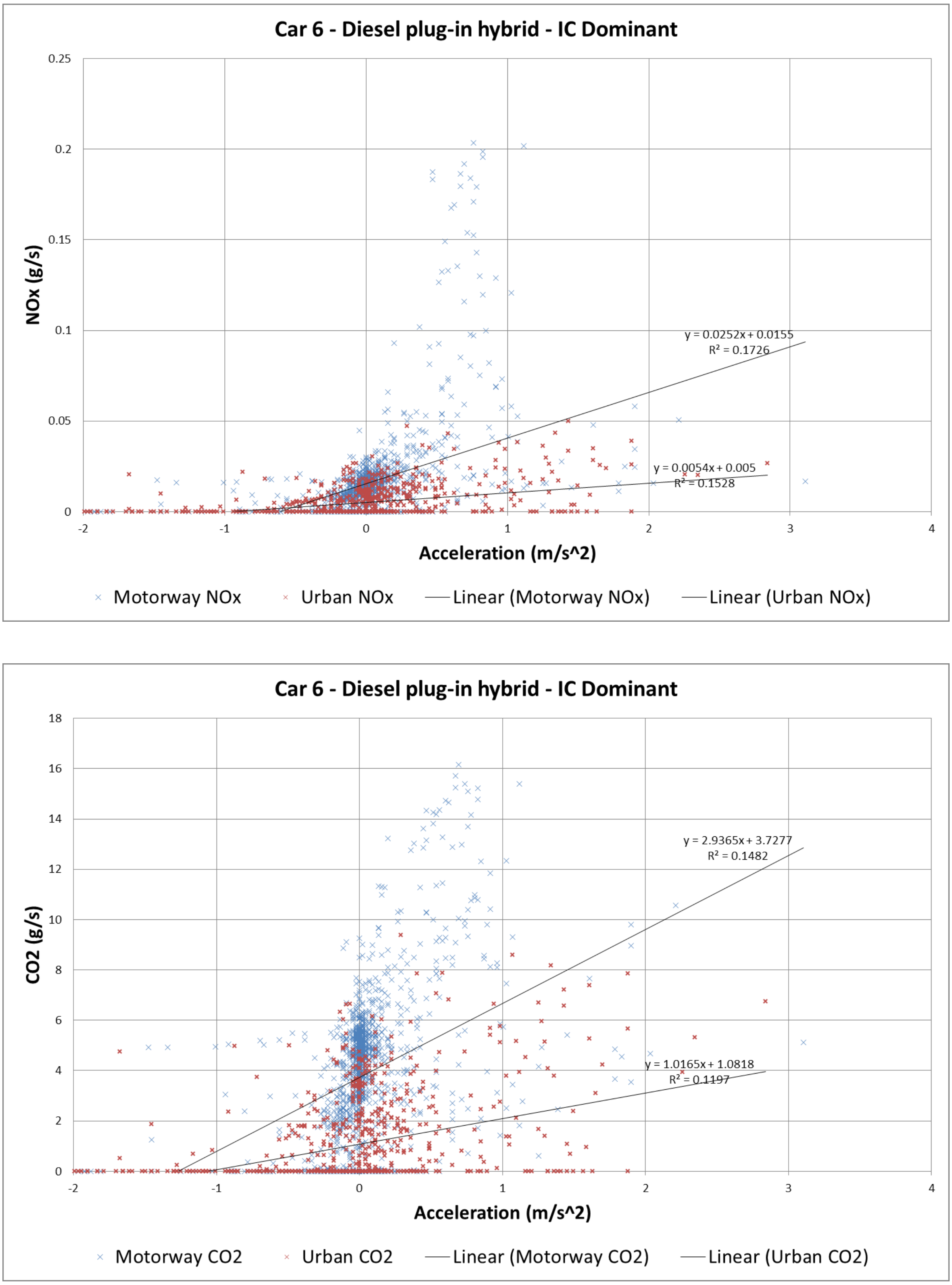


**Figure 6.17: Emissions vs accelerartion for IC dominant urban and motorway Car 6 drive cycles.**

The points from this section of urban driving appears to have a similar distribution of emissions against acceleration as seen for those in the EV dominated section of urban cycle when the engine is running: a widely- distributed set of points with very loose positive correlation that does not exceed 0.05 g/s $NO_x$ or 9 g/s $CO_2$. The key difference between IC dominated and EV dominated urbans sections is that the number of zero emission points when under acceleration that are seen in the IC dominated urban plots are far fewer than in the EV plots and that most points with acceleration are associated with positive emissions.

The similarity of the distribution of emissions under engine operation for both EV and IC dominated urban drive cycles suggests that Car 6's rate of emissions in low-speed environments may be dominated by how long its engine is operating, rather than the engine load. This may be because Car 6 has a 2.5 litre engine, which is comparatively large when considered against the 1.6 litre average engine size for the EU cars (ICCT, 2019). Operation under low speed, low acceleration conditions with some degree of battery charging underway, a 2.5 litre car is likely be subject to a much lower proportion of its maximum engine loading than a smaller engine vehicle would be. As increased engine loading is correlated with increases in $NO_x$ emissions, limited acceleration at low speeds may result in much lower proportional change in $NO_x$ than a smaller engine car.

Regardless of engine size, the changes in emission performance seen before, after and during motorway sections suggests that the characteristics such as speed and power demand of the section of a drive cycle is not a reliable indicator of emissions performance for a car with a plug-in powertrain such as Car 6's. When operating with its highest level of emissions, the gradients of the cumulative emission traces suggest that this Car 6's powertrain will only likely emit $NO_x$ and $CO_2$ at a greater rate than COPERT 5 expectations in a high-speed driving environment, such as a motorway. In an urban situation, the average emissions appear to conform well with COPERT 5 when operating in an IC dominated mode and are a fraction of COPERT 5 predicted emissions, when operating in an EV dominated more.

In the long run, Car 6 could therefore offer better-than-COPERT performance in an urban environment, if it receives regular charges from the electricity grid. If the vehicle were to be used in a predominantly motorway environment, this advantage appears to be likely to reduced significantly, or emissions may even be slightly higher than COPERT 5 predictions.

It should further be noted that Car 6 offers an option to operate in a purely electric vehicle mode, with the internal combustion engine disabled. This would allow driving with zero emissions and a high degree of predictability of emission characteristics, but the range would be limited to around 30 km, and the practicality and degree of incentive to use this may be limited to short journeys.

### 6.4.7 Car 7

**Car 7 (Diesel IC) 2.2 litre Euro 6**

| Drive cycle | Average speed (km/h) | Section length (km) | Average $NO_x$ Emissions (mg/km) | Average $CO_2$ Emissions (g/km) |
|---|---|---|---|---|
| **Urban** | 11.52 | 4.45 | 612.1 | 301.5 |
| **Motorway** | 82.21 | 12.8 | 229.4 | 154.8 |
| **Extra Urban** | 62.6 | 11.9 | 325.8 | 158.7 |
| **Motorway** | 104.6 | 24.1 | 114.7 | 130.2 |
| **Urban** | 20.2 | 15.5 | 490.8 | 193.1 |
| **OVERALL** | 40.0 | 68.8 | 289.1 | 164.9 |

**Table 6.9: Drive cycle average section emissions per km for Car 7.**

As with the “through-the-road” hybrids (Cars 4 and 5), the conventional diesel IC Car 7 shows a high degree of consistency of emissions characteristics in similar drive cycle sections. The rate of both $NO_x$ and $CO_2$ emission (in g/s) increase with both increasing average speed and with increasing drive cycle intensity, indicated by a greater first standard deviation.

Whilst average rates of $NO_x$ and $CO_2$ production both increase with increasing average speed, they do so in much lower proportions to the speed increase. Consequently, the faster Car 7 travels, the lower its emissions of $NO_x$ and $CO_2$ per km become.

Car 7 show a strong correlation of $NO_x$ peaks with acceleration. When not under acceleration, it produces around 2 mg/s - 5 mg/s $NO_x$; when accelerating, $NO_x$ peaks sharply, with non-motorway peaks of between 30 mg/s – 50 mg/s $NO_x$ and motorway peaks of 60 mg/s - 120 mg/s $NO_x$. Typical non-motorway $CO_2$ emissions for Car 7 are around 2 g/s with most peaks between 8 g/s – 10 g/s; typical motorway $CO_2$ emissions centre around 5 g/s with peaks between 7 g/s – 14 g/s.

Cumulative emission traces demonstrate that rates of real-world and predicted emissions are in proportion to each other and changes in the gradient of the predicted traces are reflected in the real-world data. However, iMOVE estimates total trip $NO_x$ emissions to be around 200% of real-world emissions and total trip $CO_2$ emissions to be around 75% of real-world emissions. This overestimation of $NO_x$ and underestimation of $CO_2$ stems from Car 7's performance in the higher speed sections of the drive cycle.

### 6.4.8 Car 8

**Car 8 (Diesel IC) 2.0 litre Euro 6**

| **Drive cycle** | **Average speed (km/h)** | **Section length (km)** | **Average $NO_x$ Emissions (mg/km)** | **Average $CO_2$ Emissions (g/km)** |
|---|---|---|---|---|
| **Urban** | 22.7 | 4.40 | 293.7 | 205.7 |
| **Motorway** | 96.2 | 49.1 | 158.7 | 136.9 |
| **Urban** | 22.6 | 36.8 | 230.3 | 157.0 |
| **OVERALL** | 38.6 | 90.3 | 194.4 | 148.4 |

**Table 6.10:** Drive cycle average section emissions per km for Car 8.

Car 8 shows a similarly high degree of consistency of emissions characteristics in similar drive cycle sections as the other conventional IC diesel, Car 7, and the "through-the-road" diesel hybrids, Cars 4 and 5. In line with these vehicles, the averages and standard deviations of Car 8's $NO_x$ and $CO_2$ emission rates both (in g/s) increase with increasing average speed and increasing drive cycle intensity.

Again, average rates of $NO_x$ and $CO_2$ production both increase in low proportions to the speed increase leading to a reduction of $NO_x$ and $CO_2$ per km with increasing speed, in the speed ranges observed.

Depending on speed, Car 8 produces around 2 mg/s – 4 mg/s $NO_x$ when not accelerating. This is a marginally smaller amount than for Car 7, which is likely to be due to the marginally smaller engine capacity (2.0 litres for Car 8, in comparison to 2.2 litres to Car 7). When accelerating, $NO_x$ peaks reach between 10 mg/s – 15 mg/s in non-motorway conditions and 30 mg/s – 80 mg/s in motorway conditions.

The sole exception for Car 8 is an anomalously reading between 5750s – 5950s in the drive cycle, where peaks of around 60 mg/s $NO_x$ arise. It is not clear what causes this, but possibilities include a non-routine action of the emissions control system, such as regeneration of a $NO_x$ adsorption catalyst, or possibly a temporary issue with the engine that leads to a higher production of $NO_x$ than the emissions aftertreatment system can abate effectively.

As with Car 7, Car 8's cumulative emission traces demonstrate that rates of real-world and predicted emissions are in proportion to each other and changes in the gradient of the predicted traces are reflected in the real-world data. Again, as for Car 7, iMOVE overestimates total trip $NO_x$ emissions and underestimates total trip $CO_2$ emissions for Car 8. In this case, these discrepancies occur in all sections of the drive cycle and lead to predictions being around 250% of real-world $NO_x$ emissions and 80% of real-world $CO_2$ emissions.

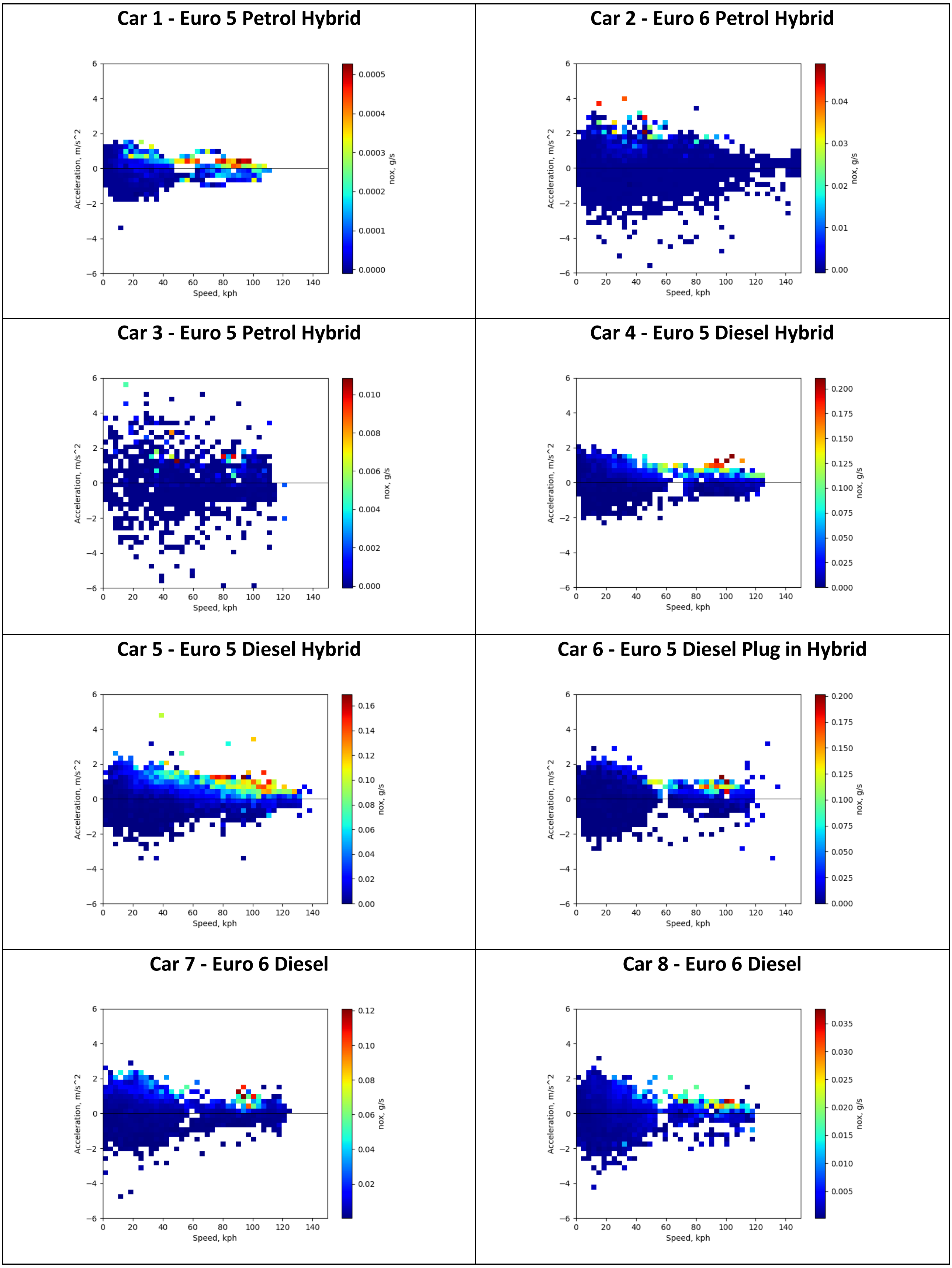
### 6.4.9 Emission variation with acceleration and speed

The PEMS system used by Emissions Analytics records emission data natively in g/s at one second intervals. Two of the key influences on the amount of power needed by a vehicle and thus engine load are speed and acceleration. Plots of emissions against these variables are shown in Figures 6.18 and 6.19. These demonstrate a clear variation amongst the vehicles considered in both the variations of the rate of pollutant emissions in relation to speed and to acceleration at a given speed. Unlike the chronological plots, cold start emissions have been omitted from these.

Five of the vehicles (cars 4, 6, 7 and 8) show two distinct groupings of speed and acceleration combinations, with a much smaller number of readings at a pinch point that occurs at various points in the range of 55 kph – 70 kph , depending on the vehicle. This implies that these vehicles are rarely travelling at speeds within this pinch point for either mechanical or regulatory reasons.

A possible mechanical cause might result from gearing ratios: it is possible that this range of speeds represent the upper end of the torque range for one gear for the vehicles and the lower end of it for the gear above it, providing an incentive to accelerate when shifting up. The pinch point occurring at the same point for several vehicles would require the gear ranges of the vehicles to be roughly identical, which is reasonably unlikely, given that they use a variety of transmission types and number of gears.

A more likely explanation could be a regulatory one: 55 kph is roughly the maximum speed that one might expected of vehicles attempting to conform with the widespread 30 mph speed limit in UK urban areas. The common tiers of speed limits on on-urban roads above this are 40 mph (64 kph) with 50 mph (80 kph) and 60 mph (97 kph) limits common on extra urban, non-motorway classes or road and 70 mph (112 kph) the norm on motorways. Such a grouping of velocity measurements would be consistent with an environment with a limited number of 40 mph zones and a lack of incentive to drive at the lower end of speed limits in uncongested conditions.



Car 1 - Euro 5 Petrol Hybrid

Car 2 - Euro 6 Petrol Hybrid

Car 3 - Euro 5 Petrol Hybrid

Car 4 - Euro 5 Diesel Hybrid

Car 5 - Euro 5 Diesel Hybrid

Car 6 - Euro 5 Diesel Plug in Hybrid

Car 7 - Euro 6 Diesel

Car 8 - Euro 6 Diesel

**Figure 6.18: Distribution of NOx emissions intensity with speed and acceleration.**

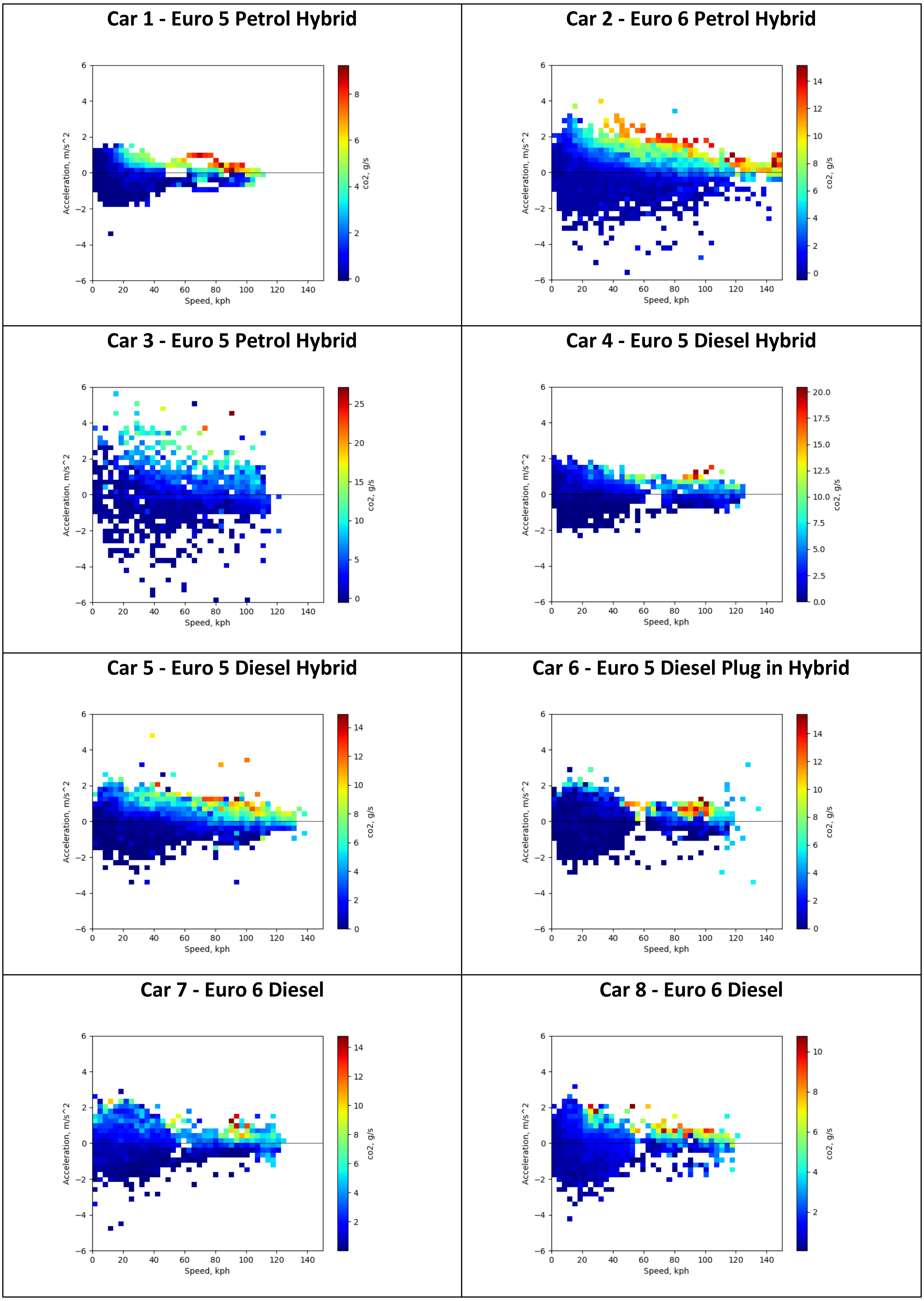


**Figure 6.19: Distribution of NO$_x$ emissions intensity with speed and acceleration.**

This conforms well to the driving environment in the routes followed in the London area, as cars 5, 6, 7 and 8 have followed, where 30 mph zones give way to 50 mph ones on major routes out of the urban area.

The diesel vehicles show a trend of increased $NO_x$ production rate with increases in speed and acceleration. This trend is particularly clear in the two "Through-the-Road" diesel hybrids (Cars 4 and 5) and is evident in the two diesel IC engine cars (Cars 7 and 8). It also influences the diesel plug in hybrid (Car 6), where some of the accelerations at high speed show increased $NO_x$ emissions, in comparison to low speed operation. However, the incidence of high $NO_x$ emission readings at these speeds is less well correlated with acceleration and much more skewed towards higher speeds than it is with the other diesel cars.

There is lower correlation of $NO_x$ emission levels with acceleration and speed in the petrol hybrid vehicles. As with the diesels, increased $NO_x$ emissions tend to be seen almost exclusively when under acceleration, but the higher readings of $NO_x$ emission are more widely distributed across the range of speeds and correlate less obviously with increasing acceleration for any given speed. Increases in the $NO_x$ emissions from Car 1 show little dependency on speed or acceleration, with some of the highest rates of emission occurring at speeds of less than 20 kph and at accelerations below the maximum observed. With Cars 2 and 3, the probability of an increased emissions reading appears to increase with acceleration, regardless of speed. Even so, the higher readings of $NO_x$ emissions rate for Cars 2 and 3 are interspersed with many low readings at adjacent speeds.

Emissions of $CO_2$ appear to correlate more strongly with acceleration and speed, with increases in either leading to an increase in $NO_x$. Cars 3, 4, 6 and 8 all show very low $CO_2$ emissions when accelerating at low speed. There is no commonality between the design of powertrain in these vehicles, as they cover unmodified IC diesels through to a petrol hybrid.

## 6.5 Overview

Two of the petrol vehicles, Cars 1 and 3, exhibited cold start emissions before engines and catalysts were at normal operational conditions. Excluding cold start emissions and stationary sections, petrol hybrids exhibited $NO_x$ emissions of between 0.3 – 18.5 mg/km in urban sections of the drive cycle, 0.7 – 48.8 mg/km in extra-urban sections and 0.25 – 7.2 mg/km in motorway sections. $CO_2$ emissions were between 41 – 207 g/km in urban sections 101 – 206 g/km in extra-urban sections and 106 – 205 g/km on motorway sections.

Diesel hybrid vehicles exhibited $NO_x$ emissions of between 105 – 1082 mg/km in urban sections of the drive cycle, 490 - 1169 mg/km in extra-urban sections and 104 - 1130 mg/km in motorway sections. $CO_2$ emissions were between 25 – 178 g/km in urban sections 74 - 154 g/km in extra-urban sections and 130-170 g/km on motorway sections.

In comparison, the two non-hybrid diesel IC vehicles considered had $NO_x$ emissions of between 230 – 612 mg/km in urban sections of the drive cycle, 490 - 1169 mg/km in extra-urban sections and 104 – 1130 mg/km in motorway sections. $CO_2$ emissions were between 25 – 178 g/km in urban sections and 130 – 154 g/km on motorway sections. Only one extra urban section was recorded (325 mg/km).

In general, a trend can be seen that high average speeds across sections can lead to lower $NO_x$ emissions per km. This trend is unbroken in the two non-hybrid vehicles considered but is much more variable across the drive cycles of the hybrids: Car 4 follows this trend completely, whilst car 6 behaves entirely counter to it and the remainder show falls in $NO_x$ per km for some transitions in their drive cycle to higher speeds, but not for others.

The average emissions for $NO_x$ across the drive cycle do not appear to correlate strongly with engine size (Figure 6.20), although average $NO_x$ emissions are significantly lower for the three petrol hybrids than any of the diesel engine vehicles and are below 400 g/km $NO_x$ for the two non-hybrid diesel vehicles. Average $NO_x$ emissions also show increases with increasing average speed. Average $CO_2$ emissions show no obvious correlation with either engine size or average drive cycle speed.

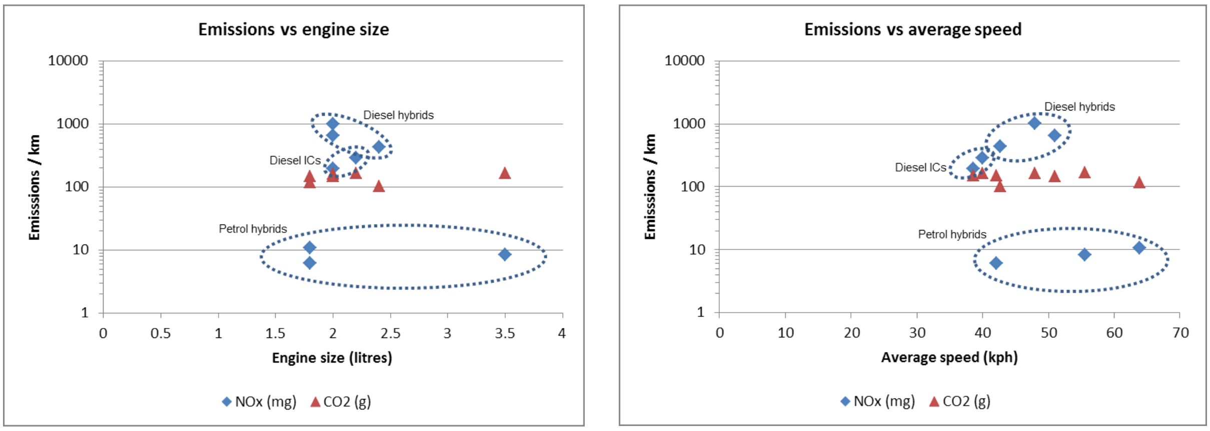


**Figure 6.20: Emissions vs engine size and average speed for cars in this study.**

There are no non-hybrid petrol vehicles in this study to compare emissions with. However, emissions data from the wider pool of vehicles that Emissions Analytics has tested has been analysed in other studies (O'Driscoll, Stettler et al., 2018). These are shown in Figure 6.21 and provide urban drive cycle average emissions for 149 petrol and diesel vehicles across the whole drive cycle using the same PEMS equipment and routes as used by most of the vehicles in this study. The two hybrids are amongst the petrol vehicles included here (Cars 1 and 3). The plot demonstrates that, in urban situations at least, the petrol hybrids have much lower emissions than the almost all the non-hybrid petrol vehicles. It also demonstrates that the $NO_x$ emissions per km from most of the urban sections covered by the diesel hybrids in this study are comparable with a great many non-hybrid diesel vehicles and that around half of the diesel vehicles have lower $NO_x$ emissions per km than these hybrids.  The $CO_2$ emissions of the diesel hybrids urban drive cycle sections also lie mostly within the main range of those for non-hybrids, but many lie in the lower half.

This suggests that, on a per kilometre basis, the hybridisation of petrol powertrains may be more successful in reducing emissions than hybridisation of diesel powertrains.

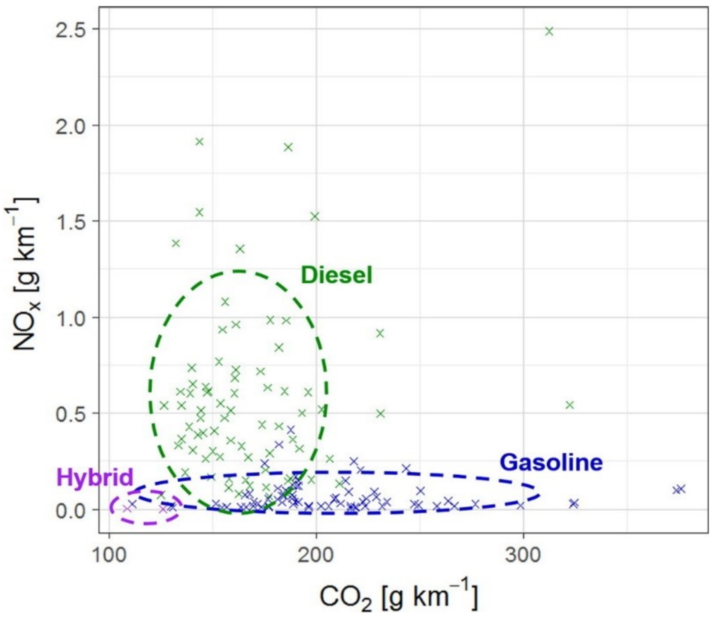


**Figure 6.21 Plot of Average $NO_x$ vs Average $CO_2$ emissions data from (O'Driscoll, Stettler et al., 2018)**

Whilst further statistical tests on the PEMS vehicle emissions data would be useful in future work, they are hampered in the data available for this study by a lack of measurement of certain key parameters. Most notably data on the battery state of charge and on power demand from electrical systems such as heating, lights etc. would be necessary to develop this.

## 6.6 Comparison with other studies

*Comparison with wider Emissions Analytics data*

O’Driscoll *et al*. have undertaken earlier studies of Emissions Analytics' datasets taken from experiments using the same PEMS equipment and similar test routes on a wider selection of 149 Euro 5 and 6 vehicles, the great majority of which have IC powertrains (O'Driscoll, Stettler et al., 2018). These examined emissions of $NO_x$ and $CO_2$ per unit distance, mainly for non-hybrid vehicles with conventional internal combustion powertrains, although two petrol-electric hybrids were considered. The emissions data used by O’Driscoll *et al*. were taken under conditions equivalent to the urban and motorway sections of the drive cycles considered in this study, often on the same roads. However, there was no assessment of vehicle performance in drive cycle sections equivalent to the extra-urban sections considered here. The average $CO_2$ emission levels in the urban and motorway sections of the drive cycles for all the non-hybrid vehicles considered in that study are shown in Figure 6.22. The vehicles in this study fall into the two largest of the four classes of engine sizes (1.4 – 2 litres and >2 litres) considered by O'Driscoll *et al*., denoted by [M] ad [L].

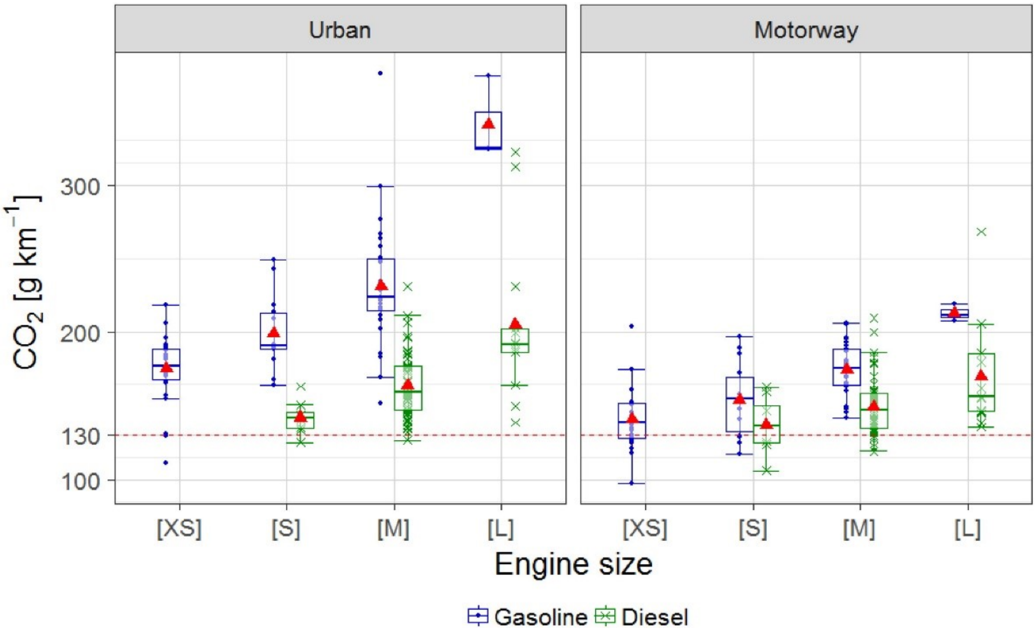


**Figure 6.22 Urban and motorway $CO_2$ emissions by engine displacement (dashed line = 130 g $CO_2$ km$^{-1}$ fleet target limit, red triangle = mean, central line in boxplot = median, top and bottom of box= 1st and 3rd quartile, whiskers= 1.5 ∗ interquartile range). Source: (O'Driscoll, Stettler et al., 2018)**

For the non-motorway sections of their drive cycle, the average section emissions of Cars 1 and 2 (the two smaller petrol hybrids, with power split powertrain architectures) lower than those the sample of conventional cars with the same engine size in O'Driscoll *et al*., which notes a 231.5 g/km average of non-motorway $CO_2$ emissions and 174.4 g/km $CO_2$ in motorway conditions. However, the 206 g/km average $CO_2$ from Car 2's first motorway section highlights that, under certain conditions, it is possible for such hybrids to exceed this average performance by a significant amount (over one standard deviation of the O'Driscoll *et al*. sample) for an extended period. The better performance of such hybrids is not always reliable: it may be expected that the state of charge of the battery is a key influence on this. However, the ratio of worse to better sections in the data presented here suggests that, overall, these vehicles will tend to have lower $CO_2$ emissions than average for similar non-hybrid vehicles.

The smaller diesel hybrids, Cars 4 and 5 exhibit similar $CO_2$ emission per kilometre to both non-motorway (163.4 g/km) and motorway (149.0 g/km) average levels observed by O'Driscoll *et al*. for vehicles of that engine size. An exception to this is the 29km section of Car 4's route in which it maintains average emission of 48 g/km $CO_2$, 5.3 standard deviations below the non-motorway average, which demonstrates that such vehicles are capable of temporary but dramatic improvements in non-motorway performance. Car 8, the two 2 litre engine conventional diesel, exhibits an overall higher (approximately 1 s.d.) than average rate of $CO_2$ emissions per kilometre over the non-motorway sections, and a slightly lower one (< 1 s.d.) over the motorway sections. This may be linked to their having engine sizes at the upper end of the class band they fall within.

After a short distance of high $CO_2$ emissions per kilometre, the single large-engine petrol hybrid car 3 exhibits significantly lower $CO_2$ emissions by 4.5 standard deviations than the average (340.9 g/km) non-motorway emissions for >2 litre petrol vehicles in the O'Driscoll *et al*. sample and its motorway emissions are nine standard deviations below the (213 g/km) average. This is despite having an engine capacity 175% that of the minimum for that grouping of vehicles. On its poorest performing non-motorway sections, its $CO_2$ emissions per km are comparable to the average diesel vehicle from the sample. Its single motorway section is still around 10 g/km (about 0.3 s.d.) $CO_2$ lower than the motorway average for the same diesels.

Car 6, the 2.4 litre diesel plug-in hybrid has similar motorway emissions to the average 170 g/km $CO_2$ quoted by O'Driscoll *et al*. for large diesels. It also has two distinctly different phases of urban drive cycle, with the sections in the earlier phase varying between 15% - 42% (4.2 – 2.7 standard deviations) of the earlier study's urban average of 205.1 g/km $CO_2$. The section that is the later phase is higher, but still significantly (around 2 s.d.) below the average.

Car 7, the larger of the non-hybrid diesel cars performs better than average for both the motorway (170 g/km $CO_2$) and non-motorway (205.1 g/km $CO_2$) averages for the population of large diesel cars considered by O'Driscoll *et al*. Such better than average performance might be expected as its 2.2 litre engine falls towards the smaller end of that study's definition of "large" and there are many more vehicles with greater engine capacities in population it considers. However, it also performs well in comparison with smaller vehicles, with its $CO_2$ emissions levels fluctuate around the averages for the engine size grouping below it (1.4 – 2 litres).

O'Driscoll *et al*. notes that $CO_2$ emissions trends correlate roughly with engine capacity, but that trends in $NO_x$ emissions are much less clear. The results of the non-hybrid vehicles in the study are summarised in Figure 6.23. The classifications G5, G6, D5 and D6 refer to petrol (gasoline) engine Euro 5 and 6 and diesel engine Euro 5 and 6 cars respectively.

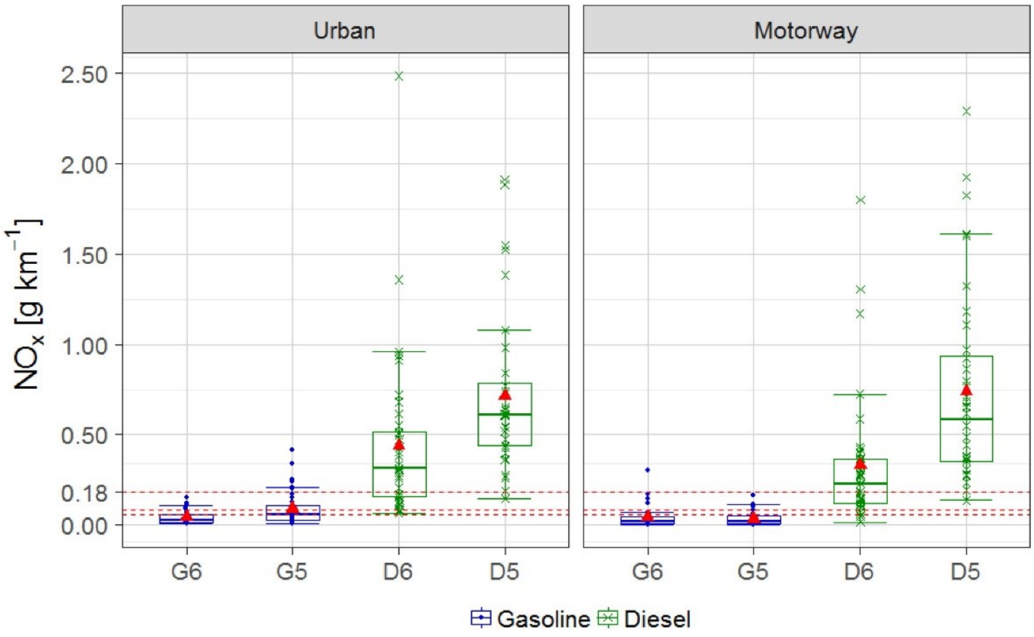


**Figure 6.23 Urban and motorway $NO_x$ emissions by vehicle category (red dashed line=type approval limits, diesel Euro 5 limit (0.18 g km−1) is labelled, below is the diesel Euro 6 limit (0.08 g km−1) and below that gasoline limit (0.06 g km−1 for both Euro 5 and Euro 6), red triangle = mean). Source: (O'Driscoll, Stettler et al., 2018)**

In this framework, the Cars 1 and 3, the two Euro 5 petrol hybrids considered above perform very well in comparison with all vehicles including convention petrol cars and diesel hybrids. Emissions are consistently below the urban average of 90 mg/km $NO_x$ and motorway average of 30 mg/km $NO_x$, with the large difference in engine capacity apparently making little impact on $NO_x$. The Euro 6 petrol hybrid Car 2 also performs well early on in the drive cycle, with $NO_x$ emission far below the average emissions of 40 mg/ km for both motorway and non-motorway conditions seen in Euro 6 petrol cars in the study. It manages to average around a quarter of this across the entire route. However, by the urban section at the end of the drive cycle, $NO_x$ emissions have risen by two orders of magnitude compared to the first urban sections, exceeding this average 40 mg/km figure by 40%, despite the similar driving environment to the early urban sections. The high variance within the drive cycle is mirrored in the extra urban emissions, although no figures for average extra-urban emissions from the wider Euro 6 fleet are available for comparison from O'Driscoll *et al*..

Cars 4 and 5, the purely parallel diesel hybrids, show no significant advantage over the average Euro 5 diesel vehicles in the O'Driscoll *et al*. study. Most of Car 4's drive cycle sections result in $NO_x$ emissions exceeding the urban average for its category in the wider study by up to 27% or just under half a standard deviation. As with other hybrids, there is a large variation within these urban sections, with one having $NO_x$ emissions far below the others of just 28% of the average or 1.2 standard deviations below. Car 5 thus performs more poorly than Car 4.

### *Comparison with other PEMS studies*

Other PEMS studies of hybrid vehicles undertaking real-world drive cycles have also been conducted. These include a real-world testing campaign for vehicles with the split-power powertrain type of Car 1 (Wu, Zhang et al., 2015). Instantaneous $NO_x$ emission data were binned according to vehicle speed and power demand and were consistent with those observed in this study. However, the process of binning data in this way results obscures the chronological variation of emissions with time and comparison of emissions with similar sections of drive cycle. Averages of the emissions variation with speed fell within the range of those of Car 1's.

## 6.7 Comparison with "Euro" air pollutant emission standards

Compliance with Euro emission standards' limits only has meaning when a vehicle is being tested under a recognised standard drive cycle. None of the drive cycles above conform to such a standard cycle and thus one cannot determine if they would achieve compliance under controlled conditions. However, the drive cycles considered here do shed light on how close the real-world emissions come to meeting the standards. As these limits are defined in terms of average performance across a drive cycle, they offer an indication of how a recently manufactured vehicle might be expected to perform in the real-world. Whilst the emissions performance of a vehicle on any particular section of drive cycle may not be indicative of its overall performance, it would be expected that any vehicle that complies with a given Euro standard would exhibit emissions below that standard's limit values for at least some of a real-world drive cycle.

The three petrol-engine vehicles succeed in keeping below the Euro 5 and 6 standards' $NO_x$ emission limits of 60 mg/km at all times during normal engine operation, both in terms of average trip emissions and average drive cycle section emissions. Cars 1 and 3 exceed the limit by a factor of around 21 and 4.5 respectively under cold start conditions.

The three diesel Euro 5 hybrids largely fail to keep $NO_x$ emissions below the Euro 5 test cycle $NO_x$ emission limit for petrol cars of 180 mg/km. All sections of drive cycle for all these vehicles exceed this limit, with the exception of the initial low speed urban section of the plug-in hybrid's (car 6's) drive cycle, which has average emissions of 103 mg/km. Otherwise, the average emissions of non-motorway drive cycle sections of the vehicles exceed 180 mg/km by factors between 1.1 and 6.5 and motorway sections exceed it by factors of between 3.4 and 5.7. These results make it seem highly unlikely that the $NO_x$ emissions from these vehicles under extended real-world operation would fall below the limits expected by Euro 5 vehicles in a standard NEDC test cycle, although it may reasonable to expect that the plug-in hybrid vehicle may be capable of compliance for a limited time in a similar operational situation to the first part of the route that its PEMs measurements were taken on.

The two Euro 6 diesel vehicles, cars 7 and 8 both have pure internal combustion powertrains. They both fail to produce average emissions on any section of their drive cycles that fall below the 80 mg/km average emission limit of a Euro 6 diesel car test cycle. However, they both produce section average $NO_x$ emissions on at least one section of motorway speed driving that falls below the Euro 5 test cycle limit of 180 mg/km.

## 6.8 Conclusions

### 6.8.1 Implications for modelling

The Emissions Analytics vehicle data provide credible evidence of patterns of behaviour in hybrid vehicles' emissions that do not conform to modelling assumptions used for non-hybrids.

These include:

- Considerable differences in vehicle emission performance and fuel consumption at different times, but in identical drive cycle sections;
- Discontinuities in emissions of $CO_2$ and air pollutants consumption within drive cycle sections, that appear to be independent of cold start effects, speed, road gradient or other demands of the drive cycle, driving environment.

The data also provide evidence of significantly different patterns of emissions behaviour between different architectures of hybrid vehicle that, again, do not appear to be linked to vehicles’ fuel type, internal combustion engine types or operating environment. Despite this, the data does confirm that some hybrids offered genuine real-world emission benefits over non-hybrids, although this appears to be dependent on powertrain architecture.

This evidence that a hybrid vehicle is less likely than a non-hybrid one to perform in a similar manner when in similar environmental and driving conditions, suggests that current air pollution, emission and energy models may be unable to represent hybrid vehicles as accurately as non-hybrids. This is because the methodology commonly used to predict atmospheric emissions from transport for moany models rely on mathematical relationships between vehicles' speed and their rates of pollutant emission. Hybrid vehicles' behaviour appears to deviate, sometimes markedly, from this assumption. The result of this reduction in accuracy of emissions prediction should be a corresponding reduction in the accuracy of these models' predictions of the impacts of emissions, such the climate impacts of vehicles' $CO_2$ emissions, instantaneous and average concentrations of air pollutants, their spatial distribution and their subsequent public health impacts.

### 6.8.2 Influences of powertrain architecture

Factors affecting hybrid vehicles' emissions performance appear to arise from differences in the hybrid powertrain architectures used and the management of energy storage and use by the electrical side of the powertrain. Observed emissions performance for at least some of hybrids behaviour cycle also appears to be linked to the initial state of charge of the vehicle battery.

Particularly low or high states of battery charge in some of the hybrid vehicles for in this study are plausible explanations for the emissions performance for at least in the early stages of a drive cycle. They appear to influence when discontinuities in behaviour might start to be observed in a drive cycle. The degree to which this happens appears to depend on the powertrain architecture: the plug-in hybrid appears to be the most clear cut case of a discontinuous shift between low emission, electrically dominated behaviour and higher emission combustion dominated effects.

The numbers of pathways through which recharging may occur also appear likely to affect the rate at which the battery state of charge can recover. Hybrids with a direct mechanical connection between engine and generator can charge the battery off engine power whist in motion and at rest. Those without this, such as the "through the road" architectures can only recharge the battery when the vehicle is in motion. This would appear to offer more opportunity to charge and therefore more rapid recovery of charge in the former than the latter, especially in situations such as congested urban conditions, when the both the demand for acceleration may be frequent and the vehicle spends a significant proportion of its time at rest.

### 6.8.3 Influences of fuel type

Both section emission averages and overall emissions average from the vehicles and drive cycles considered in this study suggest that hybridising electric and internal combustion power plant in the same powertrain can deliver improvements in vehicle emissions performance over similar internal combustion engine vehicles. Greater reductions of $NO_x$ in comparison with equivalent non-hybrid vehicles are observed in the petrol hybrids in this study than diesel hybrids, when compared with measurements of a wider selection of similar fuelled and engine sized non-hybrid vehicles that are available from the literature. The diesel hybrids in this study, including the plug in hybrid when operating in a non-EV dominated mode, do not appear to offer clear benefits in terms of $NO_x$ or $CO_2$ when compared with the two conventional diesels of similar engine considered in this study, or the with a wider selection of conventional diesel vehicles in the literature.

It is not clear how representative of all diesel hybrids those considered in this study are. Despite this, they offer a clear illustration of the fact that not all types of hybrid vehicles offer emission reductions in relation to comparable conventional vehicles. Consequently, indiscriminate incentives to promote hybrid vehicle use solely on the fact that they are hybrids is likely to achieve lower reductions in emissions in real driving conditions than targeting the better performing vehicles in the market. Such approaches may also be counterproductive by building consumer mistrust in hybrids, as consumers are likely to pay a price premium on hybrid vehicles and are likely to expect lower emissions and improved fuel economy in relation to conventional as a result. Failure to deliver on this expectation may result in consumers turning away from hybrids in a similar manner as that they appear to have done so in the immediate aftermath of the “dieselgate” events, as is evidenced in the subsequent a fall in the proportion of diesel engine cars in new vehicle sales in Europe (ACEA, 2018).

### 6.8.4 Influences of software

The behaviour shown in the power-split and parallel hybrid vehicles demonstrates the influence of power control software on hybrid emissions. Due to the additional load that charging of a hybrid vehicle’s electric powertrain can impose on the engine and the potential total elimination of engine use in certain circumstances, the software controlling power in a hybrid is a major influence on its emissions. Most hybrid vehicles offer varying amounts of user control over variations on the management of the powertrain, which will further add to the variability of emissions with drive cycle characteristics, as will software upgrades.

### 6.8.5 Impact of emissions characteristics of hybrid vehicles

The reduction in correlation of emissions with speed and acceleration for hybrid vehicles should reduce the accuracy of prediction of the timing and magnitude of the emission of air pollutants and $CO_2$ in the drive cycle and of the physical location at which these occur. Reliable air quality modelling depends on the reproducible behaviour of similar vehicles in similar conditions. The function of common air quality prediction software, such as COPERT and ADMS depends on such relationships.

The decrease in the reproducibility of emissions characteristics in hybrid vehicles and the variability of this effect between hybrid powertrain architectures (and thus between different vehicles models) further confounds the prediction of emission location. In the case of air pollutants, any reduced certainty about emission location reduces the certainty with which emission concentrations, the locations of potential air pollutant hotspots and the probability of breaching air pollutant concentration limit values can be predicted. Without this information, one cannot accurately use techniques to assess health impacts, such as commonly used measures of population exposure to pollutants. This further reduces the ability to model the effects of the penetration of hybrid vehicles into the current fleet.

In the vehicles considered here, the greatest disconnect between speed and emissions can be seen in the PHEV vehicle when it is operating in its “EV dominant” mode. In this mode, engine operation continues to occur sporadically, producing relatively high average levels of emissions during operation in comparison with the more continual operation seen in its “IC” dominant mode. This is distinct from the pure-EV mode that many conventional and plug-in hybrids offer the option of being switched to, which does not use the internal combustion engine at all and thus has very predictable, zero exhaust emissions.

Some of the greatest shifts in emissions behaviour are seen in the PHEV vehicle and one of the power split hybrids (Car 2). Both are linked to significant increases in engine usage and are plausibly caused by a low charge state of the battery reducing the amount of propulsion from the electric part of the powertrain. In the case of the power split hybrid, battery recharge must be achieved entirely by power supplied from the engine and from regenerative braking and a high state of battery charge will eventually be attained through this. Whilst this does not occur in Car 2’s drive cycle, its behaviour in the early staged of the route imply that this must be possible.

Prediction of emission behaviour for such a split-power hybrid should therefore be improved by a better understanding of power control algorithms that determine when engine, electrical motor and battery charging occur, as well as the real-world drive cycles that they tend to be subject to. The same principle applies to the other non-plug in hybrids in this study.

In the case of the PHEV, the change in behaviour does not appear to be reversed by driving, which may indicate that only external recharge to the battery to a high state of charge will switch it back to “EV dominant” mode. Prediction of this type of PHEV’s emission behaviour should therefore be improved by a better understanding of:

- Typical initial battery state in journeys, influencing the range it can operate in EV or "EV dominant" mode.
- Power control algorithms, which influence the engine usage and the degree to which the battery can be charged off the engine.
- User preferences in charging strategy and the availability of charging infrastructure, which influence whether it can resume EV or "EV dominant" operation in a journey.

The data presented here suggests that the variety of hybrid powertrains and their differences in behaviour available cannot be adequately described in current energy and emissions modelling tools. In conclusion, the observed variability of emissions characteristics implies that the emissions from a hybrid vehicle cannot be estimated merely from its fuel type and the fact that it is a hybrid or a plug-in hybrid. It is necessary to know what type of powertrain architecture it uses and to be aware of the impact this has on engine operation. Consequently, accurate prediction of emission budgets of light vehicle fleets in future transport scenarios is likely to require an understanding of trends in the types of hybrid vehicles are being used and where different engineering approaches are used most. It is currently impossible to predict the distribution of powertrains in a future hybrid fleet composition. This makes prediction using general emission factors for hybrids, as used in the air quality assessment of the 2050 Carbon Calculator, workable only in hindsight.

The market penetration and typical usage of hybrid vehicles can therefore be expected to play a key role in determining their likely impact on air pollution and contribution to $CO_2$ emissions. In the case of plug-in hybrids, increased certainty over emissions budgets may be gained from the use of power control algorithms that favour operating solely on the electric powertrain when a high state of battery charge, rather than the type of "EV dominant" mode shown by Car 2. This may also benefit air quality and greenhouse gas emissions if most of the trips taken in plug-in hybrids are under 30km, as is typical of most cars, since it more likely that they would be able to make such trips without the use of the IC engine.

### 6.8.6 Paucity of diesel hybrid data

The data used in this study covers a limited number of parameters in a limited number of environments and further investigation would help develop the available base of evidence on the factors influencing the variability of hybrid vehicle emissions. Whilst other studies on hybrids have considered the emissions performance of petrol electric hybrid powertrains, wider evidence is needed on the performance of diesel hybrid vehicles before more conclusive evidence can be drawn over their comparable performance with conventionally engine equivalents.

### 6.8.7 Understanding battery charge state

Most studies to date consider average emissions from hybrid vehicles' variation of emissions across the whole of each vehicle's drive cycle. Those that go into more detail tend undertake statistical analysis based on distribution of instantaneous emission levels across speed bins. Whilst these can demonstrate the probability distribution of emissions and go some way to describing the behaviour of hybrids, these do not capture the changes in emissions in relation to the progression of the drive cycle which is a key aspect to the behaviour discussed here. To improve understanding of this more, extensive analysis of hybrids would be needed to relate emission behaviour to drive cycle characteristics, journey length and powertrain architecture.

A key aspect of such improvements in analysis would include monitoring of the state of charge of the battery and the balance of power between engine and electric powertrains. The data presented here makes it clear that emission testing that obtains repeatable results is a much more complex endeavour with hybrid vehicles than with vehicles that only have an IC engine. Information on the state of charge of the battery appears to be essential for understanding the likely behaviour of an IC-engine hybrid vehicle's powertrain and its atmospheric emissions. Different states of battery charge in different parts of the drive cycle of the vehicles documented in this study, and the demand this places on the vehicles' powertrains is a credible explanation for some of the observed behaviour.

Unfortunately, battery charge state was not monitored in the PEMS tests used as data sources in this study, An understanding of the true state of charge of the battery would help validate this hypothesis and shed light on the way that different power management algorithms affect battery charging and vehicle performance. It could also assist in understanding the range and distribution of values of likely rates of emission on specific types of drive cycle section (e.g. urban, motorway, etc.)

### 6.8.8 Behavioural shift in typical journey type

DfT transport statistics for vehicle miles covered by vehicle type and road class in Great Britain between 2006-2018 show a roughly constant split between distance covered by passenger cars and taxis on motorways and high-speed extra-urban roads (31%), on principle extra urban and urban roads (34%) and on minor roads (35%) (DfT, 2019). 2006 is a key date in car and taxi statistics, as it marks the point in which the slow growth in total annual average car mileage driver per person stopped and remained roughly constant. There has, however, been a trend to slightly fewer, slightly longer trips per person per year (DfT, 2018a).

This study has noted that current hybrid vehicles provide least benefits in terms of emissions per unit distance (when compared with conventional IC engine equivalents) in high-speed drive cycles and greatest benefits in low speed ones. This suggests that the use of hybrid vehicles may being limited benefits in terms of greenhouse gas or air quality emissions to the 31% of high-speed vehicle distance and some of the 34% of vehicle distance driven on principle roads. However, it should be recognised that the high-speed road types likely to benefit least from hybrid vehicle emissions are those least likely to be near high-population density areas. It is the roughly 13% of vehicle distance driven on major urban roads that may prove the most challenging to reduce emissions on through the use of hybrid vehicles that charge their batteries off their own IC engines.

DfT statistics also suggest that vast majority of trips are relatively short, suggesting that these could be well served in future by purely electric vehicles or by plug-in hybrid vehicles operating on purely electric mode (“EV mode”). These could therefore provide the most effective emissions reduction option for these trips, with hybrids on non-EV mode.

# 7. Summary and discussion

This chapter draws together the findings of the research chapters, based on the approach set out in section 1.2. It highlights key findings, makes recommendations for further research and proposes options for future development of energy technology trajectory modelling.

## 7.1 Capabilities of energy technology trajectory models

Overviews of available tools for considering the future evolution of the UK's energy system suggests that only a few have the necessary properties to assess the impacts of both greenhouse gases and air pollutants.

Amongst these, two common challenges are clear:

- How to adequately describe the behaviour of emerging technologies, which may be more variable than those currently in use.
- How to accommodate geographical and spatial aspects that contribute to the cost of technology deployment, as well to the impact of its emissions.

### 7.1.1 Representing variable technology behaviour

The challenge of describing the behaviour of emerging technologies arises from the way that all the models work on the assumption that specific types of technology have specific emissions factors. This may be true if the technology definitions are narrow enough and are always operated in the same manner.

It ceases to be the case for technology types in which there is a choice of systems and the market is not yet mature. This can lead to several different types of end use technology being classified under the same label without it being clear which, if any, would see dominant use in the future. Examples of this uncertainty may occur in the case of post-combustion CCS systems, where it is not clear which $CO_2$ solvent technology is being used, leading to uncertainty on capture efficiency and the emissions from solvent degradation. Some attempts are made to overcome this in UK TIMES in the manner that emission factors can vary with fuel type for certain combustion systems, but this fails to address the above issue.

With current model architectures, this could be addressed by many more variants of emerging technologies being represented than is the case for incumbent ones. If different model architectures are developed, it could also be addressed by probabilistic modelling of emission factors. Probabilistic modelling is already used for cost handling in the ETI's ESME model (which does not yet cover air pollutant emissions), but no model yet applies probabilistic analysis to emissions factors.

Challenges also apply to describing emerging technologies that are complex systems, which may respond differently under repeatable, identical conditions, rather than ones that rely on a single energy source. From the research presented in this thesis, variable behaviour of hybrid vehicles in comparison with pure internal combustion ones is a clear example of this. Any type of hybrid vehicle powertrain is a more complex system than an IC one. The matter is further compounded by there being many different approaches to hybrid vehicle architectures, which behave differently. These are usually classified as a one technology (or two, if plug-in hybrids are differentiated) in the models considered here. A more disaggregated approach to representing these technologies may be necessary.

### 7.1.2 Representing spatial relationships

None of the model versions with the ability to represent air pollution has the capability to represent the spatial aspects of technology deployment. Whilst some versions of UK-MARKAL and UK TIMES can be operated in a regional manner to represent some spatial distribution of energy infrastructure, this does not yet include the version of UK TIMES for which air pollutant emission budgets have been developed.

This has implications for calculating the cost of deployment, as it hinders estimation of the cost of constructing network infrastructure for new technology deployment, which can affect how these technologies are deployed by cost optimisation models. It also hinders assessing the impacts of air quality pollutants in that none of the models have an intrinsic description of the distance between the sources of pollutants and where they cause damage to vulnerable environmental areas and population centres.

For now, a post-hoc approach using tools such as AIM, which are designed to capture this relationship in simple assessment process may be the best interim solution. For more complex situations, use of a full air quality predication capability, such as is found in the UKIAM, may be more appropriate. Such an approach is not without limitations: the output of energy models must be compatible with the input categories used by the air pollutant impact prediction tools. Furthermore, the prediction tools may not incorporate descriptions of the technologies being deployed: UKIAM doesn’t include distributed energy, as NAEI does not include it as a source.

This is not a barrier when using UKIAM as a tool for assessing a specific scenario, such as in the study of distributed energy in this thesis, as the location of sources are specified in the scenario. However, the use of AIM as a post hoc analysis tool for emerging technologies would require prior geographical distributions of these technologies to be decided on and for air quality modelling to take place for to determine source-receptor relationships and derive impact factors.

Realistic assessment would require sources for which impact factors are developed to include transboundary emissions and those in the NAEI.

### 7.1.3 Accounting for air quality damage costs in overall system cost optimisation

Air quality pollutants represent a key challenge in energy technology trajectory models that have cost optimisation routines, as the costs of the impacts of the air pollution will influence the solutions that these models arrive at. Energy system models could give a clearer idea of trade-offs and synergies between decarbonisation and air pollutant reduction measures if they were able to handle impact factors (or calculate air pollution transport and exposure) natively and then feed the costs back into optimisation routines. However, it should be noted that such a step would still not reduce uncertainty arising from variable behaviour of technologies, as discussed in section 7.1.2. IN the case of mobile technology, such as vehicles, this behaviour would also introduce uncertainty over the location emissions from these technologies.

## 7.2 Decentralised energy – spatial representation challenges

### 7.2.1 Choice of combustion plant

The distributed energy modelling in Chapter 4 highlights the importance of fuel type for distributed energy generation. The scenarios in which unabated biomass boilers or reciprocating engines power CHP facilities produce greater localised and wide area increases in average annual $NO_x$ concentrations across the urban area than those for district CHP based on gas turbine plant.

The case of a district CHP system run off biomass highlights a clear trade-off between reducing net greenhouse gas emissions (which it would reduce, in comparison to a natural gas fired system) and air quality impact. The case of using reciprocating engines suggests such a scenario would increase both greenhouse gases and air pollution, with associated environmental and health costs.

### 7.2.2 Distribution and the impact of urban morphology

The modelling in Chapter 4 also demonstrates that changes in annual average air pollutant concentrations from physical shifts in combustion-based power generation energy can be highly localised. This is especially the case for areas close to the combustion plant in energy scenarios with a high degree of decentralised combustion plant, such as CHP facilities feeding district heat networks. Resulting exposure and public health impacts of distributed energy in these will be highly dependent on the location of sources and potentially exposed population.

This implies that the overall economics of future energy scenarios involving highly distributed combustion plant will be affected by highly localised planning factors that affect air quality side, as these will determine the health impact costs. These include urban morphology, as the shape and distribution of buildings and the way these modify atmospheric pollutant diffusion and transport will play a key role in constraining diffusion.

Urban morphology is likely to play an even greater role in environments with taller buildings, as they may also hinder diffusion of pollutants from buoyant plumes of flue gases. This could reduce the amount of fall in annual average concentrations seen from moving from 20 m to 70 m stack heights in the examples given in Chapter 4.

For now, full assessment of the emissions from distributed combustion-based power generation appears to be one of the less-easily addressed challenges for future energy scenario modelling. Describing such localised characteristics of distributed energy is unlikely to be feasible for use in a national level model, such as the energy technology trajectory models.

Distributed generation of this sort is not yet included in the UKIAM as a source but is likely to be accommodated in the same manner that domestic boilers and transport are: as nationwide area sources, rather than as point sources. The high degree of coincidence with population centres (driven by heat demand) suggests that air pollution from these sources will have above average impacts per unit of pollutant emitted, in comparison to the average impact of the same pollutant (i.e. a tonne of $NO_x$ from distributed CHP will likely have a higher public health cost than that predicted by national average damage costs). If using impact factors that account for the geographical relation between pollution source and population, as AIM does, it may be possible to account for a degree of urban morphology. One method might be by treating distributed energy in high-rise and low-rise areas as two different sectors, with different associated levels (and uncertainty) of health impact for both.

## 7.3 Hybrid vehicles – operational representation challenges

### 7.3.1 Classification of hybrid powertrains

The findings of the chapter of this thesis on hybrid vehicles confirm that hybrid vehicles can offer clear benefits in terms of emissions reductions for greenhouse gases and air pollutants in comparison to their internal combustion engines counterparts.

Findings also suggest a clear need for finer distinctions to be drawn between different hybrid powertrain architectures. Even with the limited numbers of hybrids with data available in the PEMS studies used, there is evidence to suggest that:

- Hybrids exhibit highly variable degrees of conformation to speed dependent models of emission factors.
- The degree of reproducible emissions behaviour in similar situations varies between hybrids. This is possibly dependent on hybrid powertrain architecture. Reduced reproducibility may be linked to battery charge state and may be greater in plug-in hybrid vehicles.
- On the drive cycles considered in this study, not all hybrids delivered benefits in air quality or greenhouse gas emissions in comparison with the behaviour of range internal combustion engine equivalents.

The cause appears to be the result of such vehicles consisting of a system of multiple energy sources and stores (fuel, battery, engine and electric motor) in which the operation of one influences the operation of the other. The relationships are complicated further by the fact that stored energy can be exchanged between them (by battery charging) and that the powertrains can operate independently. The result is a system of much greater operational and behavioural complexity than a single fuel vehicle with a single powertrain or even a single powertrain, multiple fuel device.

The relationships between energy use, carbon intensity and predictability of emissions should become even more complex in the case of plug-in hybrid vehicles, which can accept energy input from an electricity grid, with a carbon intensity that will be highly dependent on location and time: the carbon intensity per mile of a vehicle charged at a period of low demand and high availability of low carbon generation (e.g. a windy night in the UK) will be very different from one charged at a time of high electricity demand and minimal low-carbon supply, when fossil fuel generation may be needed to balance the grid.

These produce challenges for representing hybrids in future energy scenarios using the methods of representation available in energy technology trajectory models.

### 7.3.2 Role of speed dependent and drive cycle dependent emission factors

The results of the PEMS measurements are sufficient to call into question the validity of the use of speed dependent emission factors for hybrid vehicles. These are currently used for predictive modelling of air pollutant emissions from the national vehicle fleet on the UK road network.

All modern vehicles have a high degree of automation in their operation and their powertrain management depends on a network of sensors, software and automated controls to optimise operation, control emission and protect the engine. The “Dieselgate” news has already shown how effectively these systems can modify emissions characteristics of vehicles. In the case of pure IC powertrain vehicles, such software needs to manage engine behaviour near-instantaneously according to power demand and operating parameters such as temperatures of the engine and exhaust gas aftertreatment system. Under normal operating conditions and temperatures this is likely to provide a high degree of correlation with power demand and speed.

A hybrid vehicle’s powertrain management system needs to account for additional operational factors, such as the need to charge its battery, how much this draws on the engine and regenerative brakes to do so and when it can supply power to the electric motor is managed. It may also account for issues such as the need to run the internal combustion engine sufficiently to keep the emissions control system at operating temperature. These are all non-instantaneous factors that apply to the drive cycle, such as the frequency and intensity of acceleration and braking. It appears plausible that hybrid vehicles' emission factors for both greenhouse gases and air pollutants may be influenced as much by drive cycle than speed.

Better representation of hybrids within current energy technology trajectory models may be helped by understanding how average emissions for hybrid vehicles vary with characteristic sections of drive cycle (high intensity, low intensity, high maximum speed, low maximum speed, etc). Understanding how these vary between hybrid powertrain architecture would facilitate this. Developing the capability of models to describe the multiple hybrid powertrain solutions separately and to understand the demand for vehicle kilometres in each type of drive cycle could help optimisation routines in these models identify the most effective types of powertrain for reducing emissions in each transport demand scenario.

## 7.4 Use of thesis findings in policy development

The evidence base developed by this thesis' research has been used in real world policy making during the course of its preparation. This includes work in the following areas:

- **Development of the 2050 Calculator successor tool (2016-19) –** The evidence on the limitations and potential improvements to the 2050 Carbon Calculator was provide to and used by the group developing the calculator designed to succeed it. This focused on clearer representation of novel technologies and of their impact on energy demand.
- **BEIS / Defra development of UK Air Quality Strategy (2017-18) –** Evidence on the importance of location of combustion sources, described in the chapter on district energy, has been used in determining the appropriate methods of considering the impact of biomass combustion.
- **DfT / Defra / DECC analysis of diesel vehicle emissions uncertainty (2014-15) –** Evidence from the vehicle PEMS analysis chapter on the behaviour of diesel hybrid and diesel vehicles

was used to illustrate the uncertainties in future vehicle emissions in an interdepartmental assessment of air pollution and greenhouse gases from road transport.

- **Understanding impact of diesel farms in the capacity / triad market (2015-16) –** Evidence on the importance of the geographical relationship between pollutant sources and exposed population, described in the chapter on district energy, has been used in understanding the risks posed by a possibility of increased diesel-fuelled internal combustion generation of electricity in populated areas.
- **Considering strategy about the role of biomass in domestic sector heat away from gas / H2 grids (2018-19) –** Evidence on the importance of location of combustion sources in relation to population density, described in the chapter on district energy, has been used in determining the appropriate methods of considering the impact of air pollution from solid biomass combustion in providing residential heating in areas off the gas grid.
- **Considering impacts of options for industrial heat decarbonisation (2018-19) –** Evidence on the importance of location of combustion sources in relation to population density, described in the chapter on district energy, and in the limitations that the temporal resolution of UK TIMES has was used in clarifying the limitations of analytical tools. This clarified these issues for policy teams working in industrial heat decarbonisation and was taken into account in their analysis.
- **Assessing net benefits / impacts of proposed BEIS energy innovation grants (2016-19) –** Evidence on the air pollution impact of diesel engines in the district energy chapter was used to explain the risk of air pollution impacts from novel energy generation technologies using bioliquids in diesel engines.

## 7.5 Recommendations for taking research forward

### 7.5.1 Publication potential

During the development of this thesis, it was the choice of the author to focus on putting the findings of the research to practical use in public policy development. This was due to the opportunities afforded by the author's direct involvement in this area. This decision precluded the preparation and publication of peer reviewed papers on the subject, although opportunities remain open to do so in the future. The evidence presented in this thesis is considered of particular relevance to publications in the following areas:

- The role of time-dependent effects and of temporal resolution in energy trajectory models.
- Representation of pollution source-receptor relationships in energy trajectory models.
- The role of spatial representation capability and spatial resolution in representing technologies in energy models.
- The role of urban characterisation (heat demand mapping, population density, urban morphology) in assessing future energy scenarios.
- Challenges and uncertainties in representing hybrid vehicle powertrains in energy models.
- Variability in emissions behaviour and differences in this variability between different hybrid vehicle powertrain architectures.
- The policy implications of public perceptions of the benefits of hybrid vehicles and how real world drive cycle data may influence this.

### 7.5.2 Recommendations for future work

This thesis highlights how the air quality impacts of an individual energy technology can vary with choices of design (e.g. powertrain architecture), location and time. It demonstrates the limitations of low spatial or temporal resolution and of low detail on technology representation in energy trajectory models and how these can hinder technology performance being represented in model output. Increased resolution in these would allow better representation of how these influence costs, efficacy and environmental impacts of technology (e.g. hybrid vehicles, energy storage, infrastructure build, etc.). Future work to develop more accurate representations of technologies' emissions behaviour and how this varies between different implementations of the same technology may help increase the number of real-world situations in which the model results have relevance. Such work should also help users to clarify and accommodate uncertainty in energy system optimisation models an offer insight into technologies' sensitivity to these.

Using models in a linked manner offers an approach to improving technology representation, as UCL has shown with its combined use of UK TIMES and HIRES. The use of air quality emissions impact factors for technologies offers another. Developing these for use with energy technology trajectory models could allow quicker assessment of air quality impacts. These should account for a specified geographical distribution of each technology in relation to major population centres and environmentally sensitive areas and will thus be specific to clearly defined geographical regions, in common with certain existing air quality emission factors Impact factors would need to be applicable to sectors and single sources, which could match with those of common national reporting or modelling tools, such as DUKES or TIMES in the case of the UK in order to maximise ease of use.

Energy technology trajectory models with optimisation routines that account for the impacts of air pollutant emission budgets should be developed to accommodate the cost of air pollution in the optimisation routines.

Development is needed of approaches to help account for highly localised factors that may affect the concentrations of air pollutants of populations and vulnerable environmental sites. These should aim to account for effects that appear when sources and receptors of pollution are near each other, as may be encountered in deployment of decentralised combustion-based power generation and should address the manner that urban and landform morphology may increase or decrease exposure. Even if it is not possible to predict the degree to which exposure changes, it should be possible to develop methods to highlight locations where there is an increased risk of uncertainty over exposure. This could be based on and differentiate between key types of urban and landform morphology.

More research is needed into how the emission of greenhouse gases and air pollutants vary with different hybrid vehicle powertrain architectures. Currently, there are a wide variety of technology approaches to implementing hybrid vehicle architectures.

Although market maturation may decrease this variety, it is not yet clear what the long-term role of hybrid vehicles may be in a lower carbon transport sector or which implementations of hybrid powertrains may come to dominate that role. Research should include direct PEMS measurements of hybrid vehicles to determine the bounds of operational behaviour under different types of real-world drive cycles. It should also include detail on the state of charge of the vehicle's battery and the power cycling of the charging and electric motor system, in order to better understand its impact on the power loading of the internal combustion engine of such vehicles. This would allow the application of statistical tests to hybrid vehicle drive cycle data to reconcile the state of the powertrain (including battery charge state) with emissions and fuel consumption. It may also prove valuable in developing an understanding of the potential of using plug-in hybrid vehicles in "vehicle-to-grid" applications, where the battery is connected to the electricity grid and used to store and retrieve energy.

PEMS emissions data from hybrid vehicles should be used to assess whether reliable emission factors for hybrids can be developed, based on characteristic sections of drive cycle, as well as speed. This should consider how this varies between different hybrid powertrain architectures and whether meaningful emission factors can be developed for use in energy scenario modelling tools.

# Glossary

**BEIS** – Department of Business, Energy and Industrial Strategy: the UK's energy ministry from 2017.

**BEV** – Battery electric vehicle.

**CCS** – Carbon Capture and Storage: the capture of carbon dioxide emissions form combustion processes and their subsequent storage to prevent their release to the atmosphere.

**CCGT** – Combined cycle gas turbine: typically referring to the electricity generation technology or plant type. This is a type of thermal electricity generation plant using gas combustion to simultaneously power two different thermodynamic cycles to drive mechanical based power generation to increase efficiency over a single (or open) cycle plant. Typical grid plant combines a Brayton cycle gas turbine and a Rankine cycle steam turbine.

**CHP** – Combined Heat and Power: cogeneration of utility heat and electricity from the same facility.

**CLRTAP** – Convention on Long-Range Transboundary Air Pollution.

**DECC** – Department of Energy and Climate Change: UK's energy ministry from 2008 – 2017.

**EMEP** - European Monitoring and Evaluation Programme for the Convention on Long Range Transboundary Air Pollution.

**EURO** (standard) – A series of standards used in the European Union to set minimum standards of air pollutant emissions for newly sold vehicles.

**EV** – Electric vehicle.

**FRAME** – Fine Resolution Atmospheric Multi-pollutant Exchange model.

**GAINS** – Greenhouse Gas and Air Pollution Interactions and Synergies model, developed by the International Institute for Applied Systems Analysis.

**HIRES** – A high temporal resolution energy model developed by University College London, with the aim of better representing the behaviour of energy systems with a high level of renewable energy deployment.

**HEV** – Hybrid electric vehicle

**IC / ICE** – Internal combustion / internal combustion engine.

**LRTAP** – Long-Range Transboundary Air Pollution.

**LULUCF –** Land Use, Land Use Change and Forestry: One of the sector classifications of national greenhouse gas emission used in the 2050 Carbon Calculator and in national reporting to the United Nations Framework Convention on Climate Change.

**OCGT** – Open cycle gas turbine: typically referring to the electricity generation technology or plant type. This is a type of thermal electricity generation plant using gas combustion to power a single thermodynamic cycle to drive mechanical based power, typically a Brayton cycle gas turbine.

**PM / $PM_{10}$ / $PM_{2.5}$** – Particulate matter, subscripts denote classification by maximum particle size in micrometres.

**PRIMES** – Price-Induced Market Equilibrium System, an energy markets model used as the basis of energy system activity in the GAINS model.

**MARKAL** – Market Allocation model, a cost optimisation model

**$NH_3$** – Ammonia.

**$NO_x$** – Oxides of nitrogen, usually applied to oxides of nitrogen in positive oxidation states.

**$NO_2$** – Nitrogen dioxide, also known as nitrous oxide.

**$O_3$** – Ozone.

**PHEV** – Plug-in hybrid electric vehicle.

**RAINS** – Regional Air Pollution Information and Simulation model, developed by the International Institute for Applied Systems Analysis.

**$SO_2$** – Sulphur dioxide.

**$SO_x$** – Oxides of sulphur.

**TIMES** – The Integrated MARKAL-EFOM System, the successor energy system optimisation model to MARKAL.

**UEP / EEP** – Updated Emissions Projections / Energy and Emissions Projections: forecasts of the UK's energy demand, energy use and atmospheric emissions from energy use produced by successive UK energy and economy ministries.

**UK TIMES** – a version of the TIMES modelling system developed to describe the UK's energy economy.

**VOC** – Volatile organic compounds : a class of air pollutant consisting of organic compounds that vaporise at ambient environmental temperatures.

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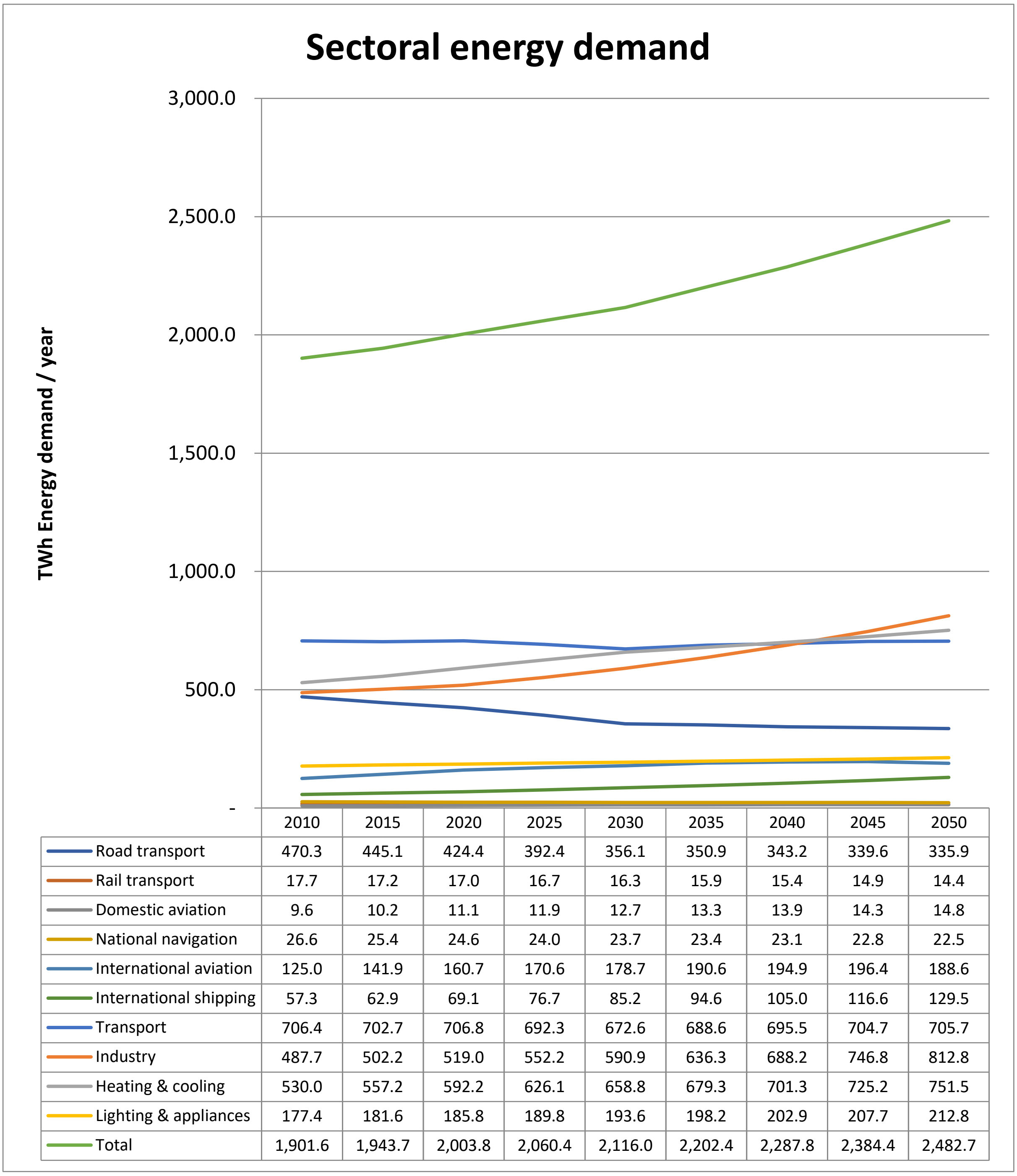
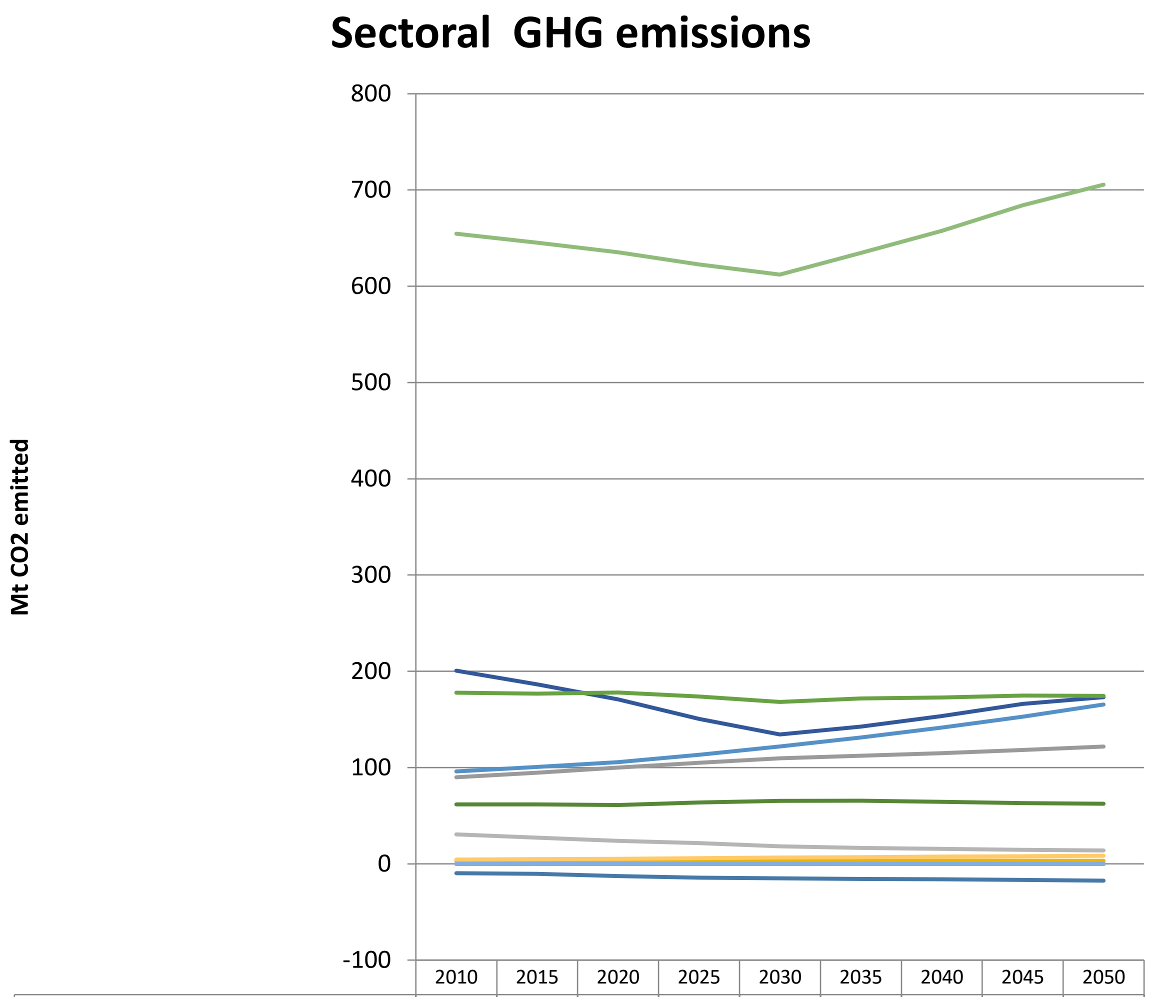
# Appendix A: Energy and air pollution data for 2050 Carbon Calculator Scenarios

## A.1 Scenario 1

Energy Landscape

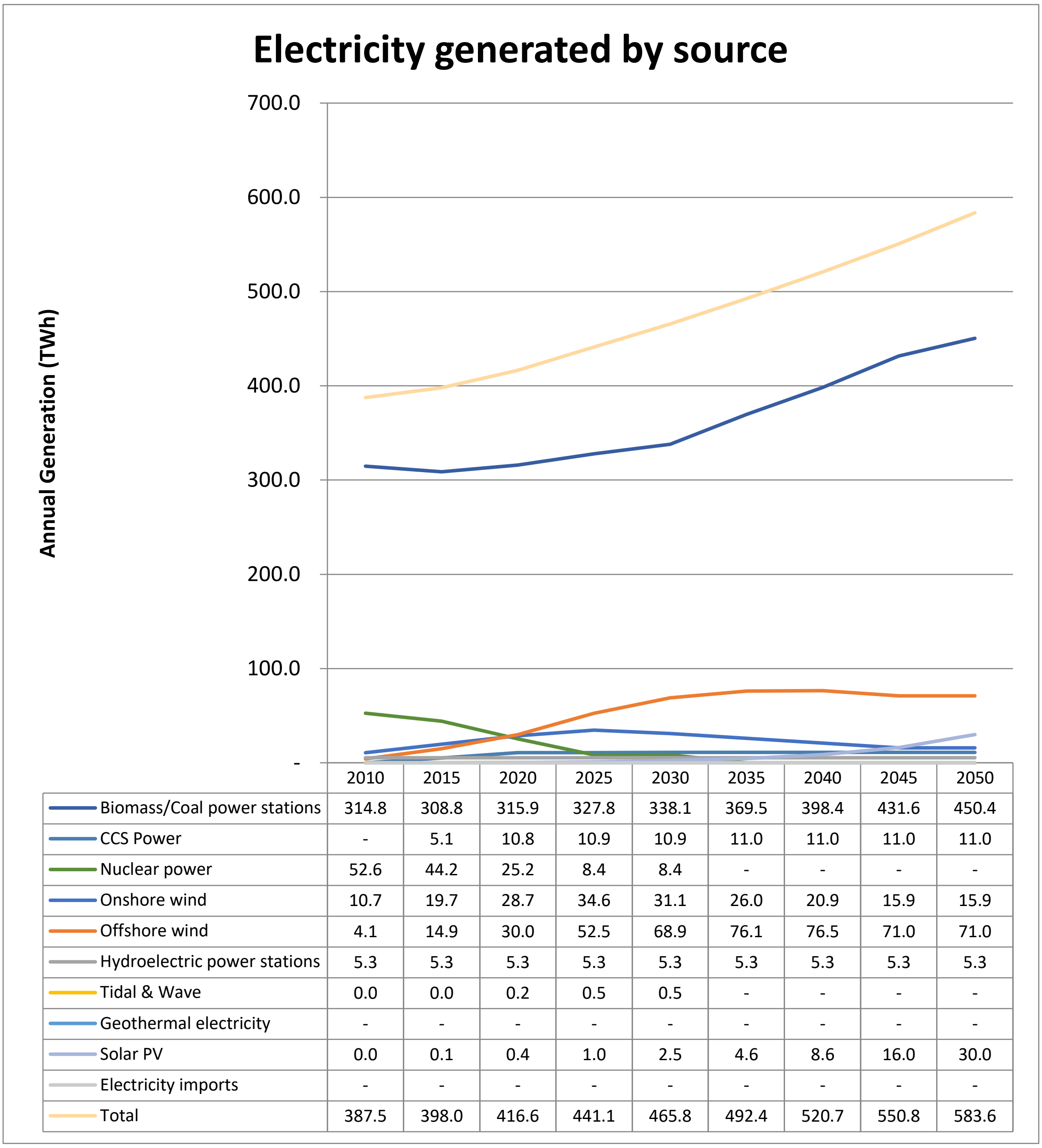


| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Road transport | 470.3 | 445.1 | 424.4 | 392.4 | 356.1 | 350.9 | 343.2 | 339.6 | 335.9 |
| Rail transport | 17.7 | 17.2 | 17.0 | 16.7 | 16.3 | 15.9 | 15.4 | 14.9 | 14.4 |
| Domestic aviation | 9.6 | 10.2 | 11.1 | 11.9 | 12.7 | 13.3 | 13.9 | 14.3 | 14.8 |
| National navigation | 26.6 | 25.4 | 24.6 | 24.0 | 23.7 | 23.4 | 23.1 | 22.8 | 22.5 |
| International aviation | 125.0 | 141.9 | 160.7 | 170.6 | 178.7 | 190.6 | 194.9 | 196.4 | 188.6 |
| International shipping | 57.3 | 62.9 | 69.1 | 76.7 | 85.2 | 94.6 | 105.0 | 116.6 | 129.5 |
| Transport | 706.4 | 702.7 | 706.8 | 692.3 | 672.6 | 688.6 | 695.5 | 704.7 | 705.7 |
| Industry | 487.7 | 502.2 | 519.0 | 552.2 | 590.9 | 636.3 | 688.2 | 746.8 | 812.8 |
| Heating & cooling | 530.0 | 557.2 | 592.2 | 626.1 | 658.8 | 679.3 | 701.3 | 725.2 | 751.5 |
| Lighting & appliances | 177.4 | 181.6 | 185.8 | 189.8 | 193.6 | 198.2 | 202.9 | 207.7 | 212.8 |
| Total | 1,901.6 | 1,943.7 | 2,003.8 | 2,060.4 | 2,116.0 | 2,202.4 | 2,287.8 | 2,384.4 | 2,482.7 |

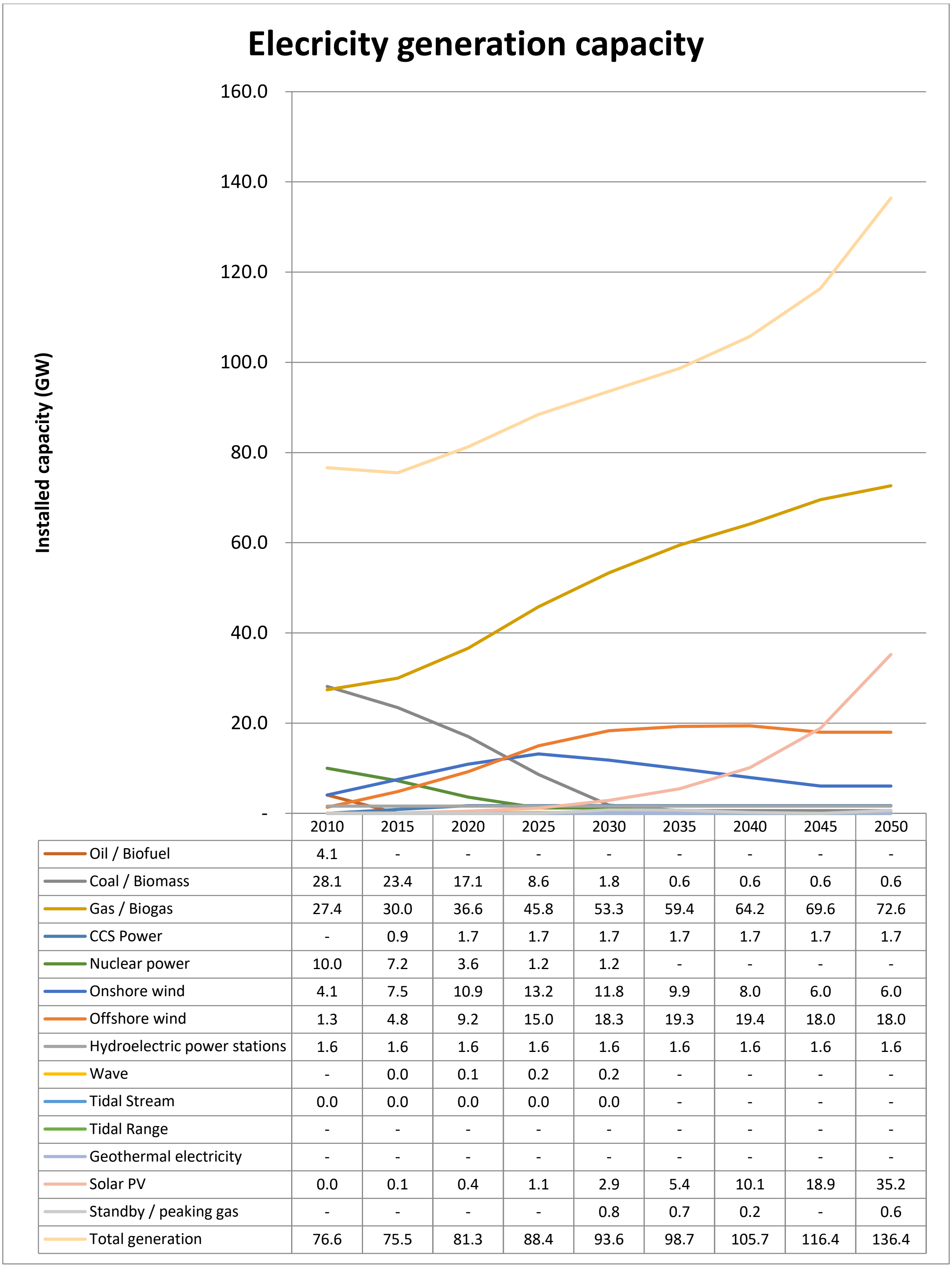


| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| — Hydrocarbon fuel power generation | 201 | 186 | 171 | 151 | 134 | 143 | 154 | 166 | 173 |
| — Nuclear power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| — National renewable power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| — Distributed renewable power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| — Bioenergy | -10 | -10 | -13 | -14 | -15 | -16 | -16 | -17 | -17 |
| — Agriculture and waste | 62 | 62 | 61 | 64 | 65 | 66 | 65 | 63 | 62 |
| — Electricity distribution, storage, and balancing | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| — H2 Production | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| — Heating | 90 | 95 | 100 | 105 | 110 | 112 | 115 | 118 | 122 |
| — Lighting and appliances | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| — Industry | 96 | 101 | 106 | 113 | 122 | 131 | 142 | 153 | 166 |
| — Transport | 178 | 177 | 178 | 174 | 168 | 172 | 173 | 175 | 175 |
| — Geosequestration | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| — Fossil fuel production | 31 | 27 | 24 | 21 | 18 | 17 | 16 | 15 | 14 |
| — Transfers | 4 | 5 | 5 | 6 | 7 | 7 | 7 | 8 | 8 |
| — District heating | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| — Total | 655 | 645 | 635 | 623 | 612 | 635 | 658 | 684 | 706 |

Electricity sector



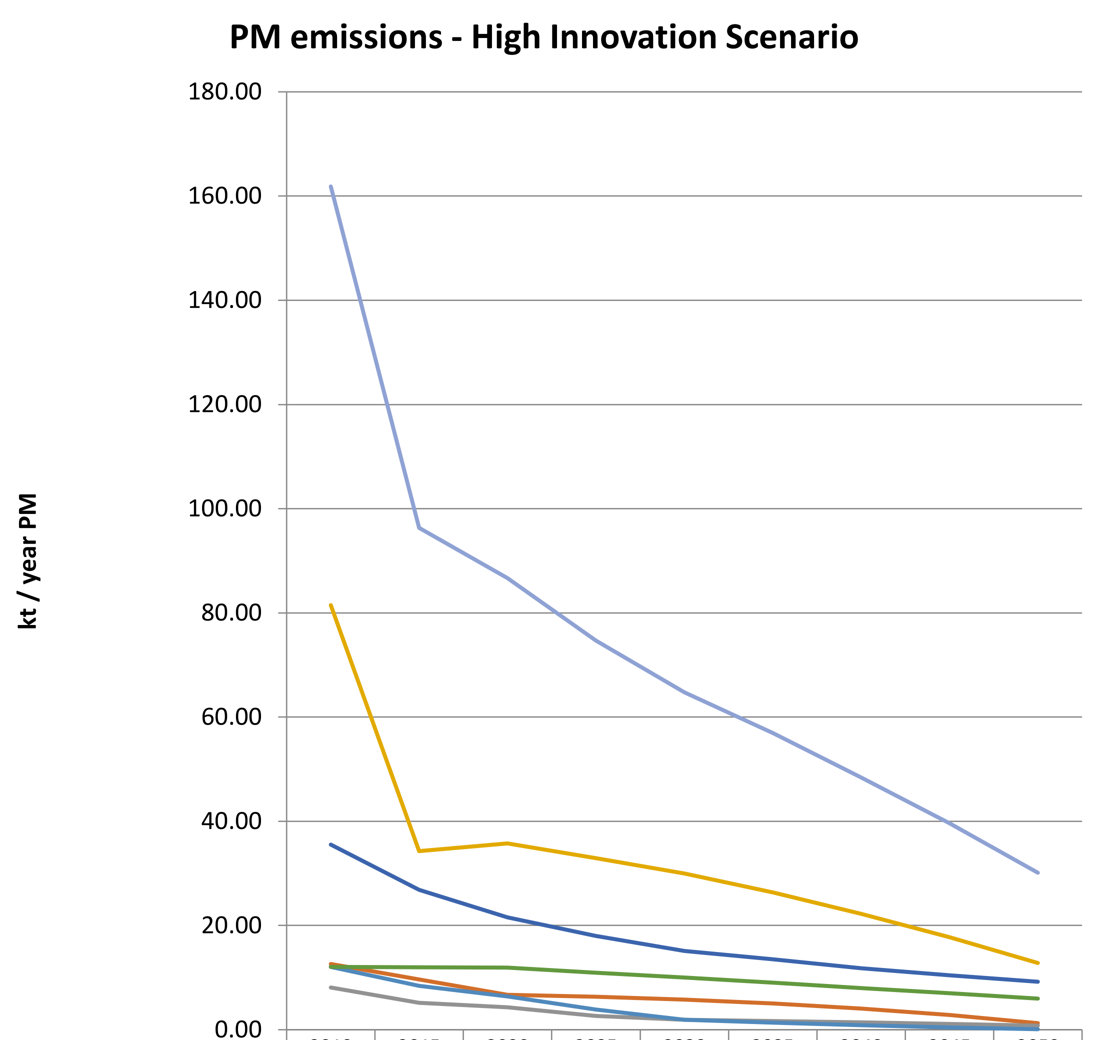
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Biomass/Coal power stations | 314.8 | 308.8 | 315.9 | 327.8 | 338.1 | 369.5 | 398.4 | 431.6 | 450.4 |
| CCS Power | - | 5.1 | 10.8 | 10.9 | 10.9 | 11.0 | 11.0 | 11.0 | 11.0 |
| Nuclear power | 52.6 | 44.2 | 25.2 | 8.4 | 8.4 | - | - | - | - |
| Onshore wind | 10.7 | 19.7 | 28.7 | 34.6 | 31.1 | 26.0 | 20.9 | 15.9 | 15.9 |
| Offshore wind | 4.1 | 14.9 | 30.0 | 52.5 | 68.9 | 76.1 | 76.5 | 71.0 | 71.0 |
| Hydroelectric power stations | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 |
| Tidal & Wave | 0.0 | 0.0 | 0.2 | 0.5 | 0.5 | - | - | - | - |
| Geothermal electricity | - | - | - | - | - | - | - | - | - |
| Solar PV | 0.0 | 0.1 | 0.4 | 1.0 | 2.5 | 4.6 | 8.6 | 16.0 | 30.0 |
| Electricity imports | - | - | - | - | - | - | - | - | - |
| Total | 387.5 | 398.0 | 416.6 | 441.1 | 465.8 | 492.4 | 520.7 | 550.8 | 583.6 |



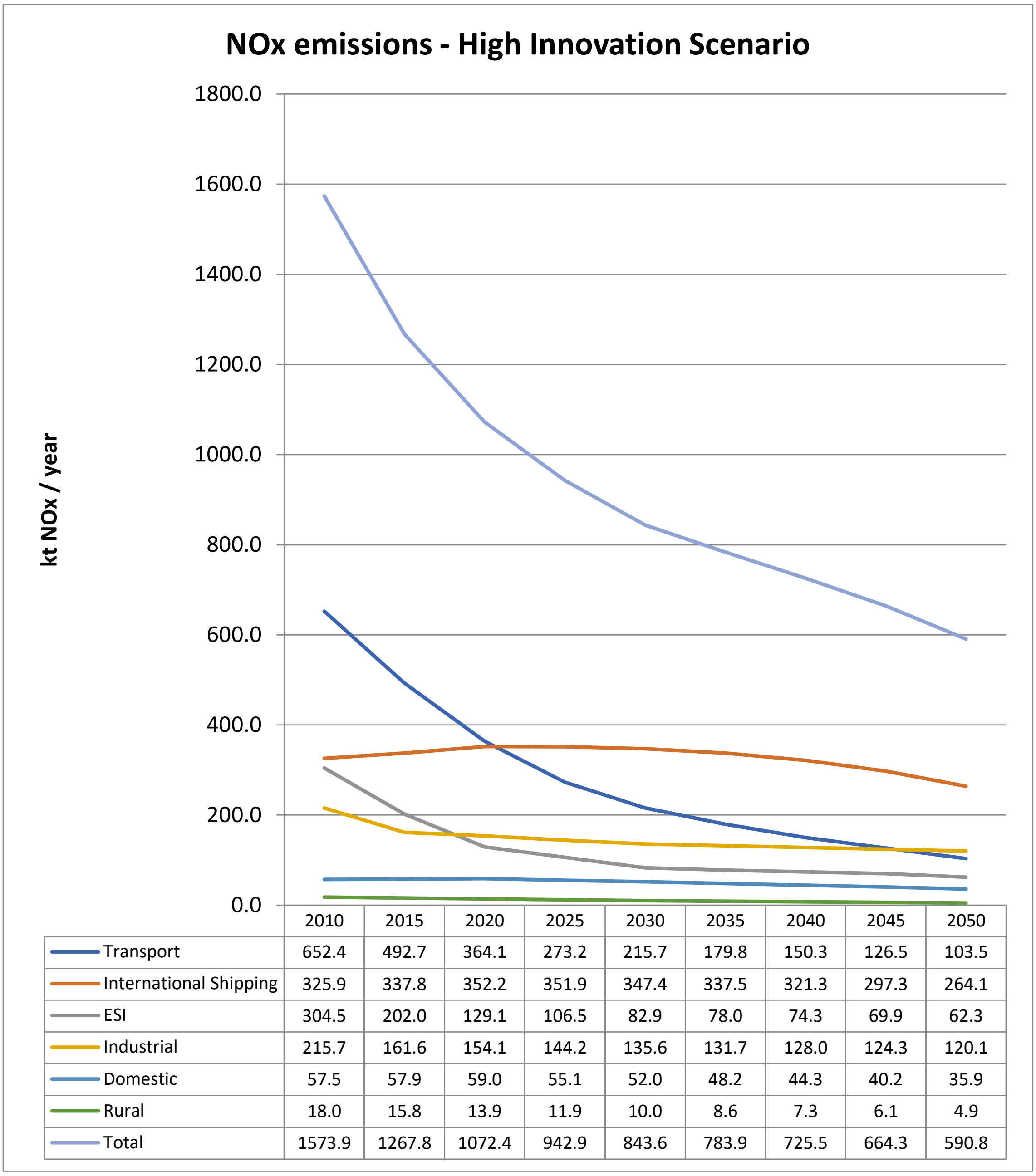
Elecricity generation capacity

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Oil / Biofuel | 4.1 | - | - | - | - | - | - | - | - |
| Coal / Biomass | 28.1 | 23.4 | 17.1 | 8.6 | 1.8 | 0.6 | 0.6 | 0.6 | 0.6 |
| Gas / Biogas | 27.4 | 30.0 | 36.6 | 45.8 | 53.3 | 59.4 | 64.2 | 69.6 | 72.6 |
| CCS Power | - | 0.9 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 |
| Nuclear power | 10.0 | 7.2 | 3.6 | 1.2 | 1.2 | - | - | - | - |
| Onshore wind | 4.1 | 7.5 | 10.9 | 13.2 | 11.8 | 9.9 | 8.0 | 6.0 | 6.0 |
| Offshore wind | 1.3 | 4.8 | 9.2 | 15.0 | 18.3 | 19.3 | 19.4 | 18.0 | 18.0 |
| Hydroelectric power stations | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |
| Wave | - | 0.0 | 0.1 | 0.2 | 0.2 | - | - | - | - |
| Tidal Stream | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | - | - | - | - |
| Tidal Range | - | - | - | - | - | - | - | - | - |
| Geothermal electricity | - | - | - | - | - | - | - | - | - |
| Solar PV | 0.0 | 0.1 | 0.4 | 1.1 | 2.9 | 5.4 | 10.1 | 18.9 | 35.2 |
| Standby / peaking gas | - | - | - | - | 0.8 | 0.7 | 0.2 | - | 0.6 |
| Total generation | 76.6 | 75.5 | 81.3 | 88.4 | 93.6 | 98.7 | 105.7 | 116.4 | 136.4 |

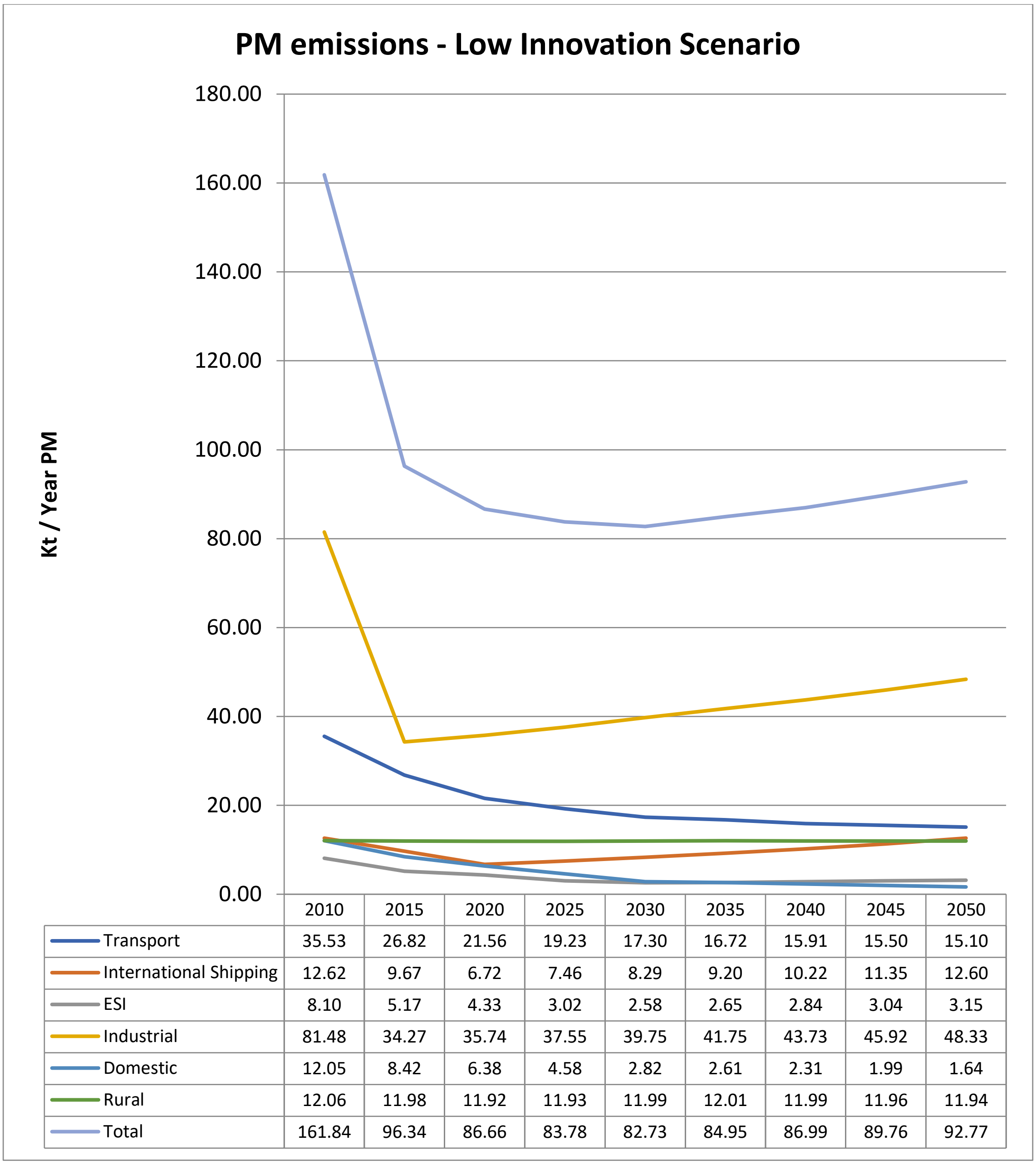
Air pollution



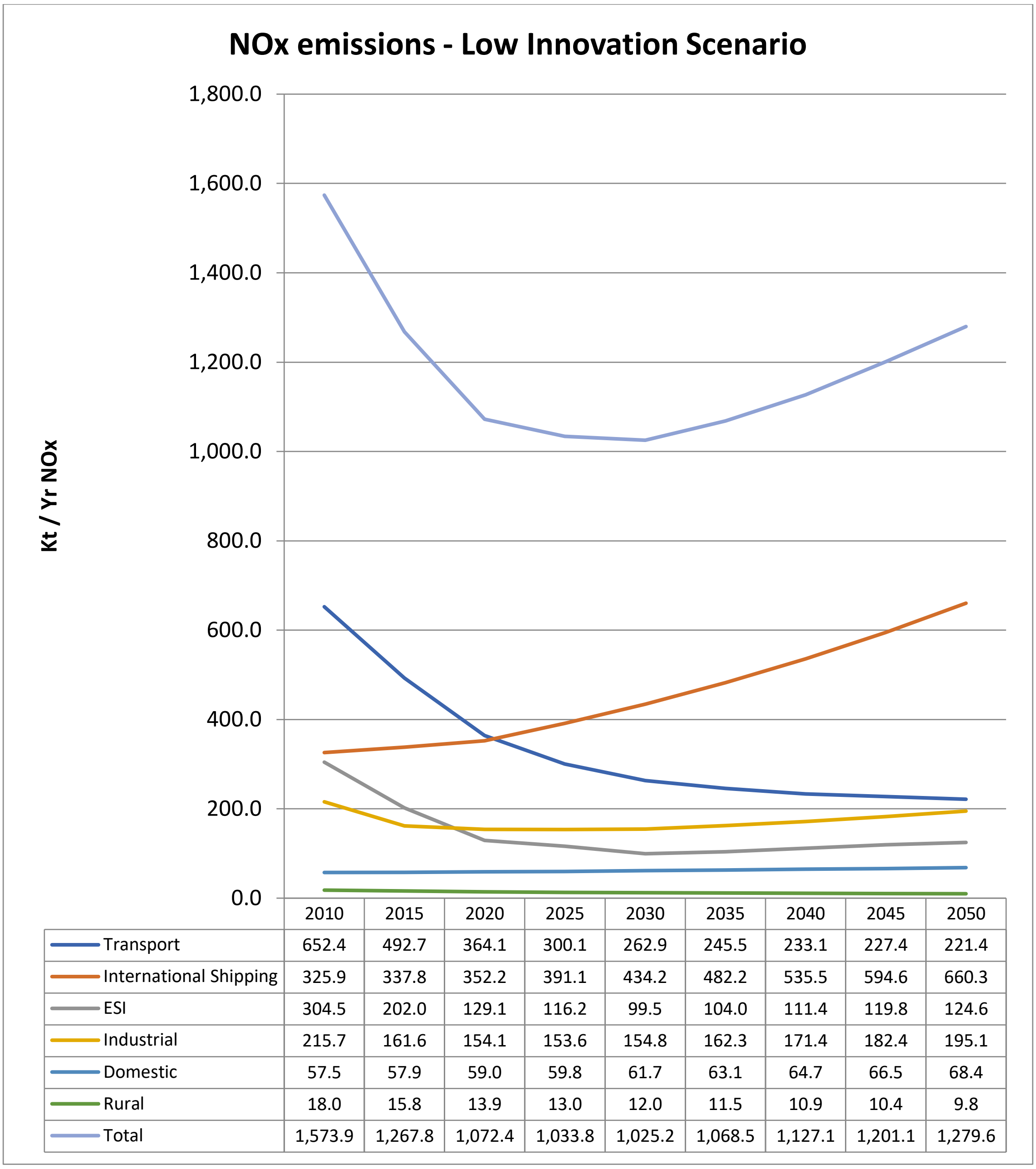
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 35.53 | 26.82 | 21.56 | 18.03 | 15.09 | 13.50 | 11.79 | 10.47 | 9.21 |
| International Shipping | 12.62 | 9.67 | 6.72 | 6.34 | 5.80 | 5.06 | 4.09 | 2.84 | 1.26 |
| ESI | 8.10 | 5.17 | 4.33 | 2.64 | 1.93 | 1.66 | 1.42 | 1.14 | 0.79 |
| Industrial | 81.48 | 34.27 | 35.74 | 32.93 | 29.97 | 26.37 | 22.27 | 17.77 | 12.81 |
| Domestic | 12.05 | 8.42 | 6.38 | 3.85 | 1.93 | 1.37 | 0.85 | 0.42 | 0.10 |
| Rural | 12.06 | 11.98 | 11.92 | 10.94 | 9.99 | 9.00 | 7.99 | 6.98 | 5.97 |
| Total | 161.84 | 96.34 | 86.66 | 74.73 | 64.72 | 56.97 | 48.41 | 39.62 | 30.13 |


NOx emissions - High Innovation Scenario

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 652.4 | 492.7 | 364.1 | 273.2 | 215.7 | 179.8 | 150.3 | 126.5 | 103.5 |
| International Shipping | 325.9 | 337.8 | 352.2 | 351.9 | 347.4 | 337.5 | 321.3 | 297.3 | 264.1 |
| ESI | 304.5 | 202.0 | 129.1 | 106.5 | 82.9 | 78.0 | 74.3 | 69.9 | 62.3 |
| Industrial | 215.7 | 161.6 | 154.1 | 144.2 | 135.6 | 131.7 | 128.0 | 124.3 | 120.1 |
| Domestic | 57.5 | 57.9 | 59.0 | 55.1 | 52.0 | 48.2 | 44.3 | 40.2 | 35.9 |
| Rural | 18.0 | 15.8 | 13.9 | 11.9 | 10.0 | 8.6 | 7.3 | 6.1 | 4.9 |
| Total | 1573.9 | 1267.8 | 1072.4 | 942.9 | 843.6 | 783.9 | 725.5 | 664.3 | 590.8 |


PM emissions - Low Innovation Scenario

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 35.53 | 26.82 | 21.56 | 19.23 | 17.30 | 16.72 | 15.91 | 15.50 | 15.10 |
| International Shipping | 12.62 | 9.67 | 6.72 | 7.46 | 8.29 | 9.20 | 10.22 | 11.35 | 12.60 |
| ESI | 8.10 | 5.17 | 4.33 | 3.02 | 2.58 | 2.65 | 2.84 | 3.04 | 3.15 |
| Industrial | 81.48 | 34.27 | 35.74 | 37.55 | 39.75 | 41.75 | 43.73 | 45.92 | 48.33 |
| Domestic | 12.05 | 8.42 | 6.38 | 4.58 | 2.82 | 2.61 | 2.31 | 1.99 | 1.64 |
| Rural | 12.06 | 11.98 | 11.92 | 11.93 | 11.99 | 12.01 | 11.99 | 11.96 | 11.94 |
| Total | 161.84 | 96.34 | 86.66 | 83.78 | 82.73 | 84.95 | 86.99 | 89.76 | 92.77 |

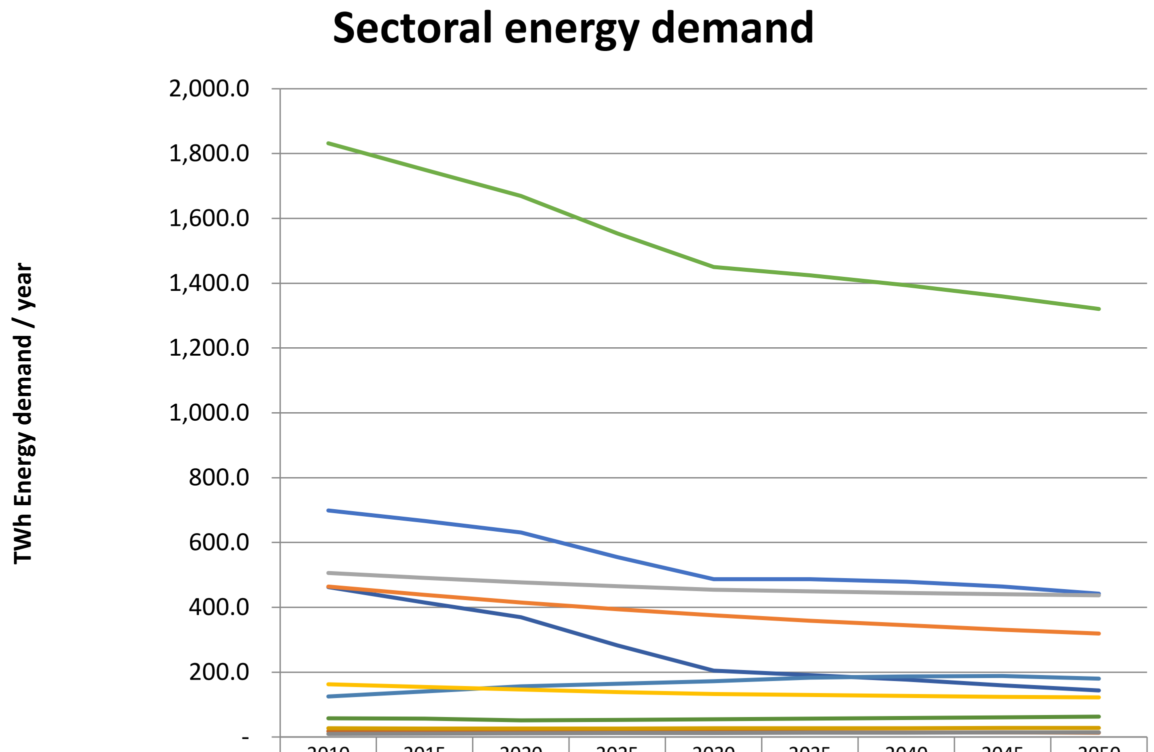


NOx emissions - Low Innovation Scenario

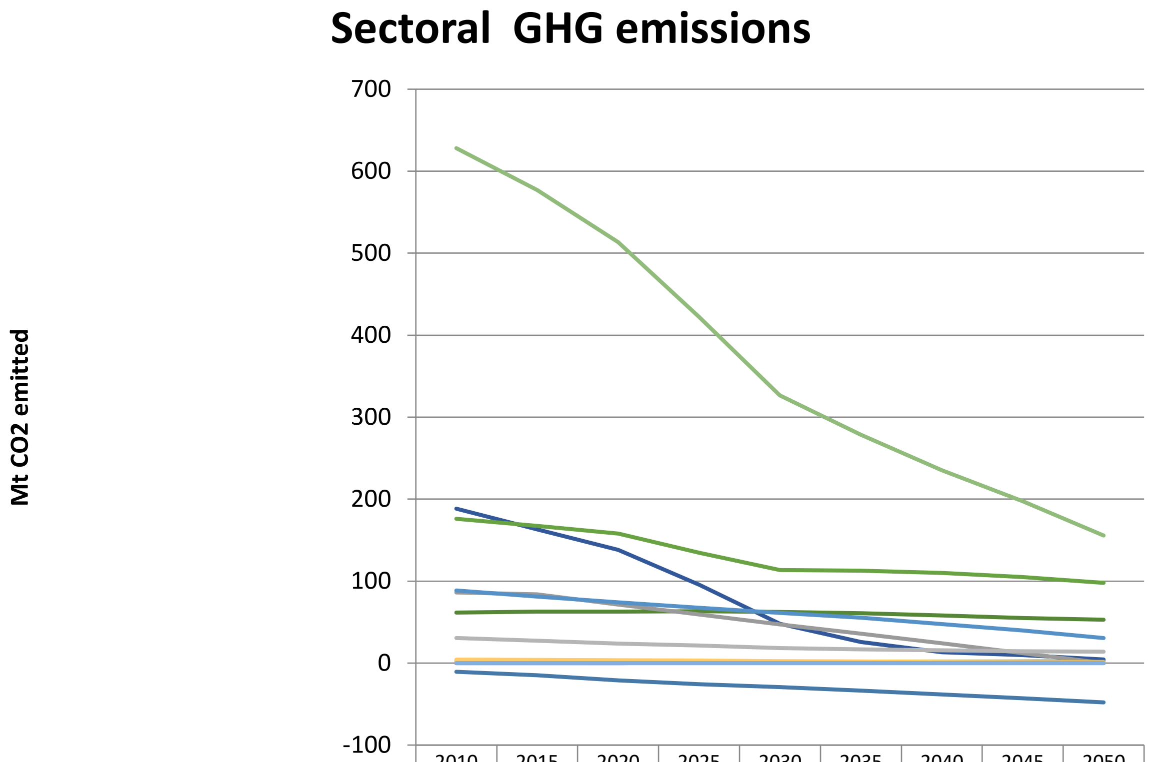
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 652.4 | 492.7 | 364.1 | 300.1 | 262.9 | 245.5 | 233.1 | 227.4 | 221.4 |
| International Shipping | 325.9 | 337.8 | 352.2 | 391.1 | 434.2 | 482.2 | 535.5 | 594.6 | 660.3 |
| ESI | 304.5 | 202.0 | 129.1 | 116.2 | 99.5 | 104.0 | 111.4 | 119.8 | 124.6 |
| Industrial | 215.7 | 161.6 | 154.1 | 153.6 | 154.8 | 162.3 | 171.4 | 182.4 | 195.1 |
| Domestic | 57.5 | 57.9 | 59.0 | 59.8 | 61.7 | 63.1 | 64.7 | 66.5 | 68.4 |
| Rural | 18.0 | 15.8 | 13.9 | 13.0 | 12.0 | 11.5 | 10.9 | 10.4 | 9.8 |
| Total | 1,573.9 | 1,267.8 | 1,072.4 | 1,033.8 | 1,025.2 | 1,068.5 | 1,127.1 | 1,201.1 | 1,279.6 |

## A.2 Scenario 2

Energy Landscape



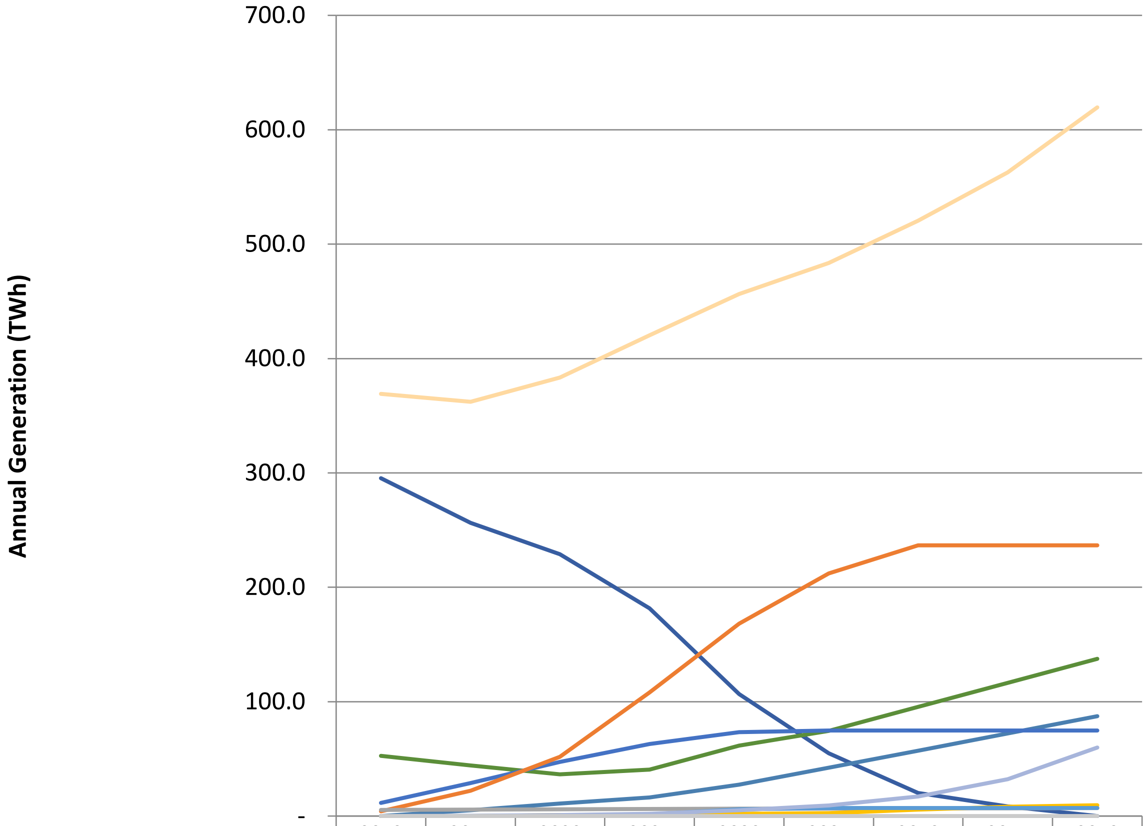
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Road transport | 462.5 | 415.2 | 369.5 | 282.5 | 204.5 | 191.1 | 177.2 | 159.5 | 143.6 |
| Rail transport | 17.9 | 17.8 | 17.1 | 16.9 | 16.0 | 15.4 | 14.6 | 13.8 | 13.1 |
| Domestic aviation | 9.4 | 10.1 | 11.0 | 11.9 | 12.6 | 13.2 | 13.7 | 14.1 | 14.5 |
| National navigation | 26.8 | 26.3 | 26.2 | 26.2 | 26.6 | 26.9 | 27.3 | 27.7 | 28.0 |
| International aviation | 125.0 | 140.7 | 156.0 | 164.6 | 172.6 | 183.3 | 187.4 | 188.2 | 180.3 |
| International shipping | 57.3 | 56.3 | 51.3 | 53.0 | 54.9 | 56.7 | 58.7 | 60.7 | 62.8 |
| Transport | 698.9 | 666.4 | 631.2 | 555.1 | 487.1 | 486.6 | 478.9 | 464.0 | 442.2 |
| Industry | 464.2 | 438.8 | 415.0 | 394.2 | 375.3 | 359.0 | 344.4 | 331.2 | 319.2 |
| Heating & cooling | 506.1 | 490.8 | 476.8 | 465.3 | 454.6 | 449.2 | 444.4 | 440.4 | 437.1 |
| Lighting & appliances | 162.6 | 154.0 | 146.1 | 139.0 | 132.9 | 129.5 | 126.5 | 124.1 | 122.2 |
| Total | 1,831.9 | 1,749.9 | 1,669.1 | 1,553.7 | 1,449.9 | 1,424.3 | 1,394.2 | 1,359.7 | 1,320.7 |



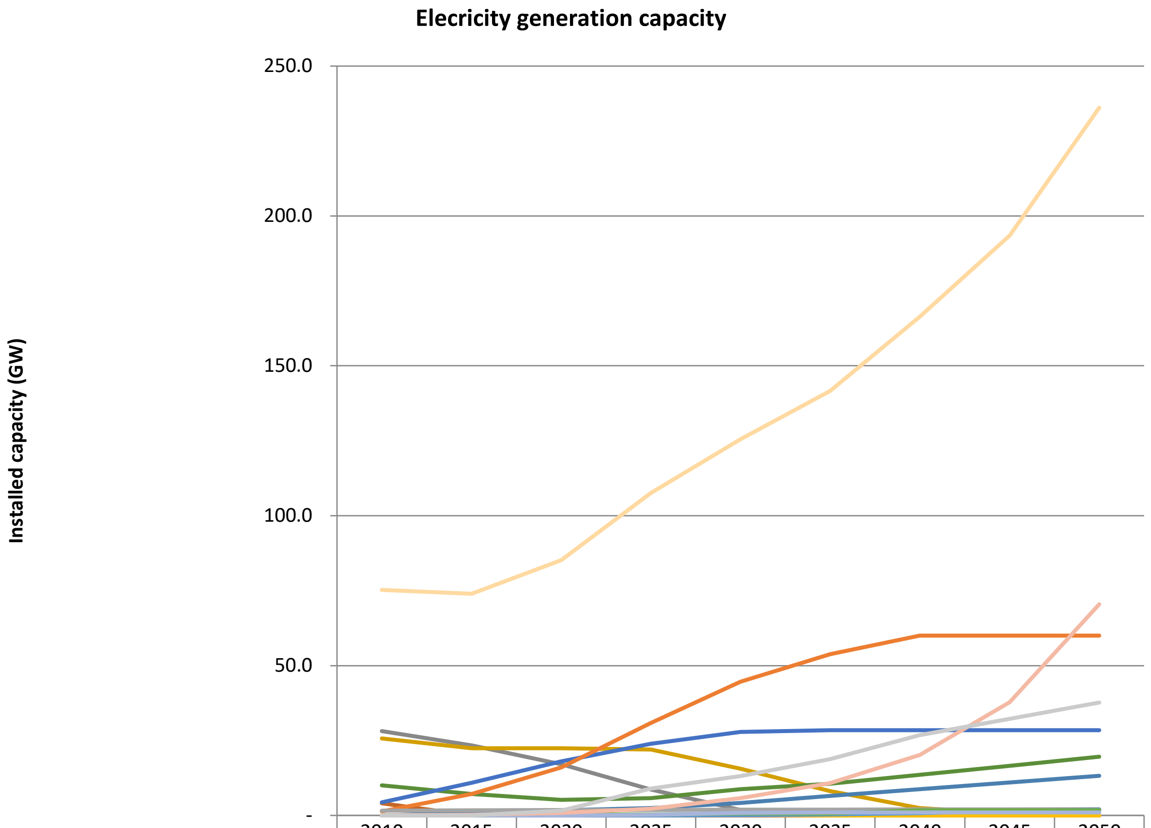
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| — Hydrocarbon fuel power generation | 188 | 163 | 138 | 96 | 48 | 26 | 13 | 10 | 4 |
| — Nuclear power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| — National renewable power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| — Distributed renewable power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| — Bioenergy | -11 | -15 | -21 | -26 | -29 | -34 | -38 | -43 | -48 |
| — Agriculture and waste | 62 | 63 | 63 | 63 | 62 | 61 | 58 | 55 | 53 |
| — Electricity distribution, storage, and balancing | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 2 |
| — H2 Production | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| — Heating | 86 | 84 | 71 | 59 | 47 | 36 | 24 | 12 | 0 |
| — Lighting and appliances | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 1 |
| — Industry | 89 | 81 | 74 | 67 | 61 | 55 | 48 | 40 | 31 |
| — Transport | 176 | 167 | 158 | 135 | 113 | 113 | 110 | 105 | 98 |
| — Geosequestration | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| — Fossil fuel production | 31 | 27 | 24 | 21 | 18 | 17 | 16 | 15 | 14 |
| — Transfers | 4 | 4 | 3 | 3 | 2 | 2 | 1 | 1 | 0 |
| — District heating | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| — Total | 628 | 577 | 513 | 422 | 326 | 278 | 235 | 197 | 156 |

Electricity sector

## Electricity generated by source

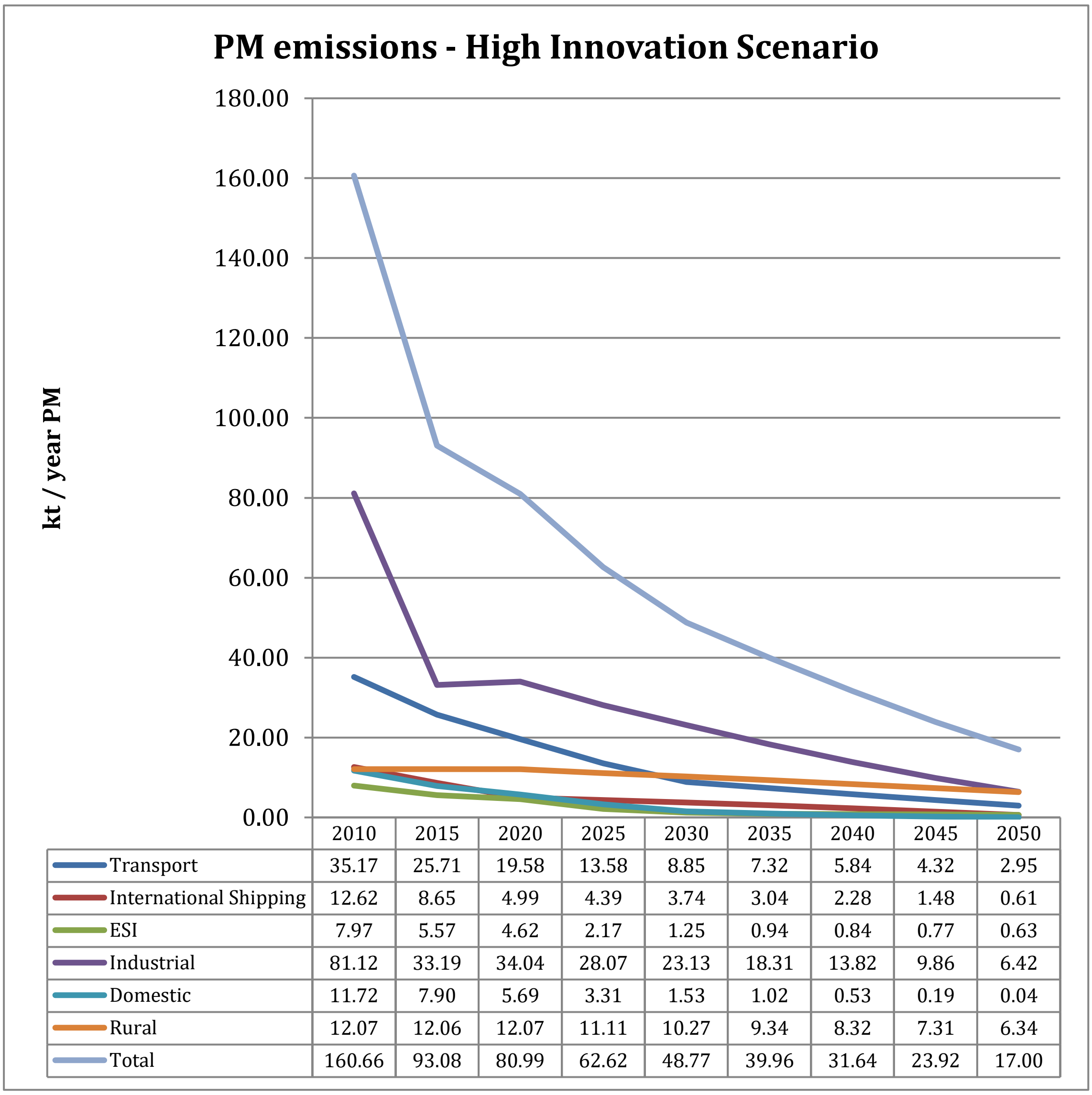


| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Biomass/Coal power stations | 295.4 | 256.2 | 228.8 | 181.7 | 106.5 | 54.9 | 20.1 | 8.5 | - |
| CCS Power | - | 5.1 | 10.8 | 16.2 | 27.4 | 42.2 | 57.1 | 72.1 | 87.3 |
| Nuclear power | 52.6 | 44.2 | 36.5 | 40.7 | 61.7 | 74.3 | 95.4 | 116.4 | 137.5 |
| Onshore wind | 11.5 | 28.7 | 47.4 | 63.0 | 73.3 | 74.8 | 74.8 | 74.8 | 74.8 |
| Offshore wind | 4.1 | 22.0 | 51.8 | 108.1 | 168.3 | 212.2 | 236.7 | 236.7 | 236.7 |
| Hydroelectric power stations | 5.3 | 5.7 | 6.0 | 6.2 | 6.3 | 6.5 | 6.7 | 6.8 | 7.0 |
| Tidal & Wave | 0.0 | 0.0 | 0.8 | 1.1 | 2.0 | 2.4 | 5.7 | 8.3 | 9.5 |
| Geothermal electricity | - | 0.1 | 0.4 | 1.5 | 5.8 | 7.0 | 7.0 | 7.0 | 7.0 |
| Solar PV | 0.0 | 0.2 | 0.8 | 1.9 | 4.9 | 9.2 | 17.2 | 32.1 | 59.9 |
| Electricity imports | - | - | - | - | - | - | - | - | - |
| Total | 369.0 | 362.2 | 383.3 | 420.3 | 456.4 | 483.5 | 520.6 | 562.7 | 619.6 |


Elecricity generation capacity

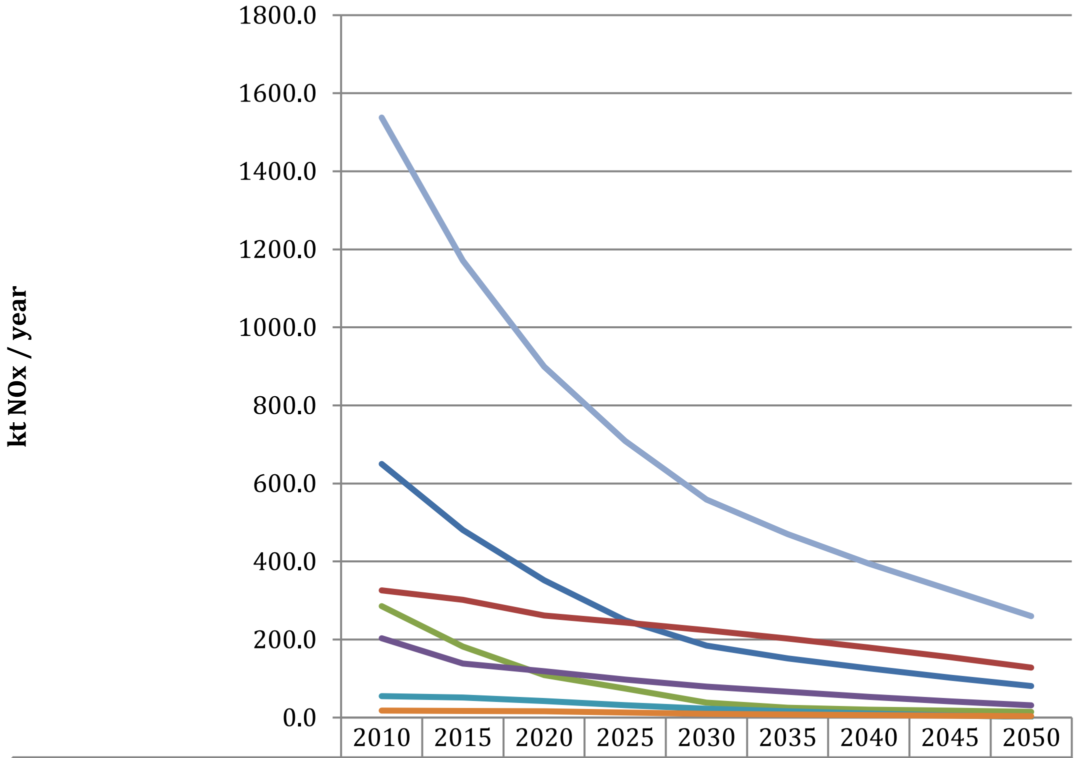
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Oil / Biofuel | 4.1 | - | - | - | - | - | - | - | - |
| Coal / Biomass | 28.1 | 23.4 | 17.1 | 8.6 | 1.8 | 0.6 | 0.6 | 0.6 | - |
| Gas / Biogas | 25.7 | 22.4 | 22.4 | 22.0 | 15.6 | 8.2 | 2.5 | 0.6 | - |
| CCS Power | - | 0.9 | 1.7 | 2.5 | 4.2 | 6.5 | 8.7 | 11.0 | 13.2 |
| Nuclear power | 10.0 | 7.2 | 5.2 | 5.8 | 8.8 | 10.6 | 13.6 | 16.6 | 19.6 |
| Onshore wind | 4.4 | 10.9 | 18.0 | 24.0 | 27.9 | 28.4 | 28.4 | 28.4 | 28.4 |
| Offshore wind | 1.3 | 7.2 | 16.0 | 30.8 | 44.6 | 53.8 | 60.0 | 60.0 | 60.0 |
| Hydroelectric power stations | 1.6 | 1.7 | 1.8 | 1.9 | 1.9 | 2.0 | 2.0 | 2.1 | 2.1 |
| Wave | - | 0.0 | 0.1 | 0.2 | 0.2 | - | - | - | - |
| Tidal Stream | 0.0 | 0.0 | 0.0 | 0.0 | 0.1 | 0.3 | 0.7 | 1.5 | 1.9 |
| Tidal Range | - | - | 0.3 | 0.3 | 0.7 | 0.7 | 1.7 | 1.7 | 1.7 |
| Geothermal electricity | - | 0.0 | 0.1 | 0.2 | 0.8 | 1.0 | 1.0 | 1.0 | 1.0 |
| Solar PV | 0.0 | 0.2 | 0.9 | 2.3 | 5.8 | 10.8 | 20.2 | 37.7 | 70.4 |
| Standby / peaking gas | - | - | 1.7 | 9.0 | 13.1 | 18.8 | 26.8 | 32.2 | 37.7 |
| Total generation | 75.3 | 73.9 | 85.2 | 107.6 | 125.5 | 141.7 | 166.3 | 193.5 | 236.1 |

Air pollution

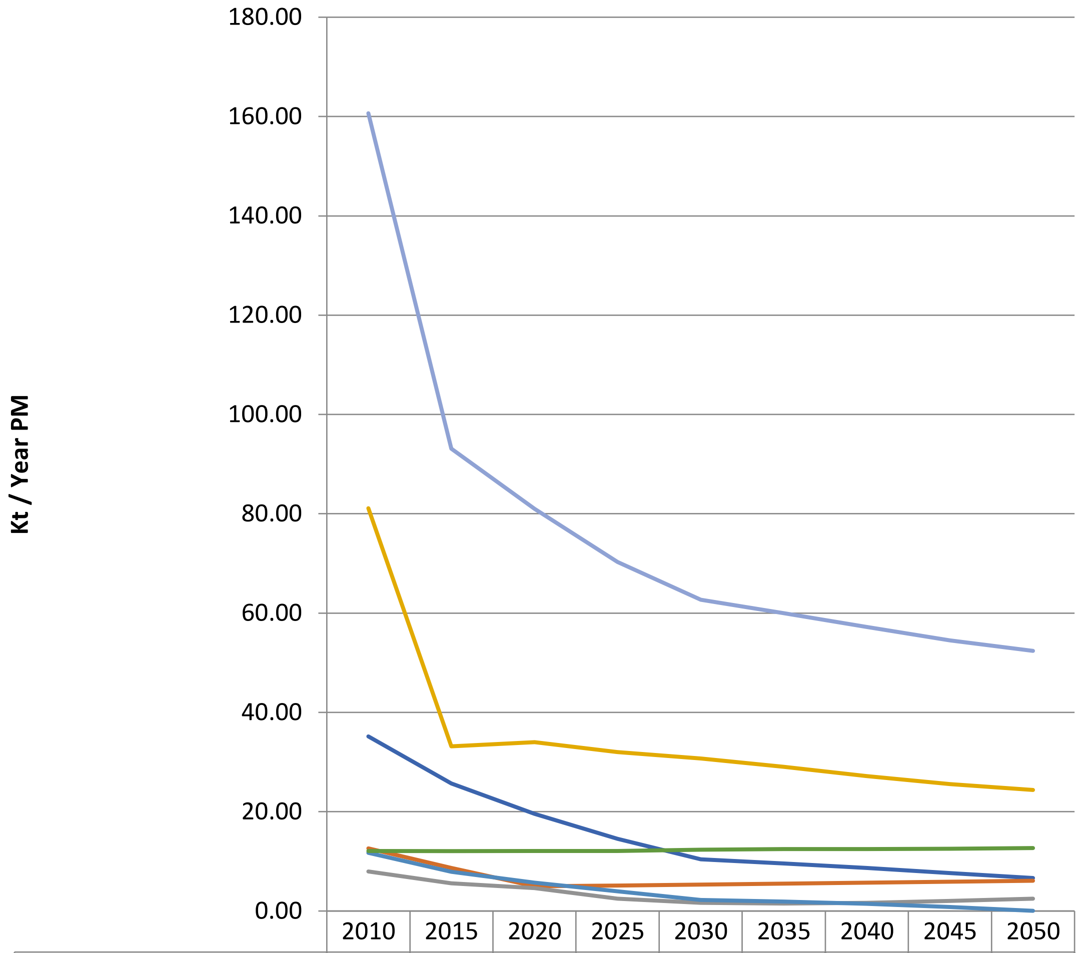


| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 35.17 | 25.71 | 19.58 | 13.58 | 8.85 | 7.32 | 5.84 | 4.32 | 2.95 |
| International Shipping | 12.62 | 8.65 | 4.99 | 4.39 | 3.74 | 3.04 | 2.28 | 1.48 | 0.61 |
| ESI | 7.97 | 5.57 | 4.62 | 2.17 | 1.25 | 0.94 | 0.84 | 0.77 | 0.63 |
| Industrial | 81.12 | 33.19 | 34.04 | 28.07 | 23.13 | 18.31 | 13.82 | 9.86 | 6.42 |
| Domestic | 11.72 | 7.90 | 5.69 | 3.31 | 1.53 | 1.02 | 0.53 | 0.19 | 0.04 |
| Rural | 12.07 | 12.06 | 12.07 | 11.11 | 10.27 | 9.34 | 8.32 | 7.31 | 6.34 |
| Total | 160.66 | 93.08 | 80.99 | 62.62 | 48.77 | 39.96 | 31.64 | 23.92 | 17.00 |

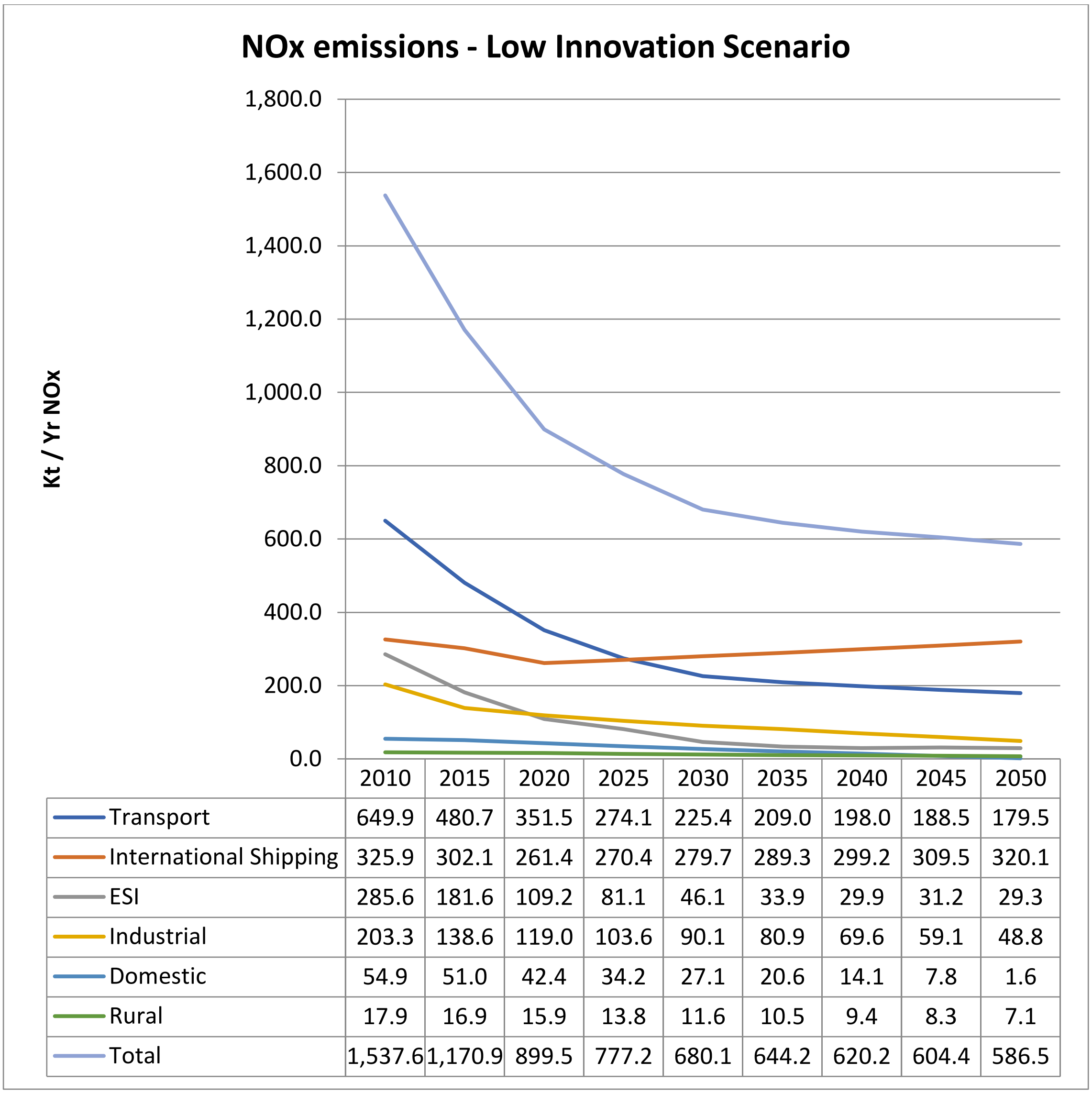
NOx emissions - High Innovation Scenario



| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 649.9 | 480.7 | 351.5 | 249.2 | 184.2 | 152.0 | 126.0 | 102.6 | 80.8 |
| International Shipping | 325.9 | 302.1 | 261.4 | 243.4 | 223.8 | 202.5 | 179.5 | 154.8 | 128.1 |
| ESI | 285.6 | 181.6 | 109.2 | 74.3 | 38.4 | 25.4 | 19.9 | 18.2 | 14.6 |
| Industrial | 203.3 | 138.6 | 119.0 | 97.5 | 79.4 | 66.5 | 53.1 | 41.6 | 31.4 |
| Domestic | 54.9 | 51.0 | 42.4 | 31.6 | 23.0 | 15.9 | 10.0 | 5.2 | 1.5 |
| Rural | 17.9 | 16.9 | 15.9 | 12.6 | 9.7 | 7.9 | 6.3 | 4.8 | 3.6 |
| Total | 1537.6 | 1170.9 | 899.5 | 708.5 | 558.5 | 470.2 | 394.8 | 327.1 | 259.9 |


PM emissions - Low Innovation Scenario

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 35.17 | 25.71 | 19.58 | 14.57 | 10.43 | 9.57 | 8.68 | 7.62 | 6.65 |
| International Shipping | 12.62 | 8.65 | 4.99 | 5.16 | 5.34 | 5.52 | 5.71 | 5.91 | 6.11 |
| ESI | 7.97 | 5.57 | 4.62 | 2.48 | 1.66 | 1.51 | 1.68 | 2.06 | 2.52 |
| Industrial | 81.12 | 33.19 | 34.04 | 32.02 | 30.69 | 29.02 | 27.19 | 25.57 | 24.38 |
| Domestic | 11.72 | 7.90 | 5.69 | 3.94 | 2.23 | 1.94 | 1.43 | 0.82 | 0.04 |
| Rural | 12.07 | 12.06 | 12.07 | 12.12 | 12.33 | 12.45 | 12.48 | 12.52 | 12.68 |
| Total | 160.66 | 93.08 | 80.99 | 70.28 | 62.69 | 60.01 | 57.19 | 54.51 | 52.39 |

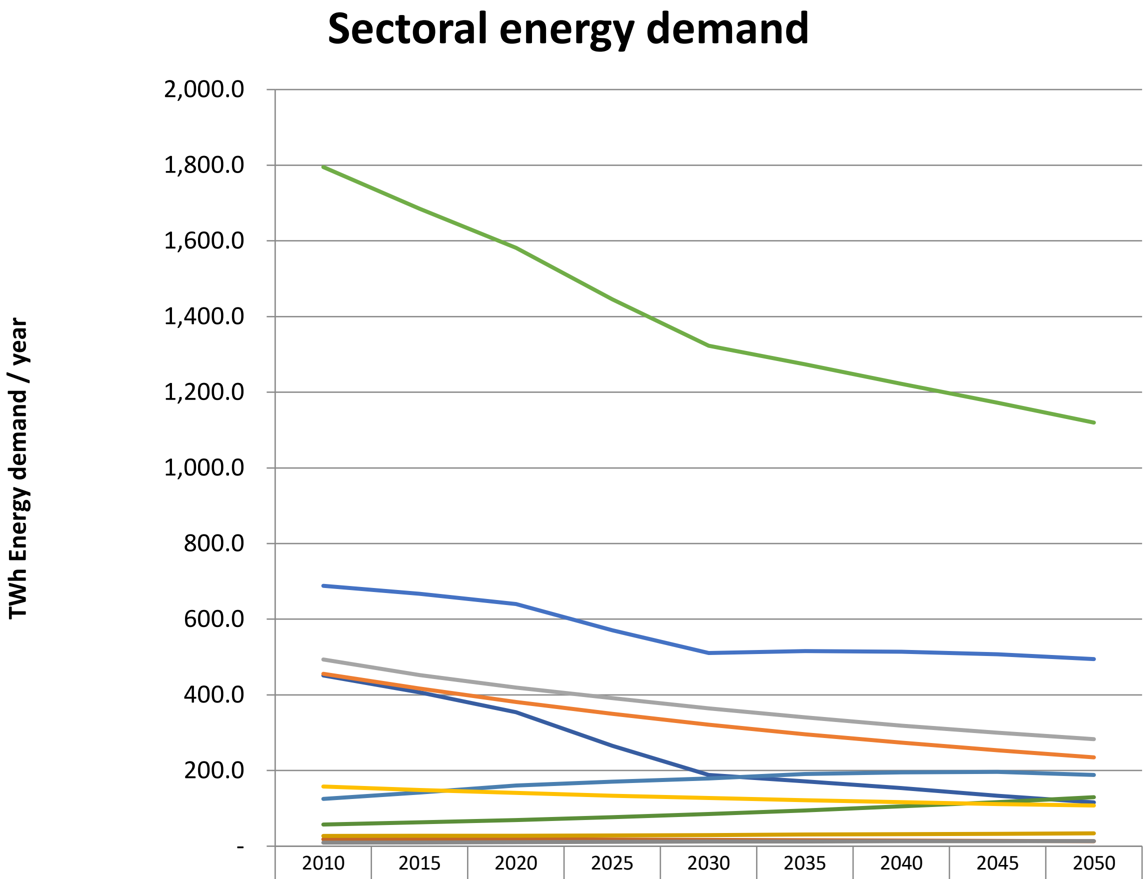


NOx emissions - Low Innovation Scenario

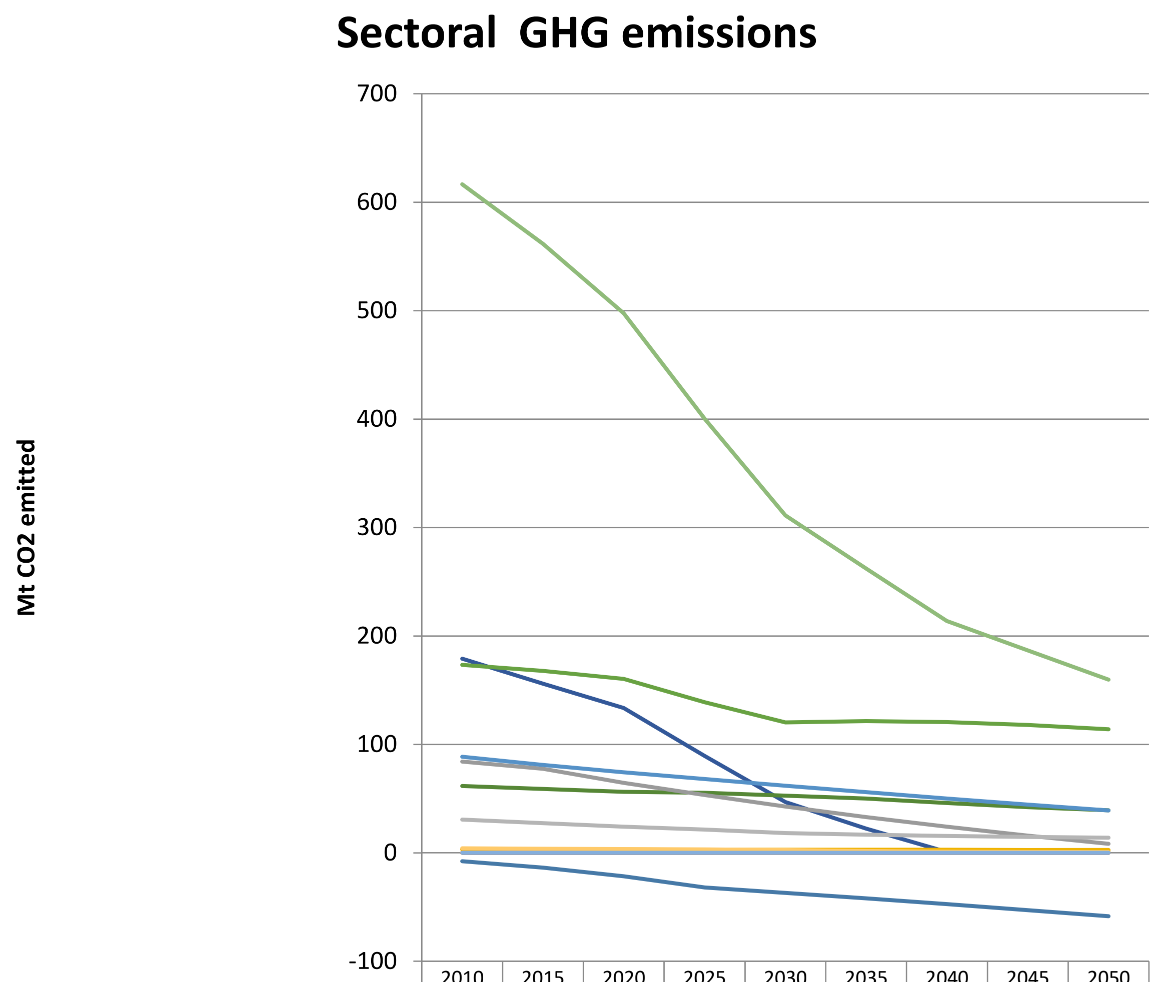
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 649.9 | 480.7 | 351.5 | 274.1 | 225.4 | 209.0 | 198.0 | 188.5 | 179.5 |
| International Shipping | 325.9 | 302.1 | 261.4 | 270.4 | 279.7 | 289.3 | 299.2 | 309.5 | 320.1 |
| ESI | 285.6 | 181.6 | 109.2 | 81.1 | 46.1 | 33.9 | 29.9 | 31.2 | 29.3 |
| Industrial | 203.3 | 138.6 | 119.0 | 103.6 | 90.1 | 80.9 | 69.6 | 59.1 | 48.8 |
| Domestic | 54.9 | 51.0 | 42.4 | 34.2 | 27.1 | 20.6 | 14.1 | 7.8 | 1.6 |
| Rural | 17.9 | 16.9 | 15.9 | 13.8 | 11.6 | 10.5 | 9.4 | 8.3 | 7.1 |
| Total | 1,537.6 | 1,170.9 | 899.5 | 777.2 | 680.1 | 644.2 | 620.2 | 604.4 | 586.5 |

## A.3 Scenario 3

Energy Landscape



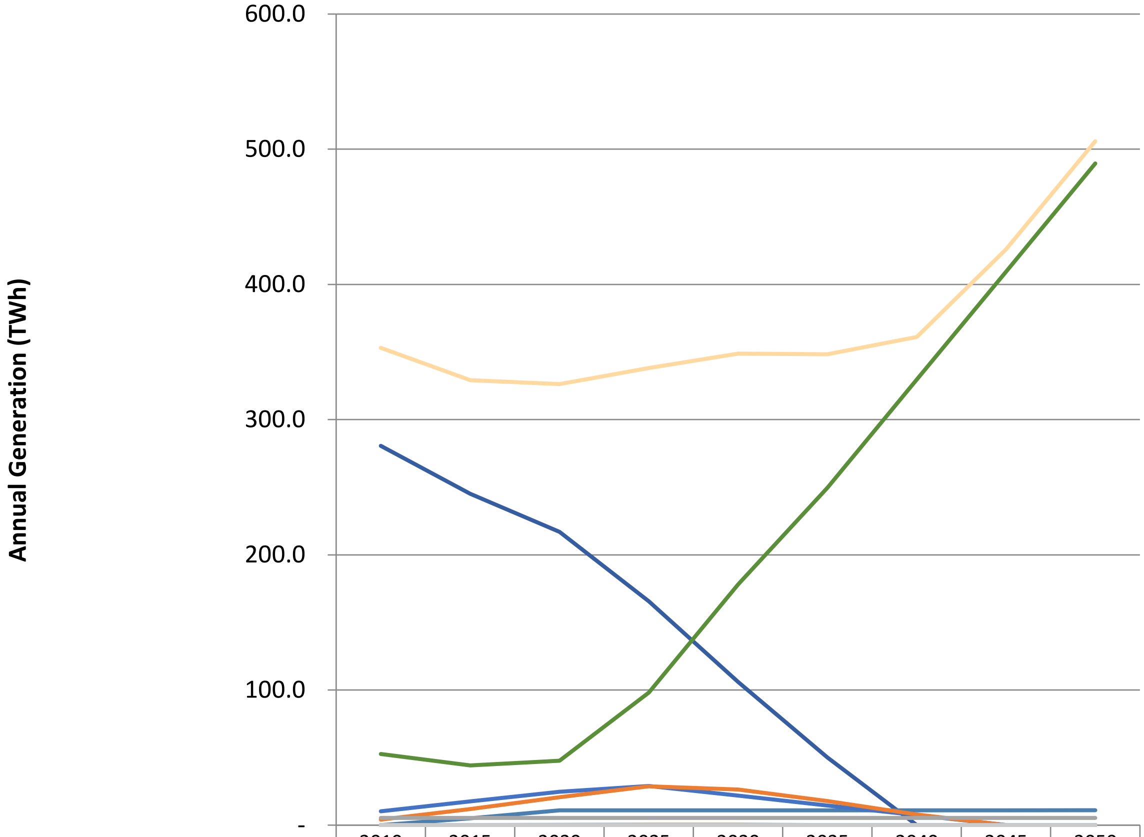
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Road transport | 451.2 | 406.9 | 353.9 | 265.2 | 188.4 | 171.2 | 153.9 | 133.7 | 115.9 |
| Rail transport | 18.1 | 18.4 | 17.9 | 17.6 | 16.7 | 15.9 | 15.0 | 14.0 | 13.0 |
| Domestic aviation | 9.4 | 10.0 | 10.9 | 11.6 | 12.2 | 12.7 | 13.0 | 13.3 | 13.5 |
| National navigation | 27.1 | 27.3 | 27.9 | 28.6 | 29.6 | 30.7 | 31.8 | 32.9 | 34.0 |
| International aviation | 125.0 | 141.9 | 160.7 | 170.6 | 178.7 | 190.6 | 194.9 | 196.4 | 188.6 |
| International shipping | 57.3 | 62.9 | 69.1 | 76.7 | 85.2 | 94.6 | 105.0 | 116.6 | 129.5 |
| Transport | 688.2 | 667.4 | 640.3 | 570.3 | 510.9 | 515.7 | 513.7 | 506.9 | 494.5 |
| Industry | 455.6 | 417.1 | 381.4 | 349.7 | 321.0 | 295.9 | 273.4 | 253.1 | 234.8 |
| Heating & cooling | 493.5 | 451.9 | 419.1 | 391.6 | 364.2 | 340.8 | 318.8 | 300.1 | 282.9 |
| Lighting & appliances | 157.7 | 148.8 | 140.7 | 133.5 | 127.1 | 121.4 | 116.2 | 111.6 | 107.5 |
| Total | 1,795.1 | 1,685.2 | 1,581.5 | 1,445.1 | 1,323.1 | 1,273.8 | 1,222.1 | 1,171.8 | 1,119.7 |



| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Hydrocarbon fuel power generation | 179 | 156 | 133 | 89 | 47 | 22 | 1 | 1 | 1 |
| Nuclear power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| National renewable power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Distributed renewable power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bioenergy | -8 | -14 | -22 | -32 | -37 | -42 | -47 | -53 | -59 |
| Agriculture and waste | 62 | 59 | 56 | 55 | 53 | 50 | 46 | 42 | 39 |
| Electricity distribution, storage, and balancing | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| H2 Production | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Heating | 84 | 78 | 65 | 53 | 42 | 33 | 24 | 16 | 8 |
| Lighting and appliances | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Industry | 89 | 81 | 74 | 68 | 62 | 56 | 50 | 44 | 39 |
| Transport | 173 | 168 | 160 | 139 | 120 | 121 | 121 | 118 | 114 |
| Geosequestration | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fossil fuel production | 31 | 27 | 24 | 21 | 18 | 17 | 16 | 15 | 14 |
| Transfers | 4 | 4 | 3 | 3 | 2 | 2 | 1 | 1 | 1 |
| District heating | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 616 | 562 | 498 | 400 | 311 | 262 | 214 | 186 | 160 |

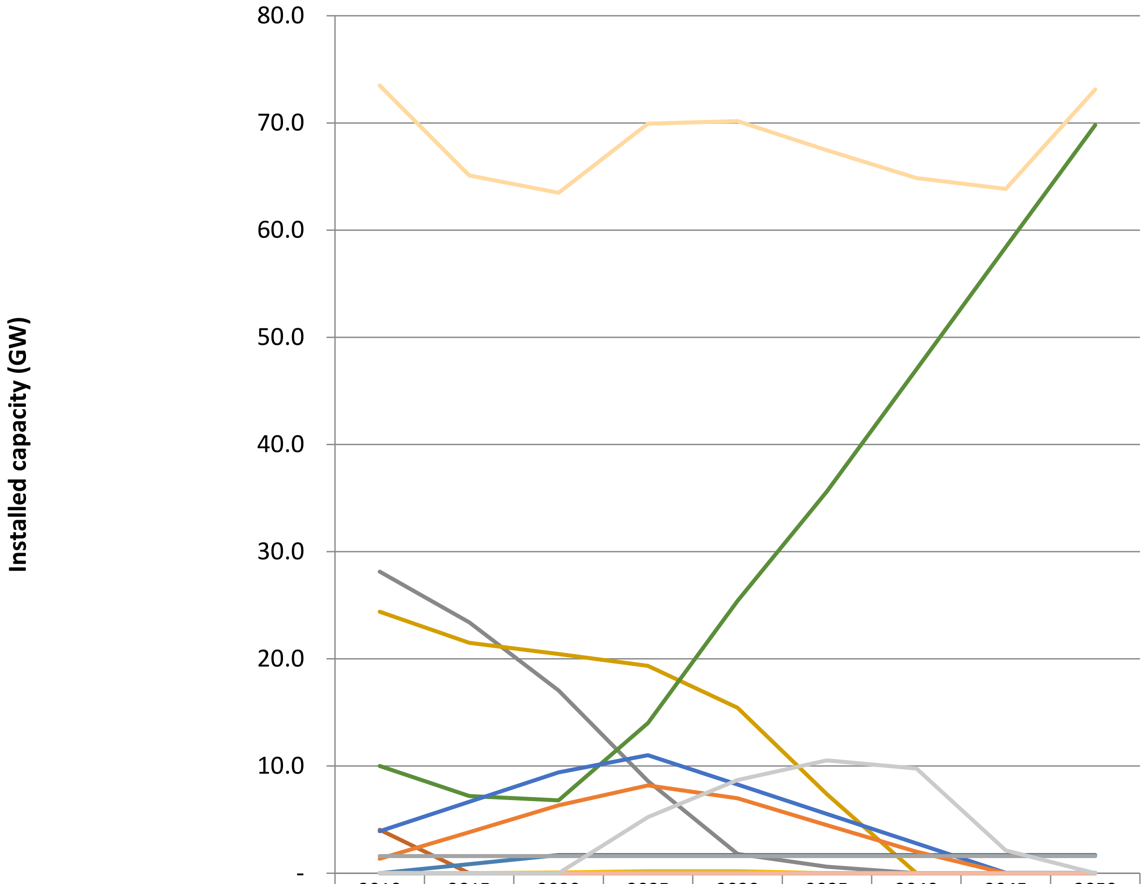
Electricity sector

## Electricity generated by source



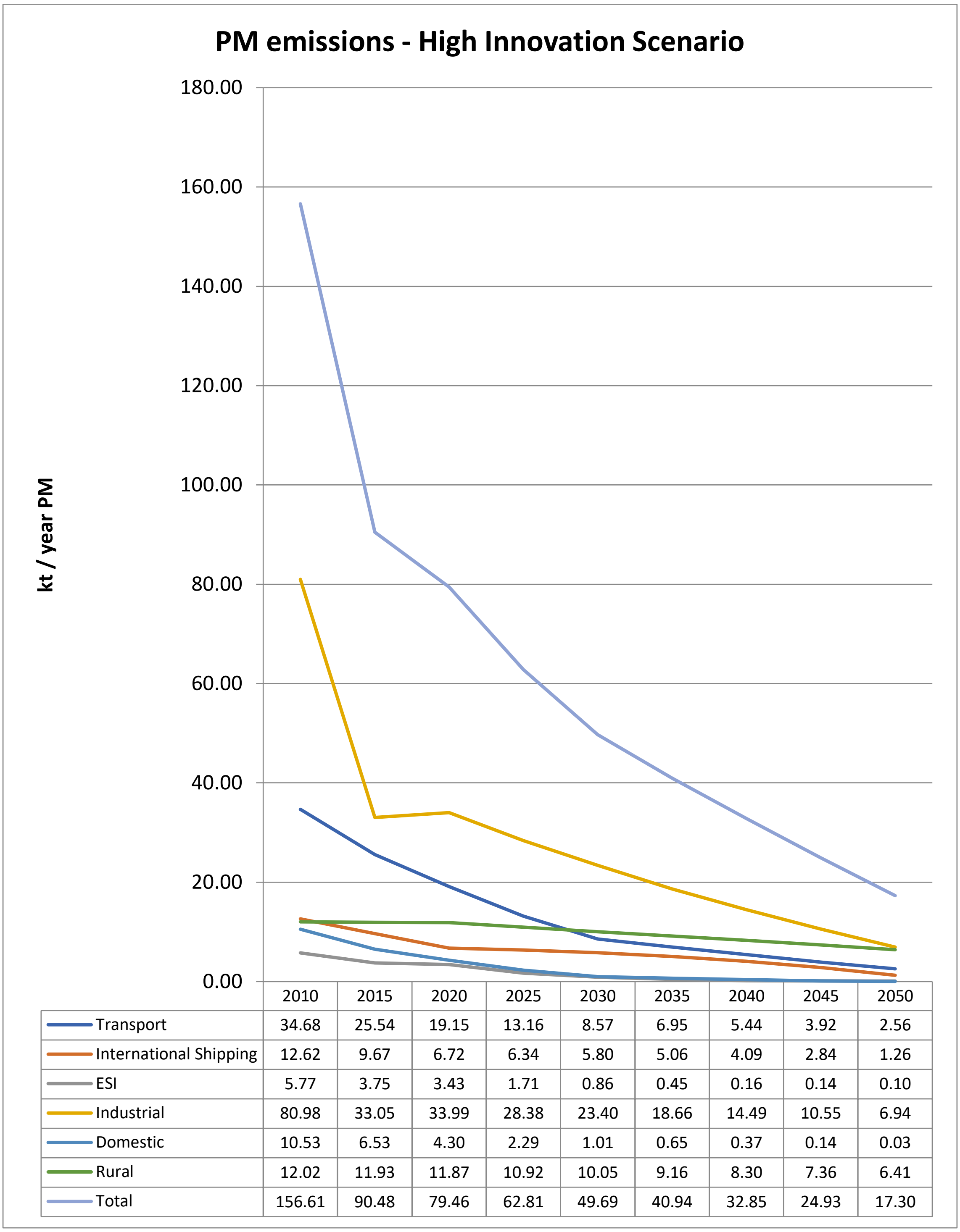
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Biomass/Coal power stations | 280.6 | 245.2 | 216.9 | 165.6 | 105.8 | 50.0 | - | - | - |
| CCS Power | - | 5.1 | 10.8 | 10.9 | 10.9 | 11.0 | 11.0 | 11.0 | 11.0 |
| Nuclear power | 52.6 | 44.2 | 47.7 | 98.2 | 178.1 | 249.7 | 329.6 | 409.5 | 489.5 |
| Onshore wind | 10.3 | 17.5 | 24.8 | 29.0 | 21.8 | 14.6 | 7.3 | 0.1 | 0.1 |
| Offshore wind | 4.1 | 11.8 | 20.6 | 28.7 | 26.4 | 17.8 | 7.9 | - | - |
| Hydroelectric power stations | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 |
| Tidal & Wave | 0.0 | 0.0 | 0.2 | 0.5 | 0.5 | - | - | - | - |
| Geothermal electricity | - | - | - | - | - | - | - | - | - |
| Solar PV | 0.0 | 0.0 | - | - | - | - | - | - | - |
| Electricity imports | - | - | - | - | - | - | - | - | - |
| Total | 353.0 | 329.2 | 326.3 | 338.2 | 348.9 | 348.2 | 361.1 | 426.0 | 505.9 |

## Elecricity generation capacity



| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Oil / Biofuel | 4.1 | - | - | - | - | - | - | - | - |
| Coal / Biomass | 28.1 | 23.4 | 17.1 | 8.6 | 1.8 | 0.6 | - | - | - |
| Gas / Biogas | 24.4 | 21.5 | 20.5 | 19.3 | 15.4 | 7.4 | - | - | - |
| CCS Power | - | 0.9 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 | 1.7 |
| Nuclear power | 10.0 | 7.2 | 6.8 | 14.0 | 25.4 | 35.6 | 47.0 | 58.4 | 69.8 |
| Onshore wind | 3.9 | 6.7 | 9.4 | 11.0 | 8.3 | 5.5 | 2.8 | 0.0 | 0.0 |
| Offshore wind | 1.3 | 3.8 | 6.3 | 8.2 | 7.0 | 4.5 | 2.0 | - | - |
| Hydroelectric power stations | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |
| Wave | - | 0.0 | 0.1 | 0.2 | 0.2 | - | - | - | - |
| Tidal Stream | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | - | - | - | - |
| Tidal Range | - | - | - | - | - | - | - | - | - |
| Geothermal electricity | - | - | - | - | - | - | - | - | - |
| Solar PV | 0.0 | 0.0 | - | - | - | - | - | - | - |
| Standby / peaking gas | - | - | - | 5.2 | 8.7 | 10.5 | 9.8 | 2.1 | - |
| Total generation | 73.5 | 65.1 | 63.5 | 69.9 | 70.2 | 67.4 | 64.9 | 63.9 | 73.1 |

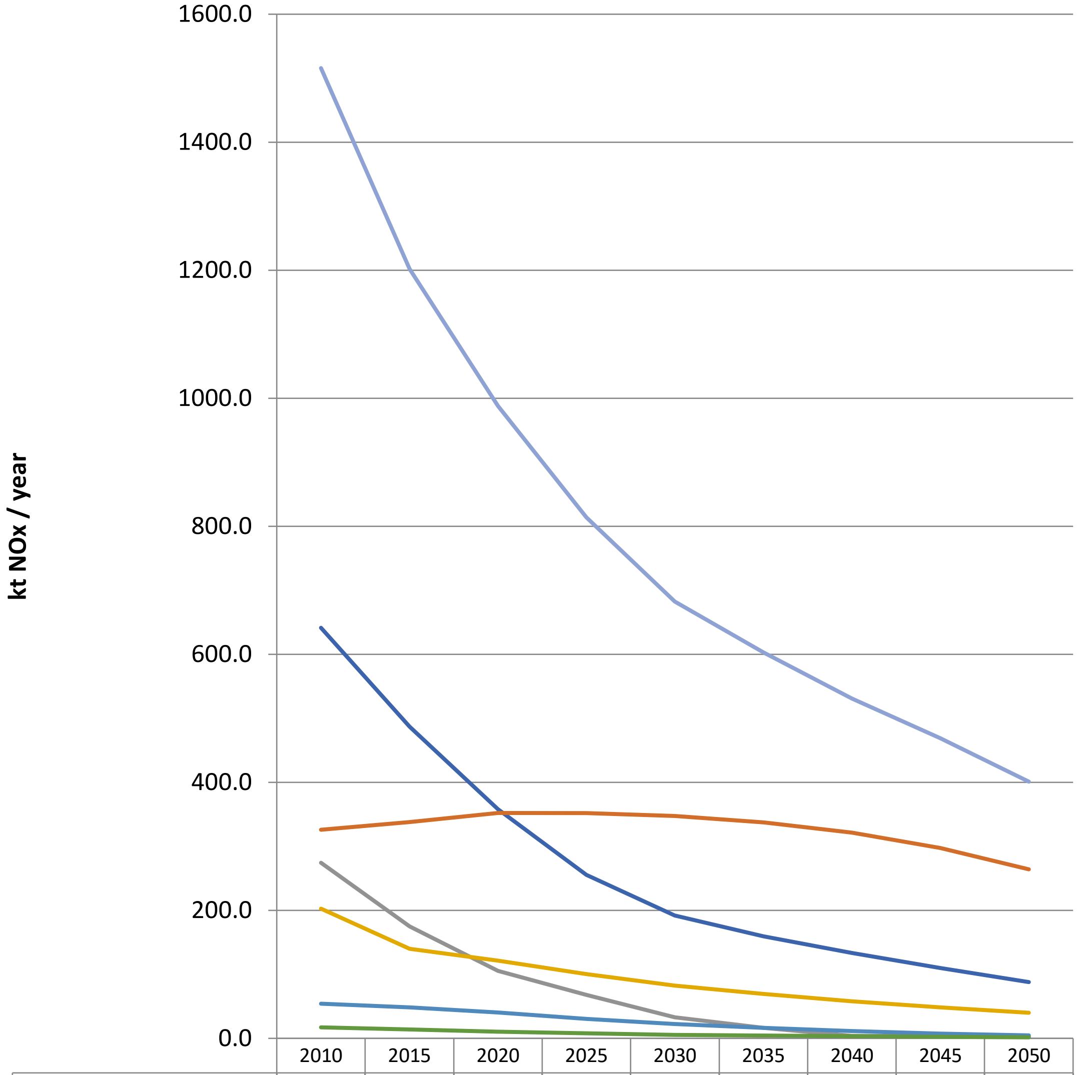
Air pollution



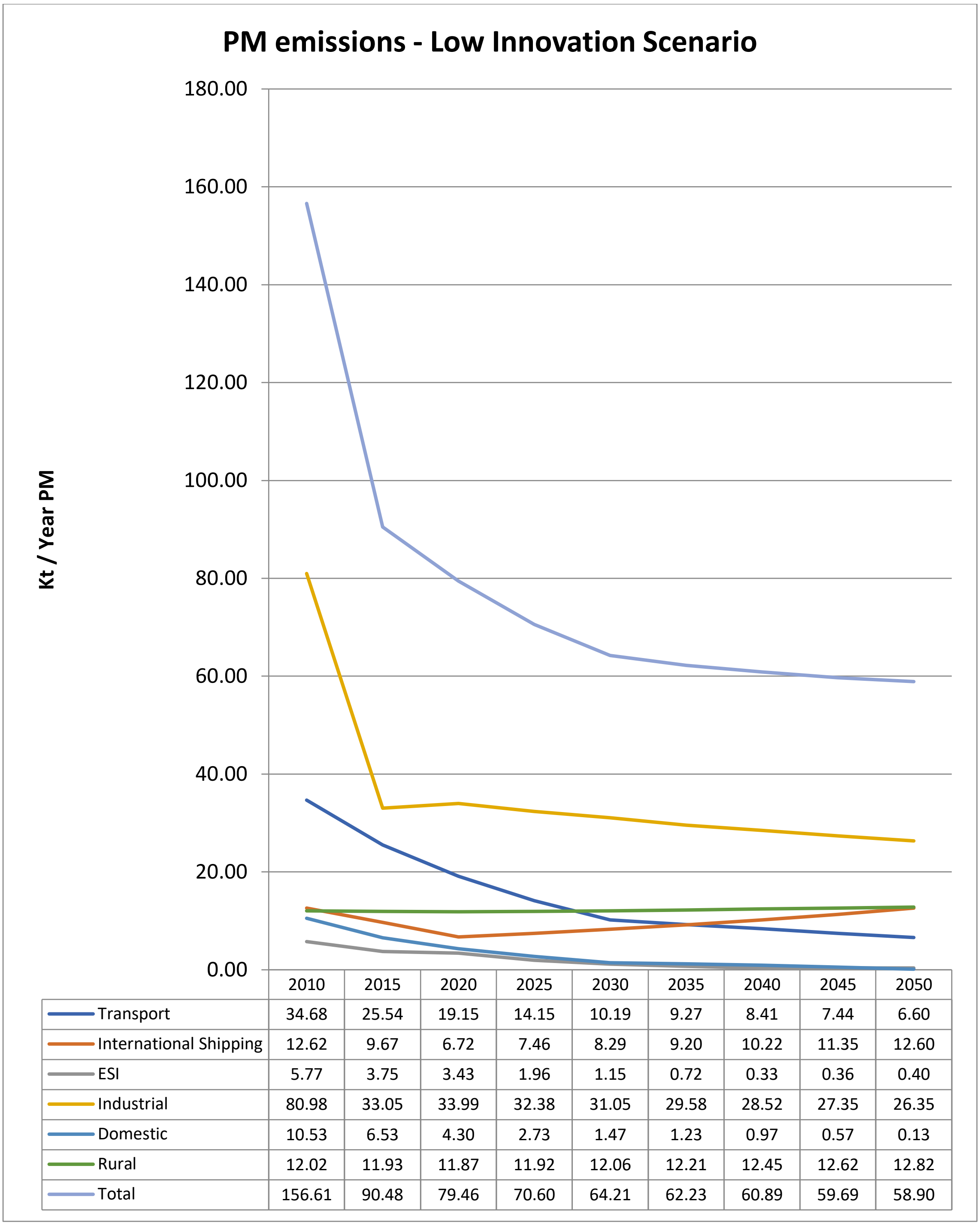
PM emissions - High Innovation Scenario

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| — Transport | 34.68 | 25.54 | 19.15 | 13.16 | 8.57 | 6.95 | 5.44 | 3.92 | 2.56 |
| — International Shipping | 12.62 | 9.67 | 6.72 | 6.34 | 5.80 | 5.06 | 4.09 | 2.84 | 1.26 |
| — ESI | 5.77 | 3.75 | 3.43 | 1.71 | 0.86 | 0.45 | 0.16 | 0.14 | 0.10 |
| — Industrial | 80.98 | 33.05 | 33.99 | 28.38 | 23.40 | 18.66 | 14.49 | 10.55 | 6.94 |
| — Domestic | 10.53 | 6.53 | 4.30 | 2.29 | 1.01 | 0.65 | 0.37 | 0.14 | 0.03 |
| — Rural | 12.02 | 11.93 | 11.87 | 10.92 | 10.05 | 9.16 | 8.30 | 7.36 | 6.41 |
| — Total | 156.61 | 90.48 | 79.46 | 62.81 | 49.69 | 40.94 | 32.85 | 24.93 | 17.30 |

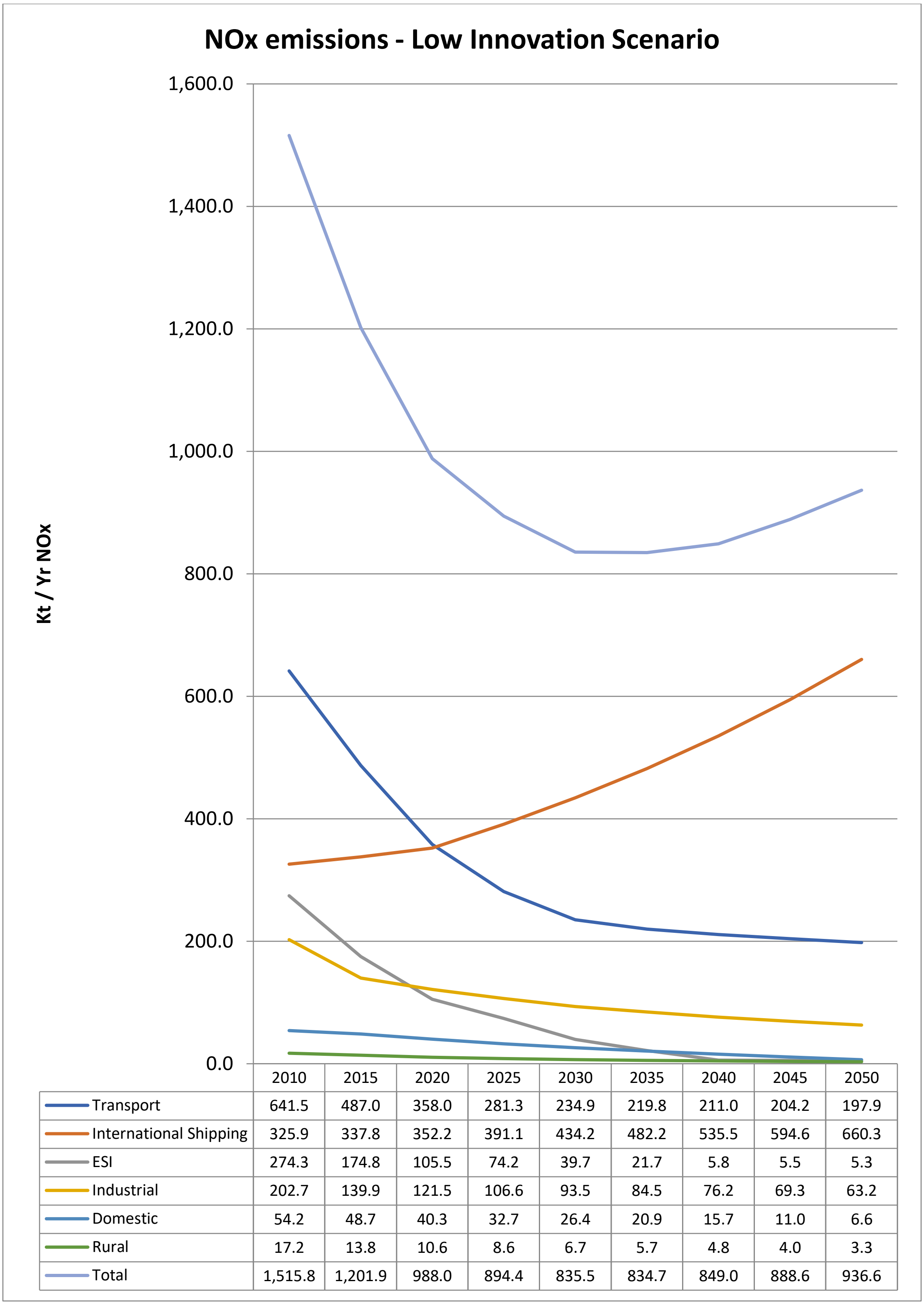
## NOx emissions - High Innovation Scenario



| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 641.5 | 487.0 | 358.0 | 255.6 | 191.7 | 159.3 | 133.6 | 110.2 | 87.9 |
| International Shipping | 325.9 | 337.8 | 352.2 | 351.9 | 347.4 | 337.5 | 321.3 | 297.3 | 264.1 |
| ESI | 274.3 | 174.8 | 105.5 | 68.0 | 33.1 | 16.2 | 3.9 | 3.2 | 2.6 |
| Industrial | 202.7 | 139.9 | 121.5 | 100.3 | 82.4 | 69.3 | 57.8 | 48.2 | 40.0 |
| Domestic | 54.2 | 48.7 | 40.3 | 30.2 | 22.5 | 16.4 | 11.4 | 7.6 | 4.7 |
| Rural | 17.2 | 13.8 | 10.6 | 7.8 | 5.6 | 4.3 | 3.2 | 2.3 | 1.7 |
| Total | 1515.8 | 1201.9 | 988.0 | 813.9 | 682.6 | 603.0 | 531.2 | 468.9 | 401.1 |


PM emissions - Low Innovation Scenario

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 34.68 | 25.54 | 19.15 | 14.15 | 10.19 | 9.27 | 8.41 | 7.44 | 6.60 |
| International Shipping | 12.62 | 9.67 | 6.72 | 7.46 | 8.29 | 9.20 | 10.22 | 11.35 | 12.60 |
| ESI | 5.77 | 3.75 | 3.43 | 1.96 | 1.15 | 0.72 | 0.33 | 0.36 | 0.40 |
| Industrial | 80.98 | 33.05 | 33.99 | 32.38 | 31.05 | 29.58 | 28.52 | 27.35 | 26.35 |
| Domestic | 10.53 | 6.53 | 4.30 | 2.73 | 1.47 | 1.23 | 0.97 | 0.57 | 0.13 |
| Rural | 12.02 | 11.93 | 11.87 | 11.92 | 12.06 | 12.21 | 12.45 | 12.62 | 12.82 |
| Total | 156.61 | 90.48 | 79.46 | 70.60 | 64.21 | 62.23 | 60.89 | 59.69 | 58.90 |

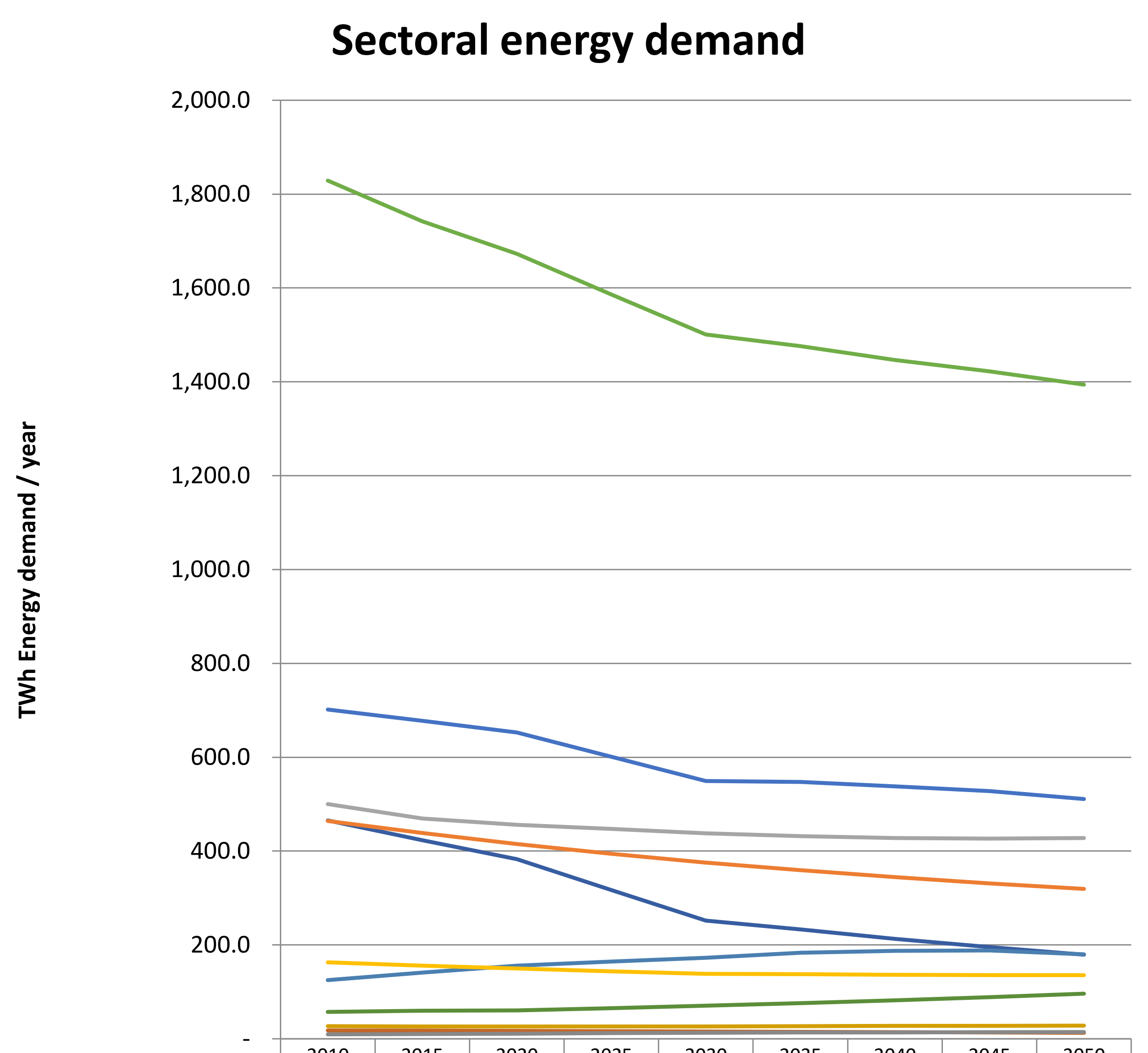


NOx emissions - Low Innovation Scenario

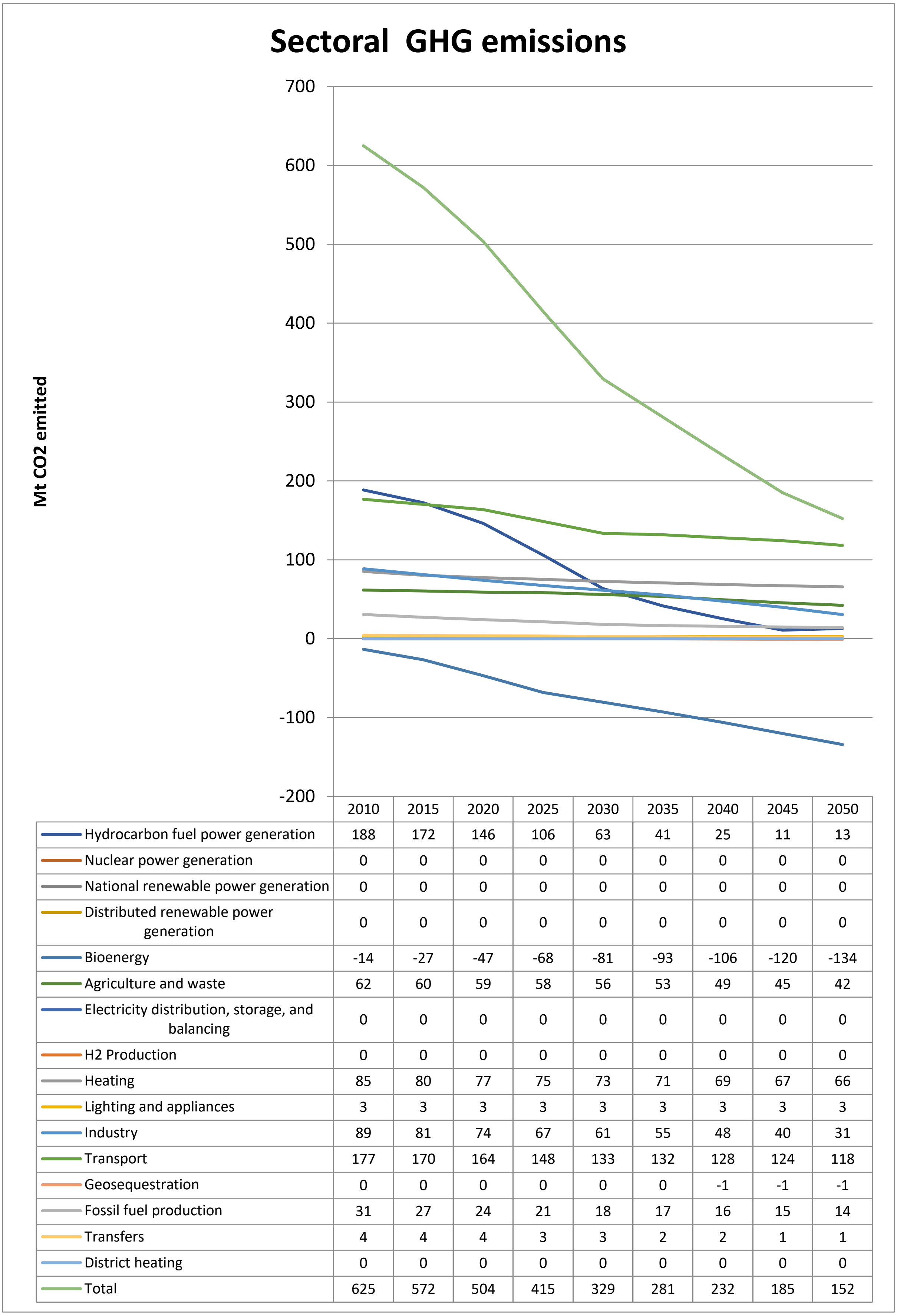
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 641.5 | 487.0 | 358.0 | 281.3 | 234.9 | 219.8 | 211.0 | 204.2 | 197.9 |
| International Shipping | 325.9 | 337.8 | 352.2 | 391.1 | 434.2 | 482.2 | 535.5 | 594.6 | 660.3 |
| ESI | 274.3 | 174.8 | 105.5 | 74.2 | 39.7 | 21.7 | 5.8 | 5.5 | 5.3 |
| Industrial | 202.7 | 139.9 | 121.5 | 106.6 | 93.5 | 84.5 | 76.2 | 69.3 | 63.2 |
| Domestic | 54.2 | 48.7 | 40.3 | 32.7 | 26.4 | 20.9 | 15.7 | 11.0 | 6.6 |
| Rural | 17.2 | 13.8 | 10.6 | 8.6 | 6.7 | 5.7 | 4.8 | 4.0 | 3.3 |
| Total | 1,515.8 | 1,201.9 | 988.0 | 894.4 | 835.5 | 834.7 | 849.0 | 888.6 | 936.6 |

## A.4 Scenario 4

Energy Landscape



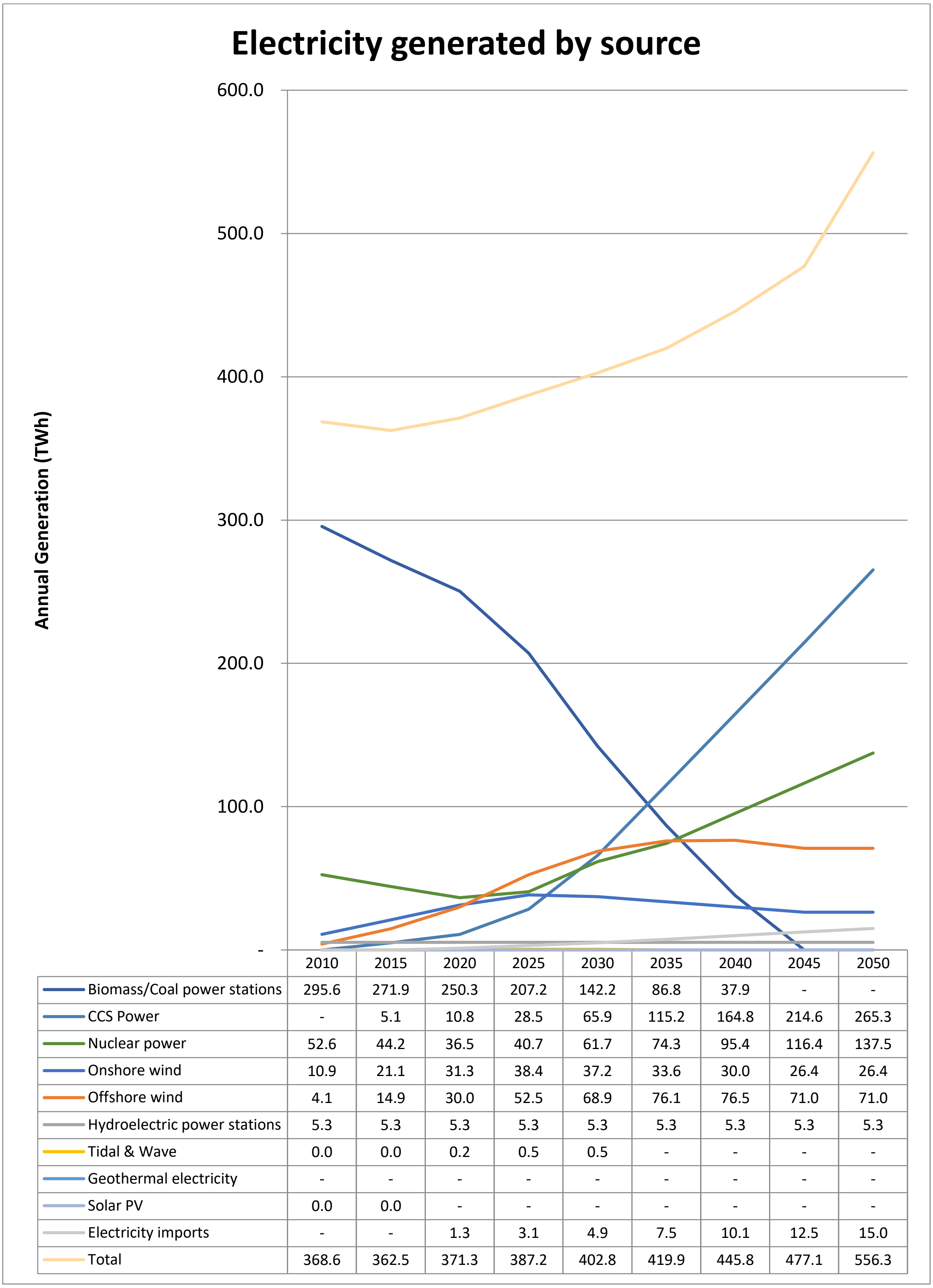
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Road transport | 465.3 | 423.4 | 382.5 | 317.2 | 252.0 | 233.2 | 212.9 | 195.8 | 179.2 |
| Rail transport | 17.7 | 17.4 | 16.5 | 16.2 | 15.4 | 14.8 | 14.2 | 13.5 | 12.8 |
| Domestic aviation | 9.4 | 10.1 | 11.0 | 11.9 | 12.6 | 13.2 | 13.7 | 14.1 | 14.5 |
| National navigation | 26.8 | 26.3 | 26.2 | 26.2 | 26.6 | 26.9 | 27.3 | 27.7 | 28.0 |
| International aviation | 125.0 | 140.7 | 156.0 | 164.6 | 172.6 | 183.3 | 187.4 | 188.2 | 180.3 |
| International shipping | 57.3 | 59.7 | 60.2 | 65.1 | 70.4 | 76.1 | 82.2 | 88.9 | 96.2 |
| Transport | 701.6 | 677.8 | 652.5 | 601.3 | 549.5 | 547.5 | 537.6 | 528.1 | 511.0 |
| Industry | 464.2 | 438.8 | 415.1 | 394.3 | 375.4 | 359.1 | 344.5 | 331.4 | 319.4 |
| Heating & cooling | 500.2 | 469.5 | 455.9 | 447.2 | 437.6 | 432.2 | 427.6 | 426.6 | 428.1 |
| Lighting & appliances | 163.0 | 156.0 | 149.5 | 143.5 | 138.7 | 137.5 | 136.6 | 135.9 | 135.6 |
| Total | 1,828.9 | 1,742.1 | 1,673.0 | 1,586.2 | 1,501.1 | 1,476.3 | 1,446.4 | 1,422.1 | 1,394.1 |



Sectoral GHG emissions

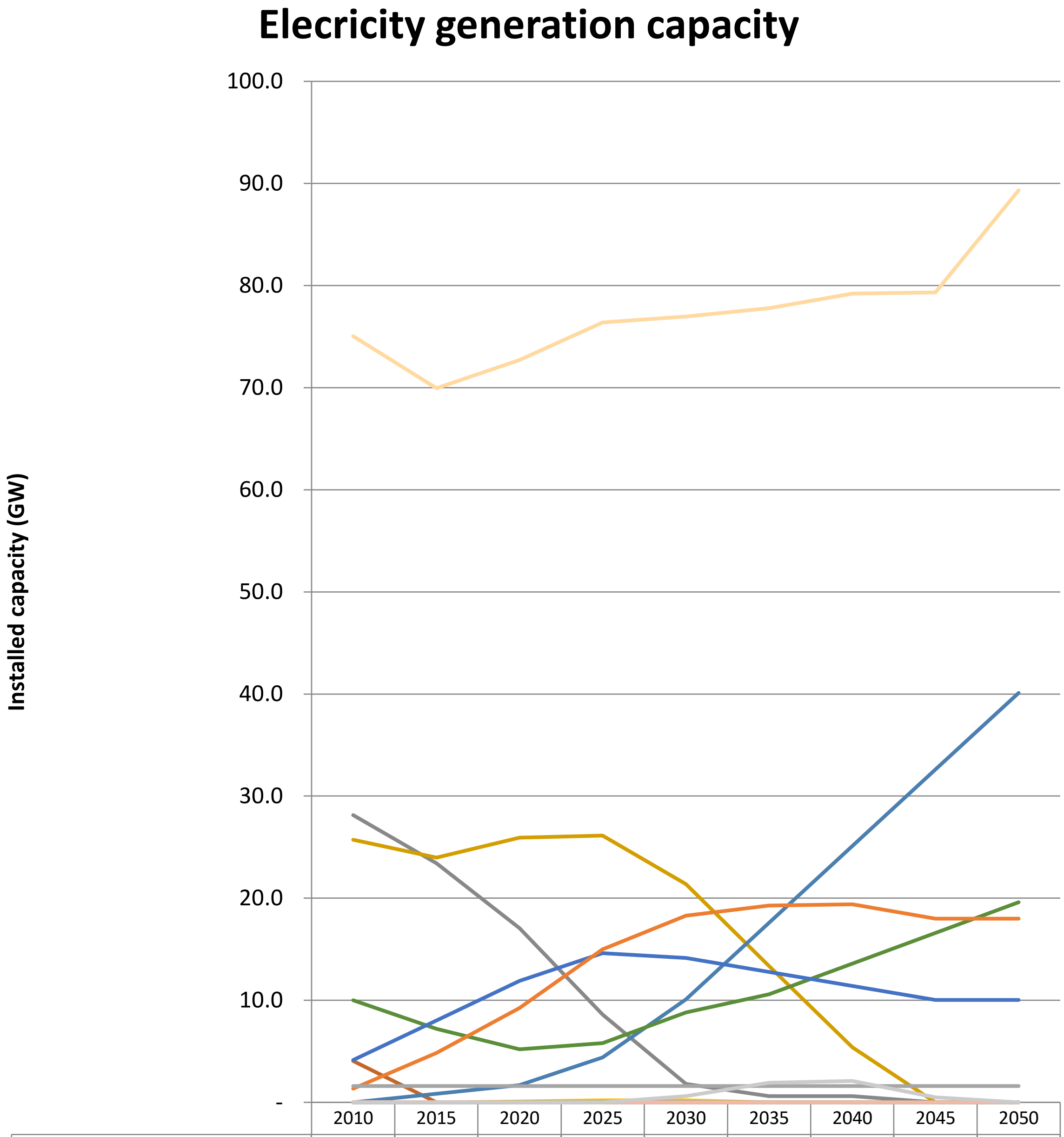
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Hydrocarbon fuel power generation | 188 | 172 | 146 | 106 | 63 | 41 | 25 | 11 | 13 |
| Nuclear power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| National renewable power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Distributed renewable power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bioenergy | -14 | -27 | -47 | -68 | -81 | -93 | -106 | -120 | -134 |
| Agriculture and waste | 62 | 60 | 59 | 58 | 56 | 53 | 49 | 45 | 42 |
| Electricity distribution, storage, and balancing | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| H2 Production | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Heating | 85 | 80 | 77 | 75 | 73 | 71 | 69 | 67 | 66 |
| Lighting and appliances | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Industry | 89 | 81 | 74 | 67 | 61 | 55 | 48 | 40 | 31 |
| Transport | 177 | 170 | 164 | 148 | 133 | 132 | 128 | 124 | 118 |
| Geosequestration | 0 | 0 | 0 | 0 | 0 | 0 | -1 | -1 | -1 |
| Fossil fuel production | 31 | 27 | 24 | 21 | 18 | 17 | 16 | 15 | 14 |
| Transfers | 4 | 4 | 4 | 3 | 3 | 2 | 2 | 1 | 1 |
| District heating | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 625 | 572 | 504 | 415 | 329 | 281 | 232 | 185 | 152 |

Electricity sector



Electricity generated by source

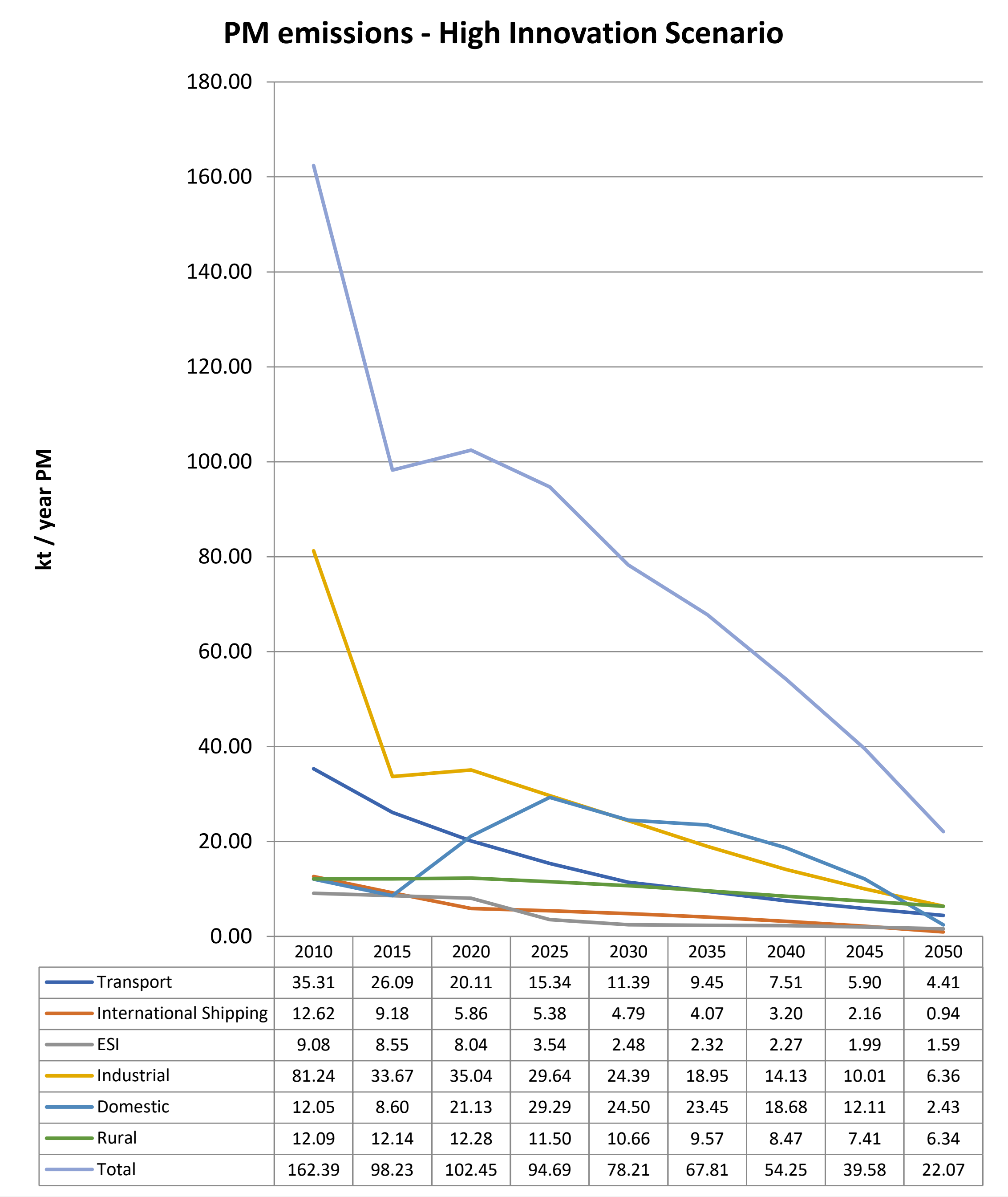
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Biomass/Coal power stations | 295.6 | 271.9 | 250.3 | 207.2 | 142.2 | 86.8 | 37.9 | - | - |
| CCS Power | - | 5.1 | 10.8 | 28.5 | 65.9 | 115.2 | 164.8 | 214.6 | 265.3 |
| Nuclear power | 52.6 | 44.2 | 36.5 | 40.7 | 61.7 | 74.3 | 95.4 | 116.4 | 137.5 |
| Onshore wind | 10.9 | 21.1 | 31.3 | 38.4 | 37.2 | 33.6 | 30.0 | 26.4 | 26.4 |
| Offshore wind | 4.1 | 14.9 | 30.0 | 52.5 | 68.9 | 76.1 | 76.5 | 71.0 | 71.0 |
| Hydroelectric power stations | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 |
| Tidal & Wave | 0.0 | 0.0 | 0.2 | 0.5 | 0.5 | - | - | - | - |
| Geothermal electricity | - | - | - | - | - | - | - | - | - |
| Solar PV | 0.0 | 0.0 | - | - | - | - | - | - | - |
| Electricity imports | - | - | 1.3 | 3.1 | 4.9 | 7.5 | 10.1 | 12.5 | 15.0 |
| Total | 368.6 | 362.5 | 371.3 | 387.2 | 402.8 | 419.9 | 445.8 | 477.1 | 556.3 |



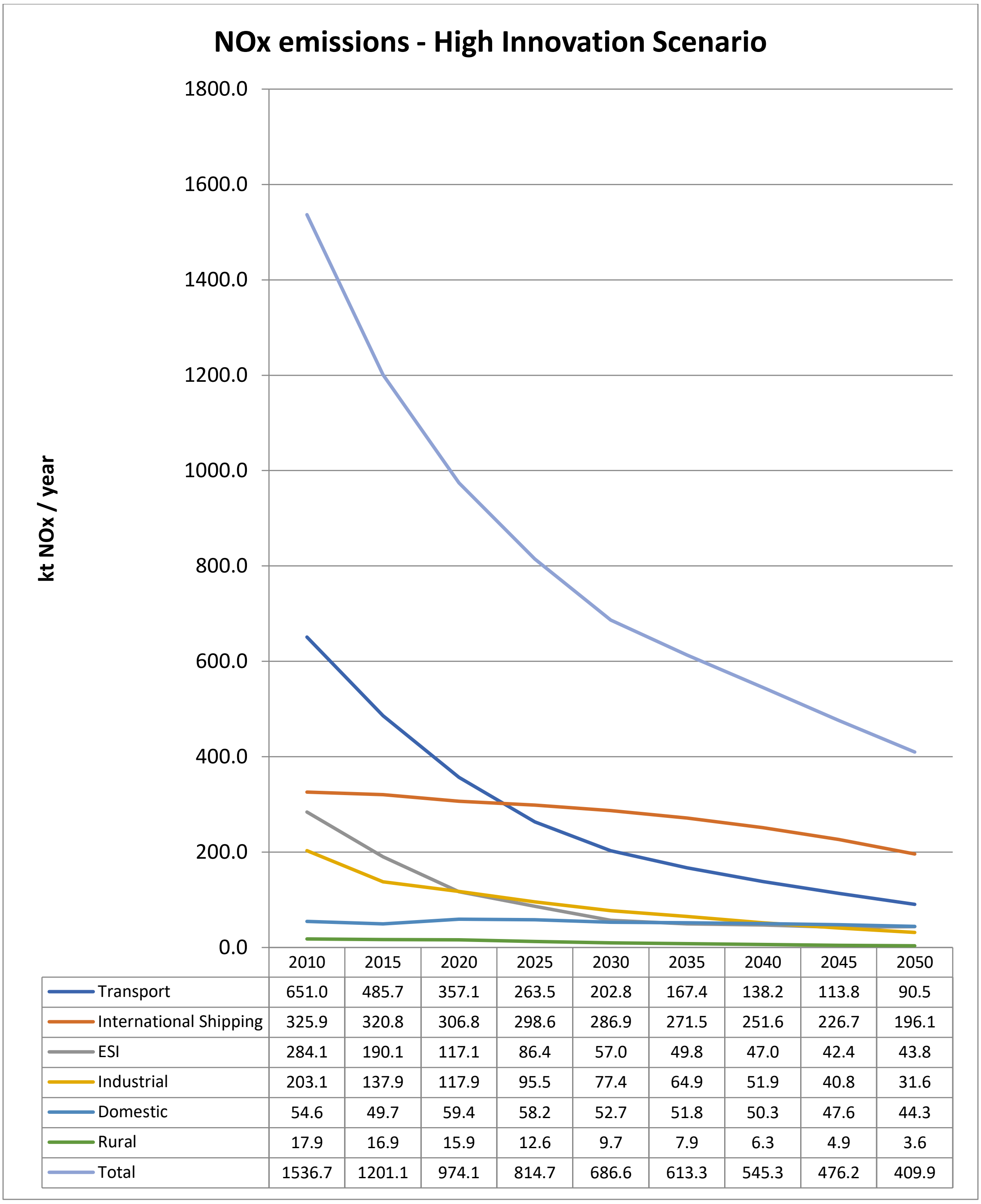
Elecricity generation capacity

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Oil / Biofuel | 4.1 | - | - | - | - | - | - | - | - |
| Coal / Biomass | 28.1 | 23.4 | 17.1 | 8.6 | 1.8 | 0.6 | 0.6 | - | - |
| Gas / Biogas | 25.7 | 24.0 | 25.9 | 26.1 | 21.4 | 13.4 | 5.4 | - | - |
| CCS Power | - | 0.9 | 1.7 | 4.4 | 10.1 | 17.6 | 25.1 | 32.6 | 40.1 |
| Nuclear power | 10.0 | 7.2 | 5.2 | 5.8 | 8.8 | 10.6 | 13.6 | 16.6 | 19.6 |
| Onshore wind | 4.1 | 8.0 | 11.9 | 14.6 | 14.2 | 12.8 | 11.4 | 10.0 | 10.0 |
| Offshore wind | 1.3 | 4.8 | 9.2 | 15.0 | 18.3 | 19.3 | 19.4 | 18.0 | 18.0 |
| Hydroelectric power stations | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |
| Wave | - | 0.0 | 0.1 | 0.2 | 0.2 | - | - | - | - |
| Tidal Stream | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | - | - | - | - |
| Tidal Range | - | - | - | - | - | - | - | - | - |
| Geothermal electricity | - | - | - | - | - | - | - | - | - |
| Solar PV | 0.0 | 0.0 | - | - | - | - | - | - | - |
| Standby / peaking gas | - | - | - | - | 0.6 | 1.9 | 2.1 | 0.5 | - |
| Total generation | 75.0 | 69.9 | 72.7 | 76.4 | 77.0 | 77.8 | 79.2 | 79.3 | 89.3 |

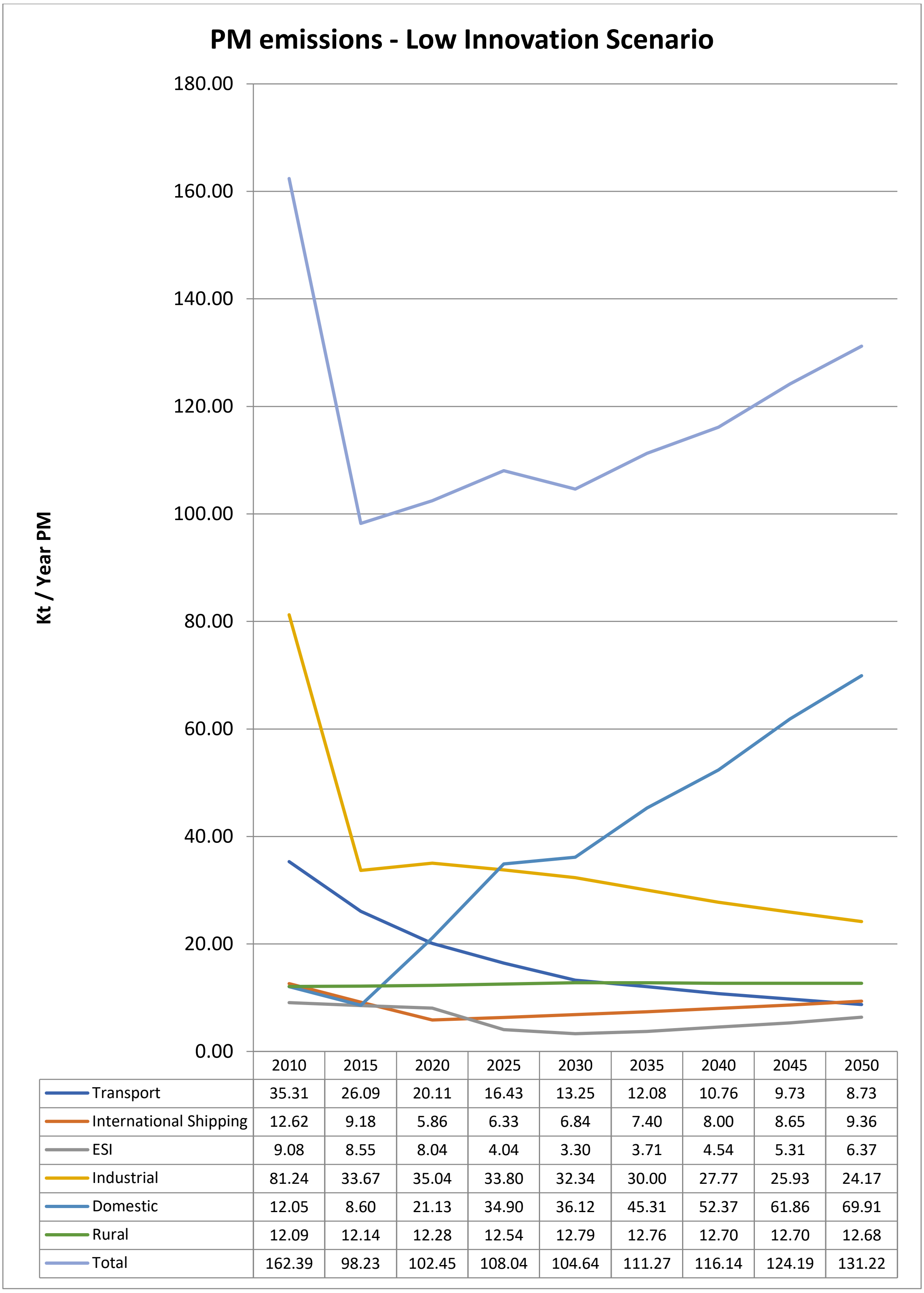
Air pollution



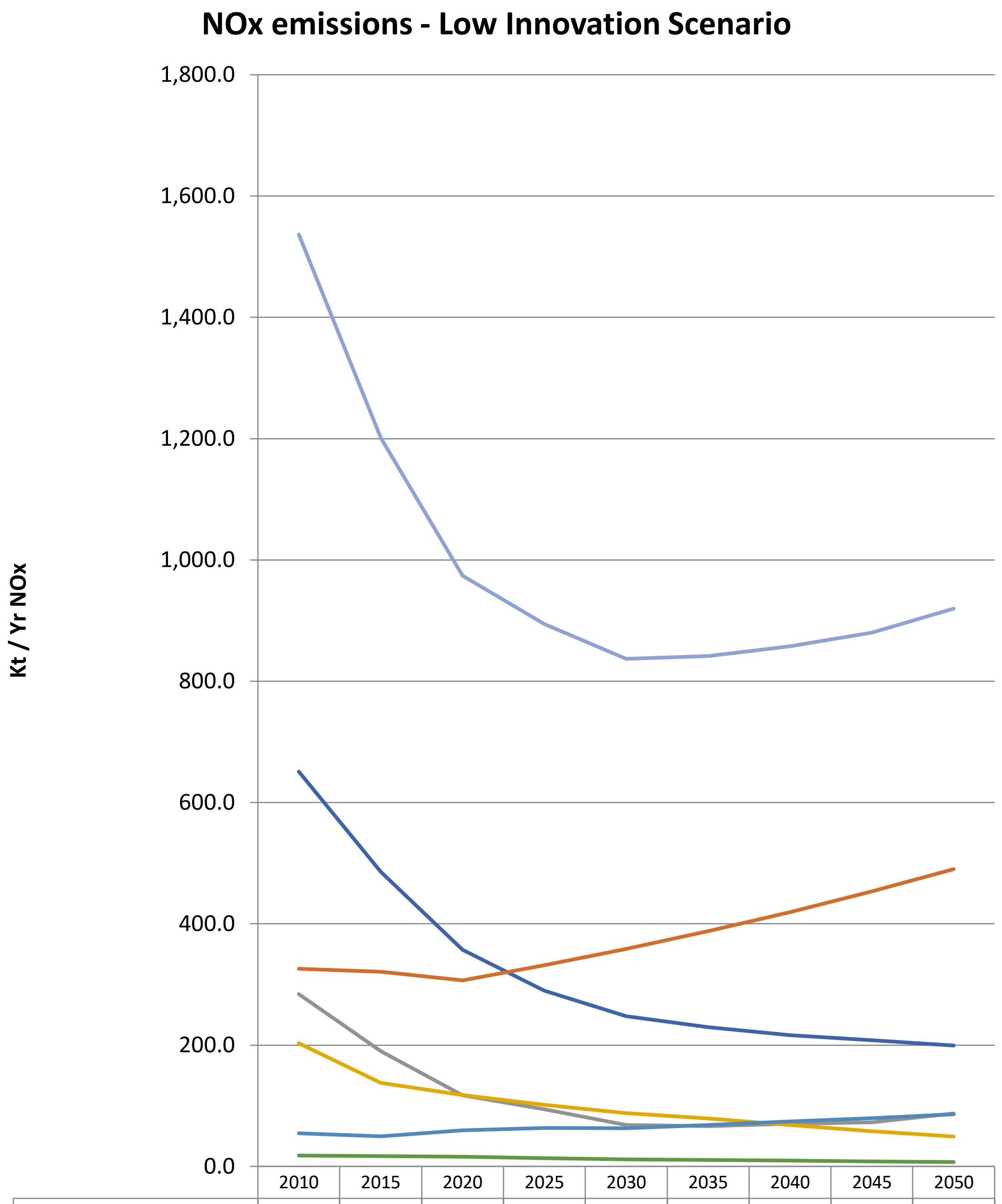
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 35.31 | 26.09 | 20.11 | 15.34 | 11.39 | 9.45 | 7.51 | 5.90 | 4.41 |
| International Shipping | 12.62 | 9.18 | 5.86 | 5.38 | 4.79 | 4.07 | 3.20 | 2.16 | 0.94 |
| ESI | 9.08 | 8.55 | 8.04 | 3.54 | 2.48 | 2.32 | 2.27 | 1.99 | 1.59 |
| Industrial | 81.24 | 33.67 | 35.04 | 29.64 | 24.39 | 18.95 | 14.13 | 10.01 | 6.36 |
| Domestic | 12.05 | 8.60 | 21.13 | 29.29 | 24.50 | 23.45 | 18.68 | 12.11 | 2.43 |
| Rural | 12.09 | 12.14 | 12.28 | 11.50 | 10.66 | 9.57 | 8.47 | 7.41 | 6.34 |
| Total | 162.39 | 98.23 | 102.45 | 94.69 | 78.21 | 67.81 | 54.25 | 39.58 | 22.07 |



| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 651.0 | 485.7 | 357.1 | 263.5 | 202.8 | 167.4 | 138.2 | 113.8 | 90.5 |
| International Shipping | 325.9 | 320.8 | 306.8 | 298.6 | 286.9 | 271.5 | 251.6 | 226.7 | 196.1 |
| ESI | 284.1 | 190.1 | 117.1 | 86.4 | 57.0 | 49.8 | 47.0 | 42.4 | 43.8 |
| Industrial | 203.1 | 137.9 | 117.9 | 95.5 | 77.4 | 64.9 | 51.9 | 40.8 | 31.6 |
| Domestic | 54.6 | 49.7 | 59.4 | 58.2 | 52.7 | 51.8 | 50.3 | 47.6 | 44.3 |
| Rural | 17.9 | 16.9 | 15.9 | 12.6 | 9.7 | 7.9 | 6.3 | 4.9 | 3.6 |
| Total | 1536.7 | 1201.1 | 974.1 | 814.7 | 686.6 | 613.3 | 545.3 | 476.2 | 409.9 |



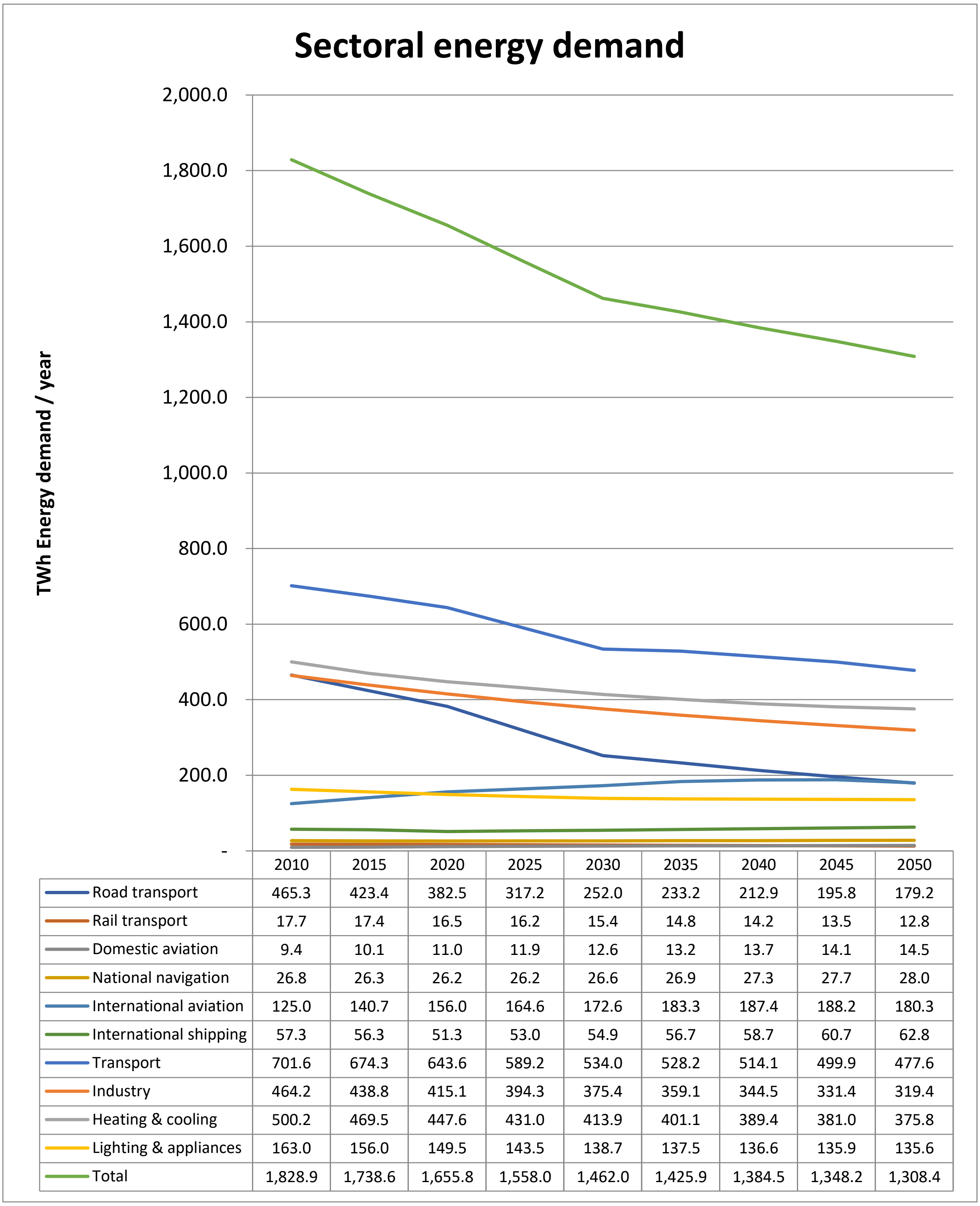
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 35.31 | 26.09 | 20.11 | 16.43 | 13.25 | 12.08 | 10.76 | 9.73 | 8.73 |
| International Shipping | 12.62 | 9.18 | 5.86 | 6.33 | 6.84 | 7.40 | 8.00 | 8.65 | 9.36 |
| ESI | 9.08 | 8.55 | 8.04 | 4.04 | 3.30 | 3.71 | 4.54 | 5.31 | 6.37 |
| Industrial | 81.24 | 33.67 | 35.04 | 33.80 | 32.34 | 30.00 | 27.77 | 25.93 | 24.17 |
| Domestic | 12.05 | 8.60 | 21.13 | 34.90 | 36.12 | 45.31 | 52.37 | 61.86 | 69.91 |
| Rural | 12.09 | 12.14 | 12.28 | 12.54 | 12.79 | 12.76 | 12.70 | 12.70 | 12.68 |
| Total | 162.39 | 98.23 | 102.45 | 108.04 | 104.64 | 111.27 | 116.14 | 124.19 | 131.22 |



| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| — Transport | 651.0 | 485.7 | 357.1 | 289.7 | 247.7 | 229.7 | 216.4 | 208.0 | 199.3 |
| — International Shipping | 325.9 | 320.8 | 306.8 | 331.7 | 358.7 | 387.8 | 419.3 | 453.4 | 490.2 |
| — ESI | 284.1 | 190.1 | 117.1 | 94.3 | 68.4 | 66.4 | 70.5 | 72.7 | 87.6 |
| — Industrial | 203.1 | 137.9 | 117.9 | 101.4 | 87.8 | 79.0 | 68.2 | 58.2 | 49.3 |
| — Domestic | 54.6 | 49.7 | 59.4 | 63.2 | 62.7 | 68.2 | 74.1 | 79.7 | 86.0 |
| — Rural | 17.9 | 16.9 | 15.9 | 13.7 | 11.6 | 10.5 | 9.4 | 8.3 | 7.2 |
| — Total | 1,536.7 | 1,201.1 | 974.1 | 894.1 | 837.0 | 841.6 | 857.9 | 880.3 | 919.6 |

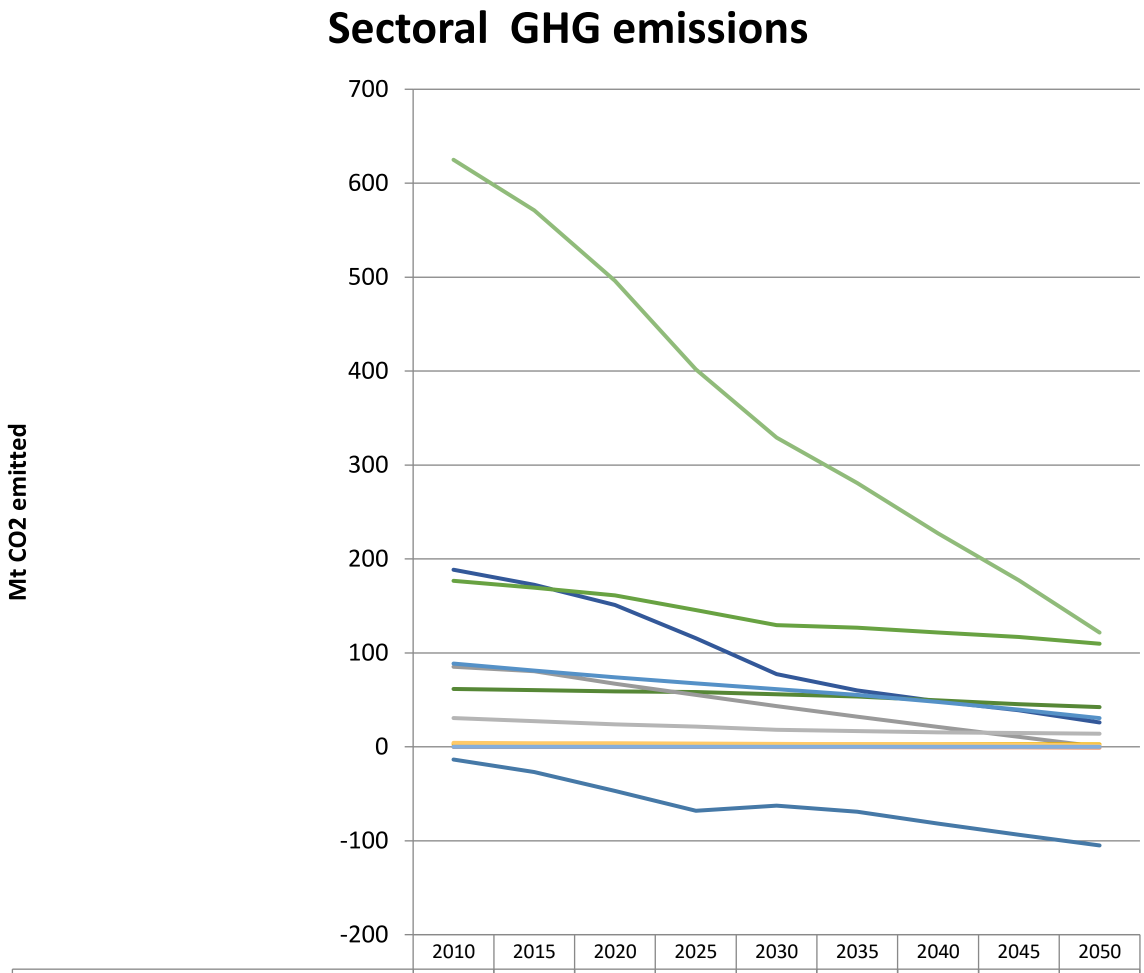
## A.5 Scenario 5

Energy Landscape



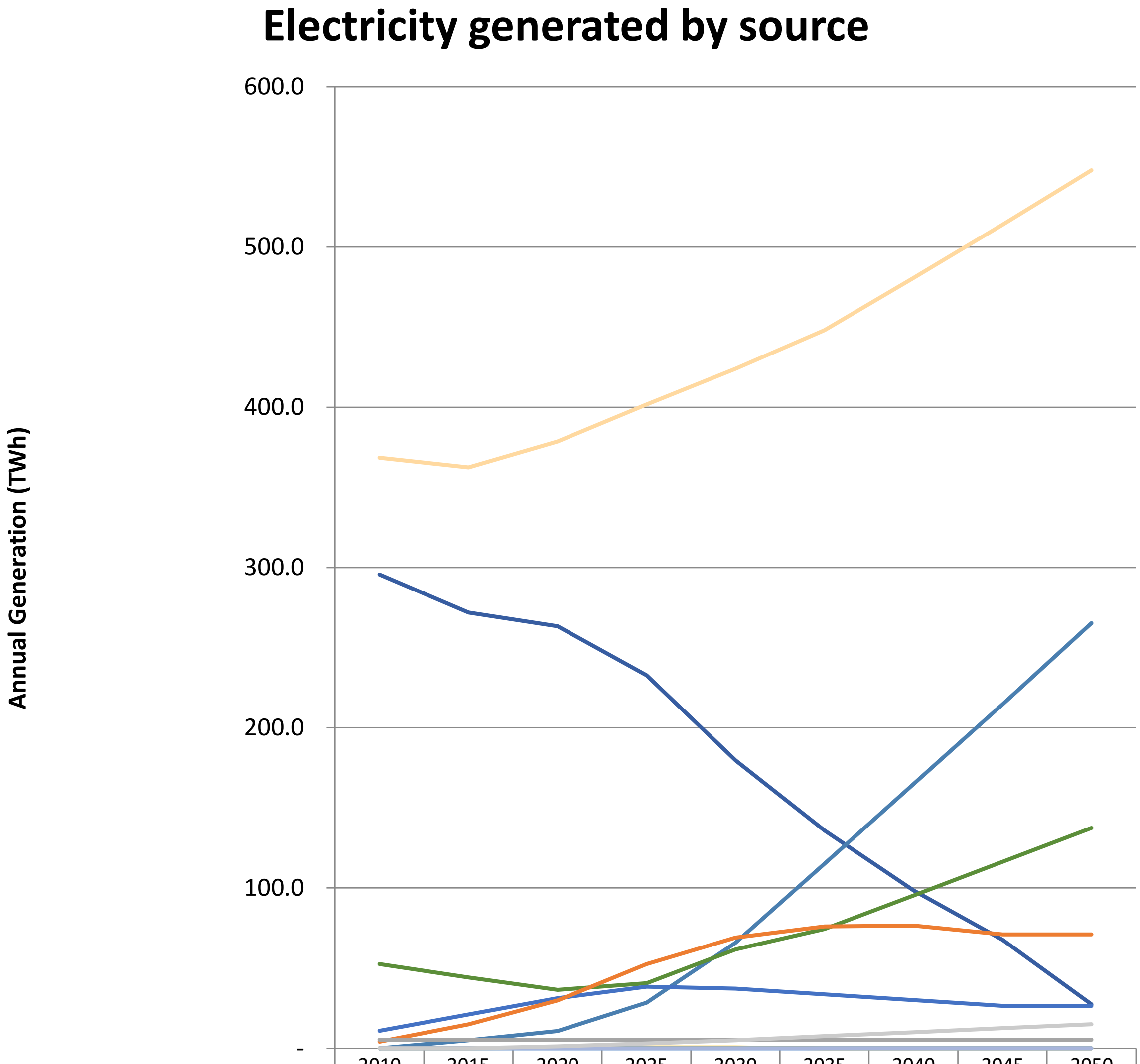
Sectoral energy demand

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Road transport | 465.3 | 423.4 | 382.5 | 317.2 | 252.0 | 233.2 | 212.9 | 195.8 | 179.2 |
| Rail transport | 17.7 | 17.4 | 16.5 | 16.2 | 15.4 | 14.8 | 14.2 | 13.5 | 12.8 |
| Domestic aviation | 9.4 | 10.1 | 11.0 | 11.9 | 12.6 | 13.2 | 13.7 | 14.1 | 14.5 |
| National navigation | 26.8 | 26.3 | 26.2 | 26.2 | 26.6 | 26.9 | 27.3 | 27.7 | 28.0 |
| International aviation | 125.0 | 140.7 | 156.0 | 164.6 | 172.6 | 183.3 | 187.4 | 188.2 | 180.3 |
| International shipping | 57.3 | 56.3 | 51.3 | 53.0 | 54.9 | 56.7 | 58.7 | 60.7 | 62.8 |
| Transport | 701.6 | 674.3 | 643.6 | 589.2 | 534.0 | 528.2 | 514.1 | 499.9 | 477.6 |
| Industry | 464.2 | 438.8 | 415.1 | 394.3 | 375.4 | 359.1 | 344.5 | 331.4 | 319.4 |
| Heating & cooling | 500.2 | 469.5 | 447.6 | 431.0 | 413.9 | 401.1 | 389.4 | 381.0 | 375.8 |
| Lighting & appliances | 163.0 | 156.0 | 149.5 | 143.5 | 138.7 | 137.5 | 136.6 | 135.9 | 135.6 |
| Total | 1,828.9 | 1,738.6 | 1,655.8 | 1,558.0 | 1,462.0 | 1,425.9 | 1,384.5 | 1,348.2 | 1,308.4 |

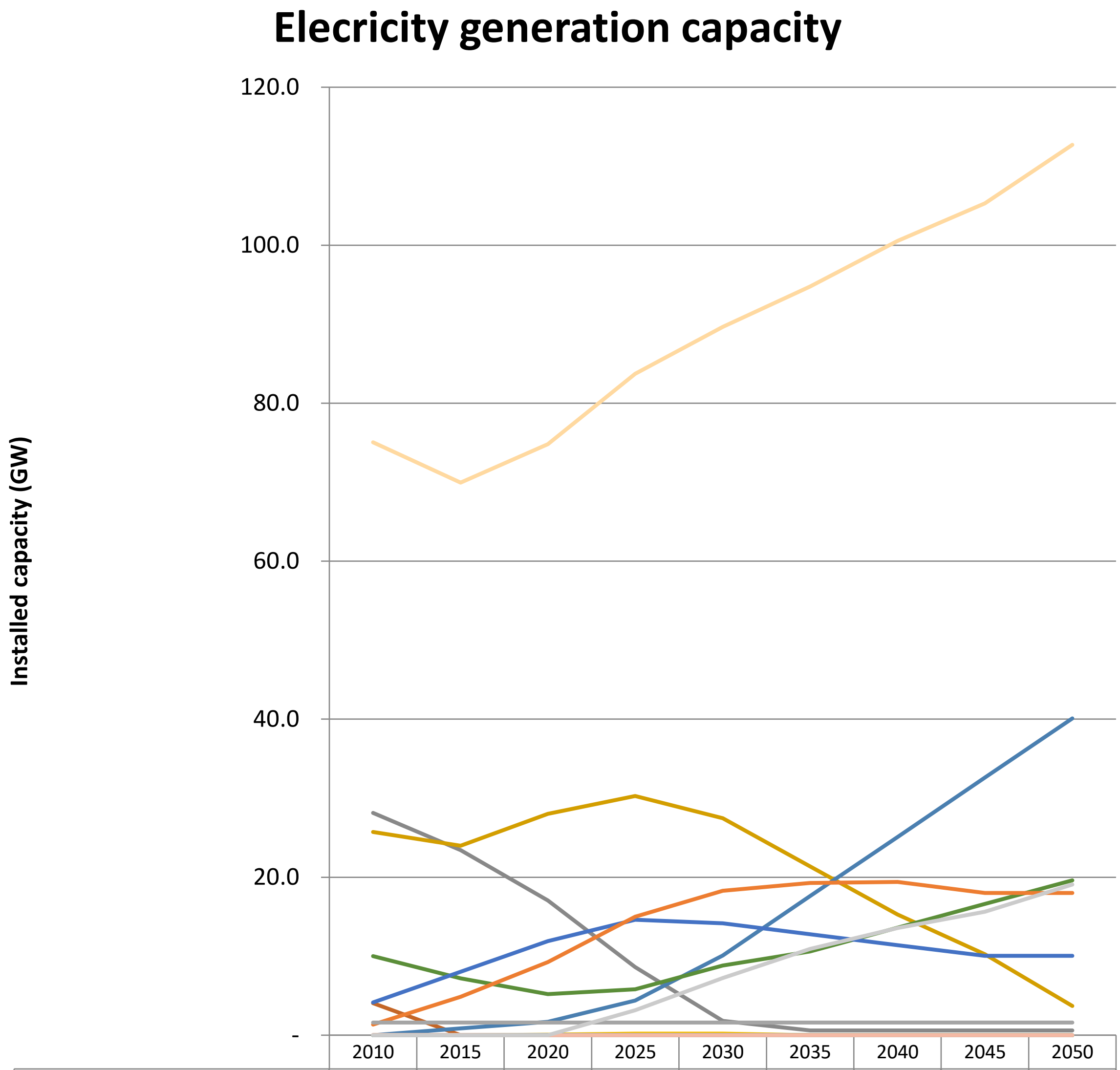


| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Hydrocarbon fuel power generation | 188 | 172 | 151 | 116 | 77 | 60 | 48 | 39 | 26 |
| Nuclear power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| National renewable power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Distributed renewable power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bioenergy | -14 | -27 | -47 | -68 | -63 | -69 | -82 | -94 | -105 |
| Agriculture and waste | 62 | 60 | 59 | 58 | 56 | 53 | 49 | 45 | 42 |
| Electricity distribution, storage, and balancing | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| H2 Production | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Heating | 85 | 80 | 67 | 55 | 43 | 32 | 21 | 11 | 0 |
| Lighting and appliances | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Industry | 89 | 81 | 74 | 67 | 61 | 55 | 48 | 40 | 31 |
| Transport | 177 | 169 | 161 | 145 | 129 | 127 | 122 | 117 | 110 |
| Geosequestration | 0 | 0 | 0 | 0 | 0 | 0 | -1 | -1 | -1 |
| Fossil fuel production | 31 | 27 | 24 | 21 | 18 | 17 | 16 | 15 | 14 |
| Transfers | 4 | 4 | 4 | 3 | 3 | 3 | 2 | 2 | 2 |
| District heating | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Total | 625 | 571 | 496 | 402 | 329 | 281 | 227 | 177 | 122 |

Electricity sector

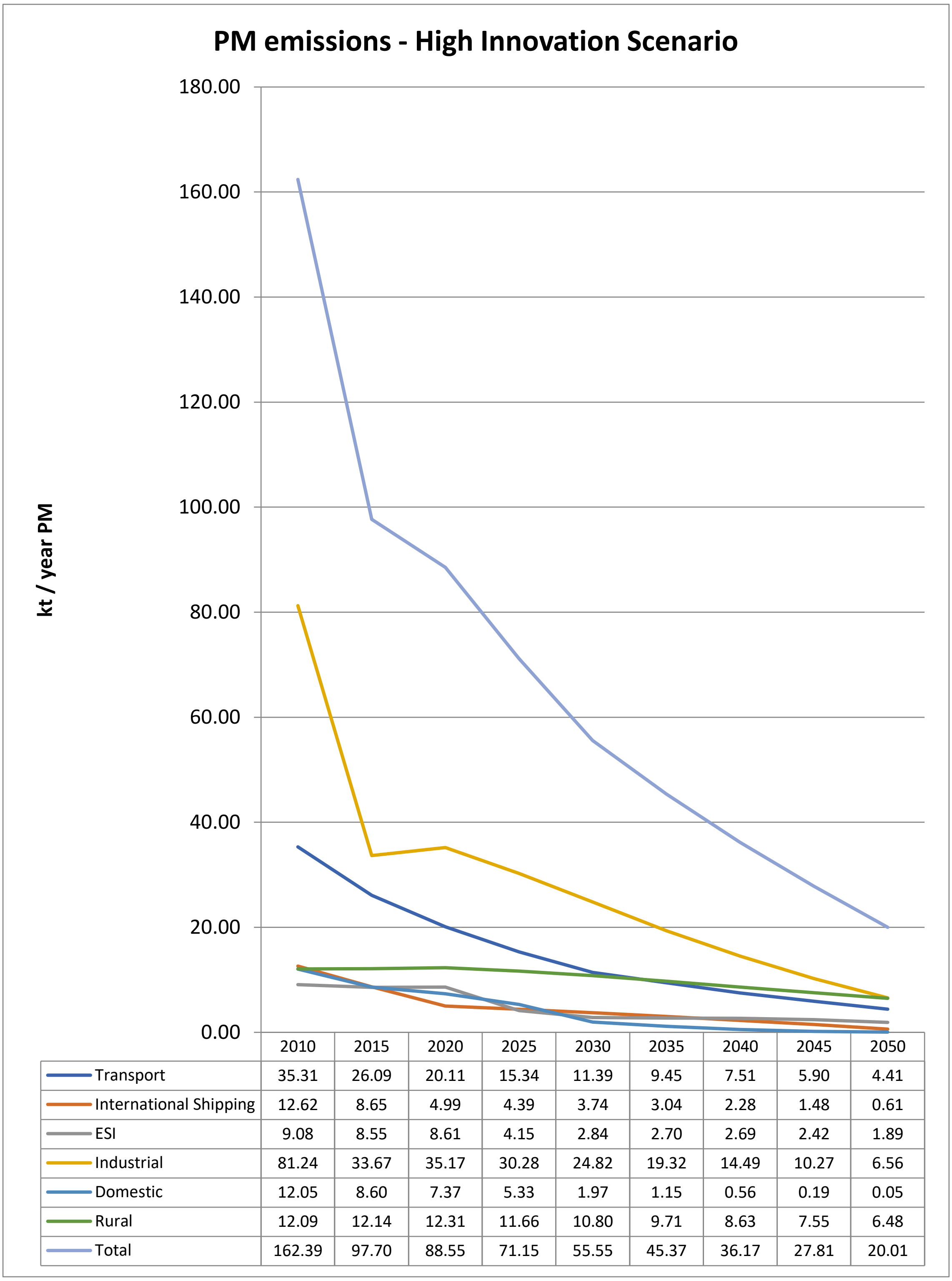


| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Biomass/Coal power stations | 295.6 | 271.9 | 263.3 | 232.7 | 179.5 | 135.9 | 98.5 | 67.6 | 27.4 |
| CCS Power | - | 5.1 | 10.8 | 28.5 | 65.9 | 115.2 | 164.8 | 214.6 | 265.3 |
| Nuclear power | 52.6 | 44.2 | 36.5 | 40.7 | 61.7 | 74.3 | 95.4 | 116.4 | 137.5 |
| Onshore wind | 10.9 | 21.1 | 31.3 | 38.4 | 37.2 | 33.6 | 30.0 | 26.4 | 26.4 |
| Offshore wind | 4.1 | 14.9 | 30.0 | 52.5 | 68.9 | 76.1 | 76.5 | 71.0 | 71.0 |
| Hydroelectric power stations | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 |
| Tidal & Wave | 0.0 | 0.0 | 0.2 | 0.5 | 0.5 | - | - | - | - |
| Geothermal electricity | - | - | - | - | - | - | - | - | - |
| Solar PV | 0.0 | 0.0 | - | - | - | - | - | - | - |
| Electricity imports | - | - | 1.3 | 3.1 | 4.9 | 7.5 | 10.1 | 12.5 | 15.0 |
| Total | 368.6 | 362.5 | 378.6 | 401.7 | 424.1 | 448.0 | 480.6 | 513.9 | 547.9 |

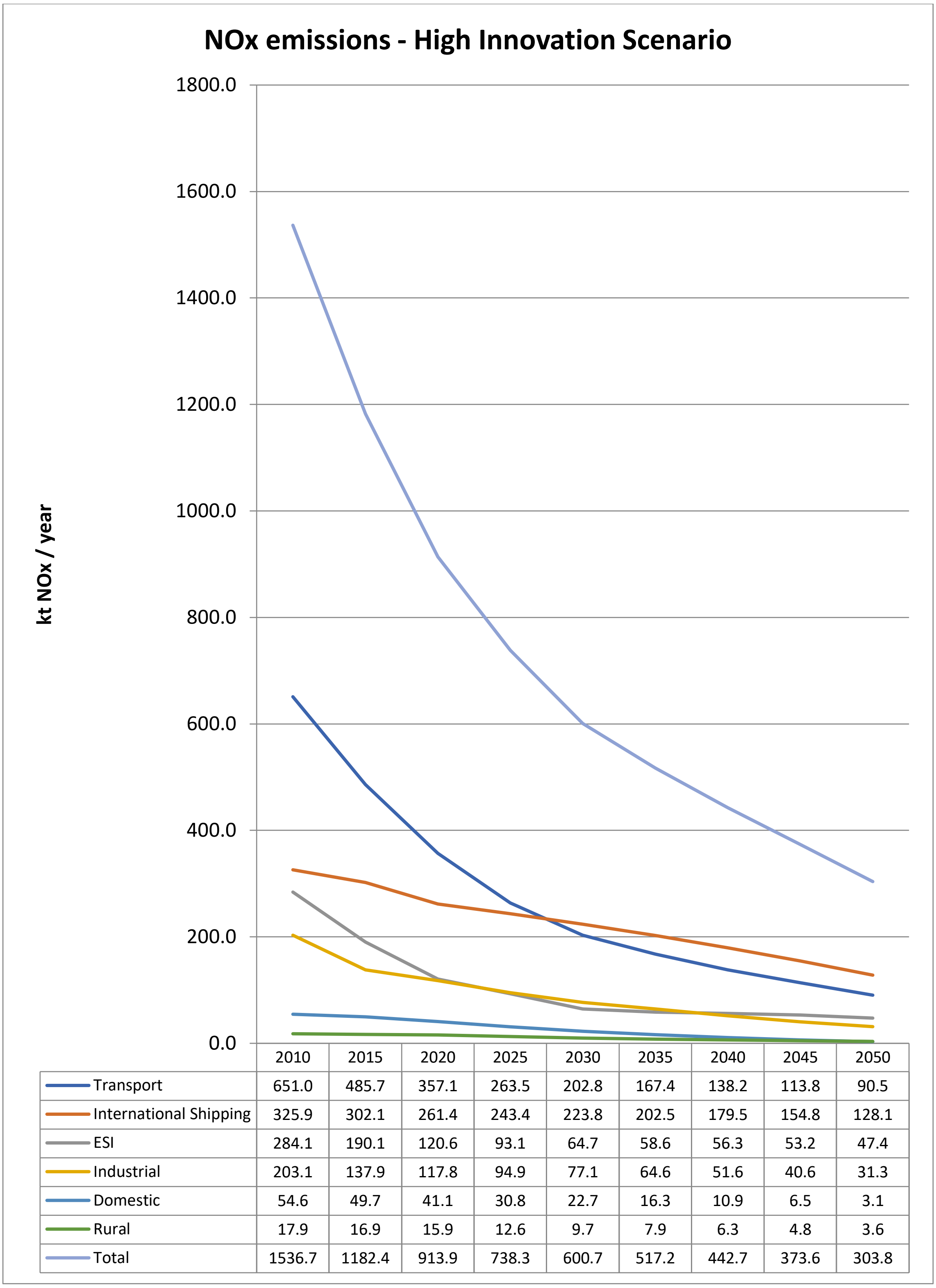


| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Oil / Biofuel | 4.1 | - | - | - | - | - | - | - | - |
| Coal / Biomass | 28.1 | 23.4 | 17.1 | 8.6 | 1.8 | 0.6 | 0.6 | 0.6 | 0.6 |
| Gas / Biogas | 25.7 | 24.0 | 28.0 | 30.3 | 27.5 | 21.4 | 15.3 | 10.2 | 3.7 |
| CCS Power | - | 0.9 | 1.7 | 4.4 | 10.1 | 17.6 | 25.1 | 32.6 | 40.1 |
| Nuclear power | 10.0 | 7.2 | 5.2 | 5.8 | 8.8 | 10.6 | 13.6 | 16.6 | 19.6 |
| Onshore wind | 4.1 | 8.0 | 11.9 | 14.6 | 14.2 | 12.8 | 11.4 | 10.0 | 10.0 |
| Offshore wind | 1.3 | 4.8 | 9.2 | 15.0 | 18.3 | 19.3 | 19.4 | 18.0 | 18.0 |
| Hydroelectric power stations | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 | 1.6 |
| Wave | - | 0.0 | 0.1 | 0.2 | 0.2 | - | - | - | - |
| Tidal Stream | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | - | - | - | - |
| Tidal Range | - | - | - | - | - | - | - | - | - |
| Geothermal electricity | - | - | - | - | - | - | - | - | - |
| Solar PV | 0.0 | 0.0 | - | - | - | - | - | - | - |
| Standby / peaking gas | - | - | - | 3.2 | 7.2 | 10.9 | 13.6 | 15.6 | 19.1 |
| Total generation | 75.0 | 69.9 | 74.8 | 83.7 | 89.7 | 94.8 | 100.5 | 105.3 | 112.7 |

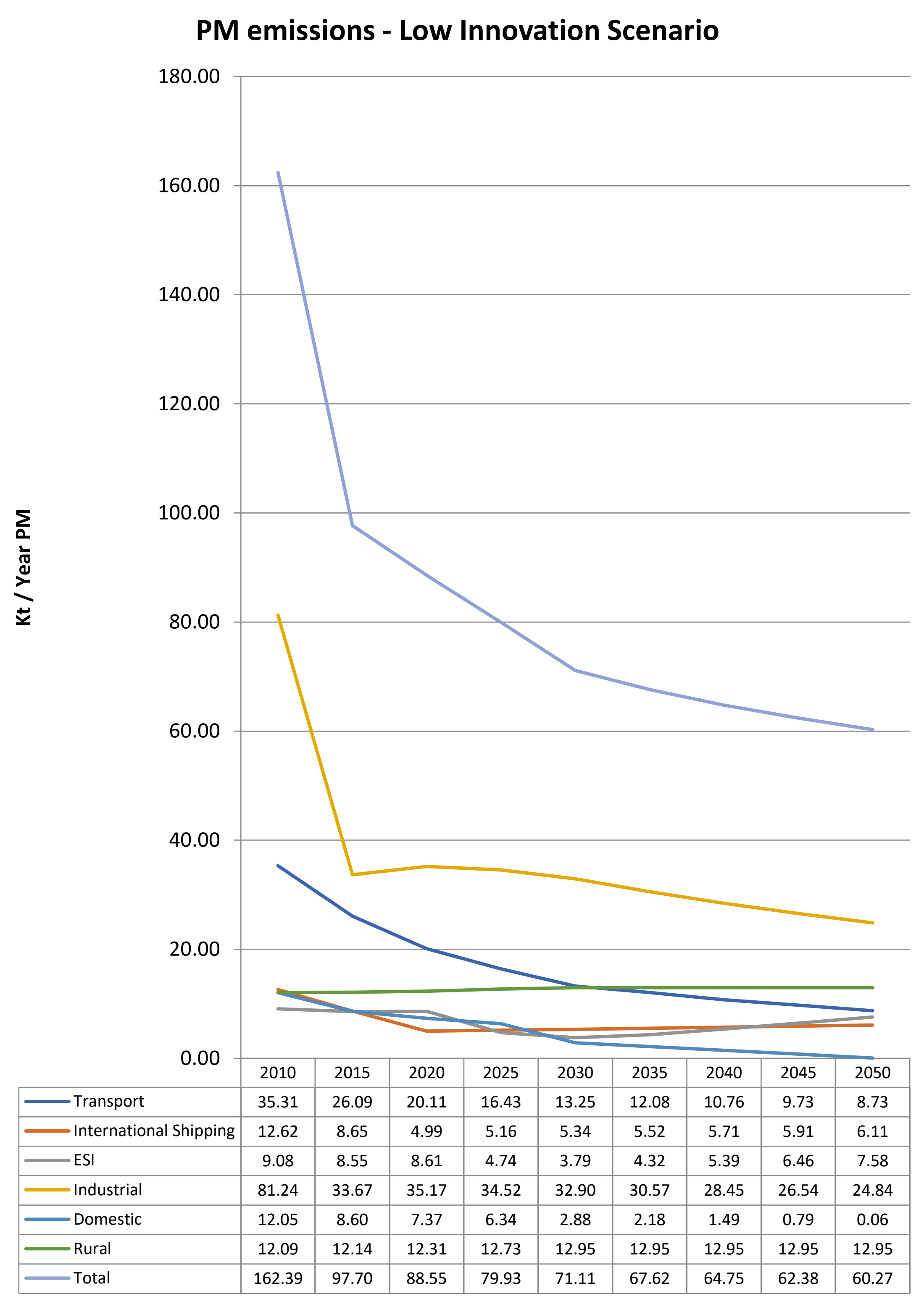
Air pollution



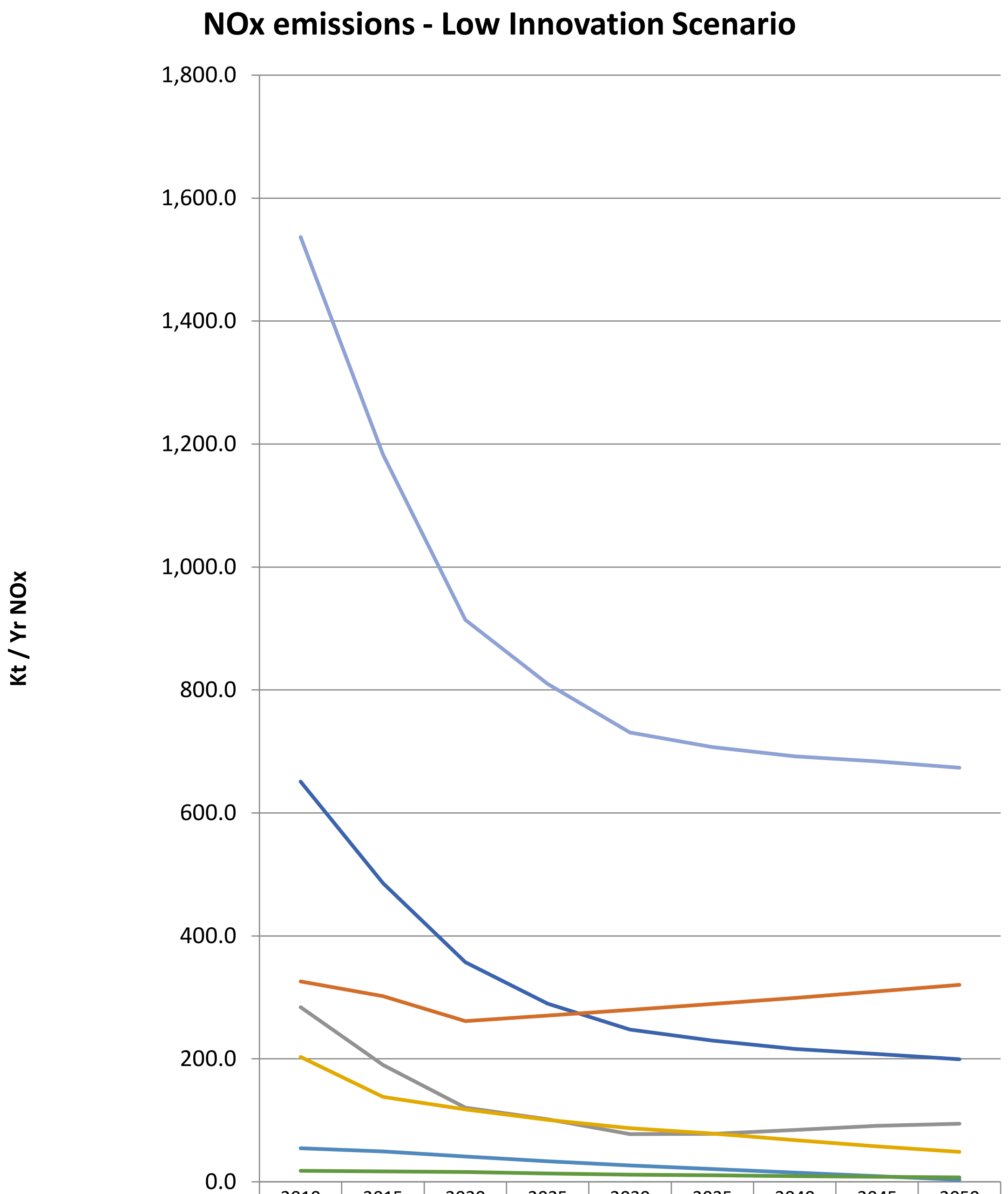
| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 35.31 | 26.09 | 20.11 | 15.34 | 11.39 | 9.45 | 7.51 | 5.90 | 4.41 |
| International Shipping | 12.62 | 8.65 | 4.99 | 4.39 | 3.74 | 3.04 | 2.28 | 1.48 | 0.61 |
| ESI | 9.08 | 8.55 | 8.61 | 4.15 | 2.84 | 2.70 | 2.69 | 2.42 | 1.89 |
| Industrial | 81.24 | 33.67 | 35.17 | 30.28 | 24.82 | 19.32 | 14.49 | 10.27 | 6.56 |
| Domestic | 12.05 | 8.60 | 7.37 | 5.33 | 1.97 | 1.15 | 0.56 | 0.19 | 0.05 |
| Rural | 12.09 | 12.14 | 12.31 | 11.66 | 10.80 | 9.71 | 8.63 | 7.55 | 6.48 |
| Total | 162.39 | 97.70 | 88.55 | 71.15 | 55.55 | 45.37 | 36.17 | 27.81 | 20.01 |


NOx emissions - High Innovation Scenario

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 651.0 | 485.7 | 357.1 | 263.5 | 202.8 | 167.4 | 138.2 | 113.8 | 90.5 |
| International Shipping | 325.9 | 302.1 | 261.4 | 243.4 | 223.8 | 202.5 | 179.5 | 154.8 | 128.1 |
| ESI | 284.1 | 190.1 | 120.6 | 93.1 | 64.7 | 58.6 | 56.3 | 53.2 | 47.4 |
| Industrial | 203.1 | 137.9 | 117.8 | 94.9 | 77.1 | 64.6 | 51.6 | 40.6 | 31.3 |
| Domestic | 54.6 | 49.7 | 41.1 | 30.8 | 22.7 | 16.3 | 10.9 | 6.5 | 3.1 |
| Rural | 17.9 | 16.9 | 15.9 | 12.6 | 9.7 | 7.9 | 6.3 | 4.8 | 3.6 |
| Total | 1536.7 | 1182.4 | 913.9 | 738.3 | 600.7 | 517.2 | 442.7 | 373.6 | 303.8 |



| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| Transport | 35.31 | 26.09 | 20.11 | 16.43 | 13.25 | 12.08 | 10.76 | 9.73 | 8.73 |
| International Shipping | 12.62 | 8.65 | 4.99 | 5.16 | 5.34 | 5.52 | 5.71 | 5.91 | 6.11 |
| ESI | 9.08 | 8.55 | 8.61 | 4.74 | 3.79 | 4.32 | 5.39 | 6.46 | 7.58 |
| Industrial | 81.24 | 33.67 | 35.17 | 34.52 | 32.90 | 30.57 | 28.45 | 26.54 | 24.84 |
| Domestic | 12.05 | 8.60 | 7.37 | 6.34 | 2.88 | 2.18 | 1.49 | 0.79 | 0.06 |
| Rural | 12.09 | 12.14 | 12.31 | 12.73 | 12.95 | 12.95 | 12.95 | 12.95 | 12.95 |
| Total | 162.39 | 97.70 | 88.55 | 79.93 | 71.11 | 67.62 | 64.75 | 62.38 | 60.27 |


NOx emissions - Low Innovation Scenario

| | 2010 | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|---|
| — Transport | 651.0 | 485.7 | 357.1 | 289.7 | 247.7 | 229.7 | 216.4 | 208.0 | 199.3 |
| — International Shipping | 325.9 | 302.1 | 261.4 | 270.4 | 279.7 | 289.3 | 299.2 | 309.5 | 320.1 |
| — ESI | 284.1 | 190.1 | 120.6 | 101.6 | 77.6 | 78.1 | 84.4 | 91.2 | 94.7 |
| — Industrial | 203.1 | 137.9 | 117.8 | 100.9 | 87.4 | 78.6 | 67.7 | 57.8 | 48.7 |
| — Domestic | 54.6 | 49.7 | 41.1 | 33.3 | 26.7 | 20.8 | 14.9 | 9.2 | 3.4 |
| — Rural | 17.9 | 16.9 | 15.9 | 13.7 | 11.6 | 10.5 | 9.4 | 8.3 | 7.2 |
| — Total | 1,536.7 | 1,182.4 | 913.9 | 809.6 | 730.8 | 707.0 | 692.0 | 684.0 | 673.5 |

# Appendix B : Locations of CHP plant in Chapter 3

| Easting (OS Grid) | Northing (OS Grid) | Thermal Generation Capacity (MWth) | Electrical Generation Capacity (MWe) | Location in London |
|---|---|---|---|---|
| **Contiguous potential networkable heat load** | | | | |
| 509630.247 | 179189.366 | 5 | 2.55 | Hayes - matched load area |
| 515784.296 | 188682.241 | 20 | 10.2 | Harrow - Matched load area |
| 521122.338 | 189158.245 | 10 | 5.1 | Collindale |
| 523141.954 | 188770.642 | 20 | 10.2 | Hendon / Brent cross |
| 526331.18 | 189280.646 | 10 | 5.1 | Hampstead |
| 534079.841 | 191497.464 | 40 | 20.4 | Edmonton / Tottenham |
| 525375.772 | 185391.015 | 40 | 20.4 | Southern Hampstead |
| 525375.772 | 185391.015 | 40 | 20.4 | Camden Town |
| 525579.564 | 181618.861 | 78.4 | 40 | Paddington |
| 531885.645 | 181828.597 | 39.2 | 20 | City - double capacity of City Heat Network |
| 535184.509 | 182320.231 | 78.4 | 40 | Shoreditch / Stepney |
| 522468.471 | 178822.373 | 78.4 | 40 | Hammersmith |
| 526942.852 | 178752.46 | 78.4 | 40 | Kensington and Chelsea |
| 531962.548 | 178822.373 | 78.4 | 40 | Lambeth |
| 534171.774 | 179074.057 | 39.2 | 20 | Bermondsey |
| 525684.433 | 177256.339 | 78.4 | 40 | Fulham |
| 531055.854 | 175775.699 | 78.4 | 40 | Brixton |
| 533796.412 | 176894.294 | 78.4 | 40 | Camberwell |

| | | | | |
|---|---|---|---|---|
| 540577.895 | 181298.763 | 39.2 | 20 | Thames gateway / City Airport |
| 525556.359 | 174222.912 | 78.4 | 40 | Putney / Wandsworth |
| 539846.413 | 177690.557 | 39.2 | 20 | Greenwich / Plumstead |
| | | | | |
| **Potential standalone networks** | | | | |
| 513419.601 | 175565.226 | 39.2 | 20 | Hounslow |
| 517115.361 | 180543.711 | 19.6 | 10 | Ealing |
| 518229.56 | 174894.069 | 39.2 | 20 | Richmond |
| 521249.767 | 175788.945 | 39.2 | 20 | Mortlake |
| 515740.686 | 171202.705 | 19.6 | 10 | Teddington |
| 525080.956 | 170503.583 | 39.2 | 20 | Wimbledon |
| 527541.865 | 171957.757 | 39.2 | 20 | Tooting |
| 525975.832 | 164099.625 | 39.2 | 20 | Sutton |
| 532351.825 | 166196.991 | 58.8 | 30 | Croydon |
| 549242.613 | 178613.398 | 39.2 | 20 | Thamesmead |
| 536798.241 | 187897.738 | 19.6 | 10 | Leyton |
| 534155.56 | 191491.226 | 19.6 | 10 | Tottenham |
| 535693.628 | 196049.501 | 19.6 | 10 | Eastern Enfield |

# Appendix C : Graphs of PEMS emission measurements from vehicles in Chapter 6

## Car 1 – Petrol power-split hybrid

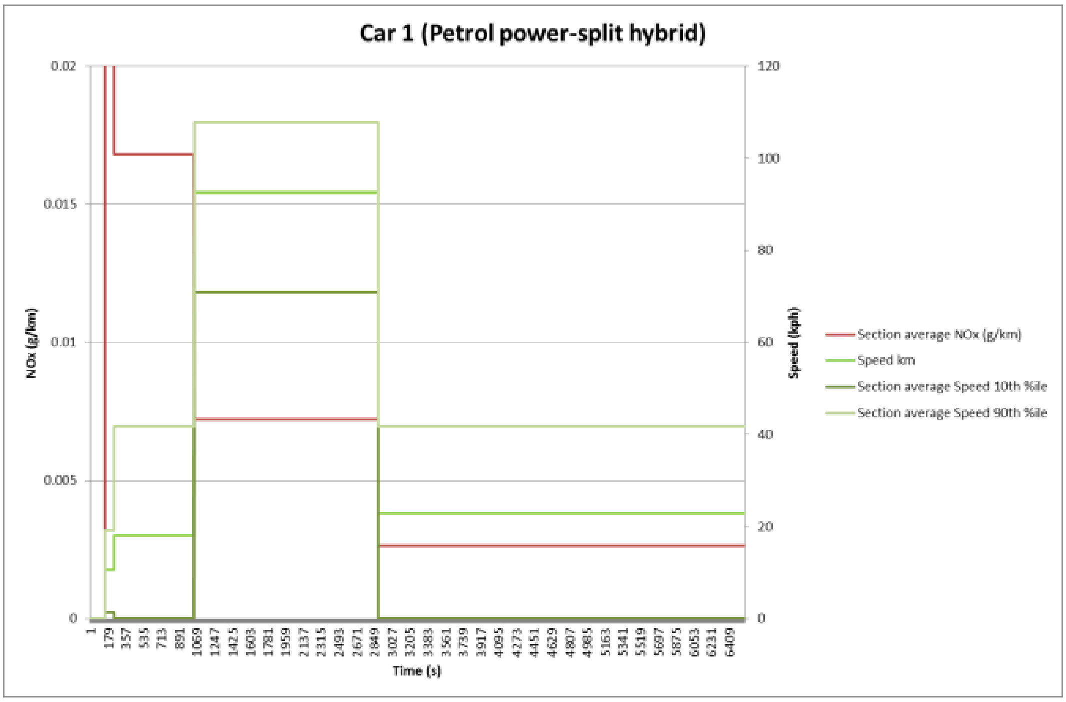


Figure C.1: Car 1 $NO_x$ g/km with time

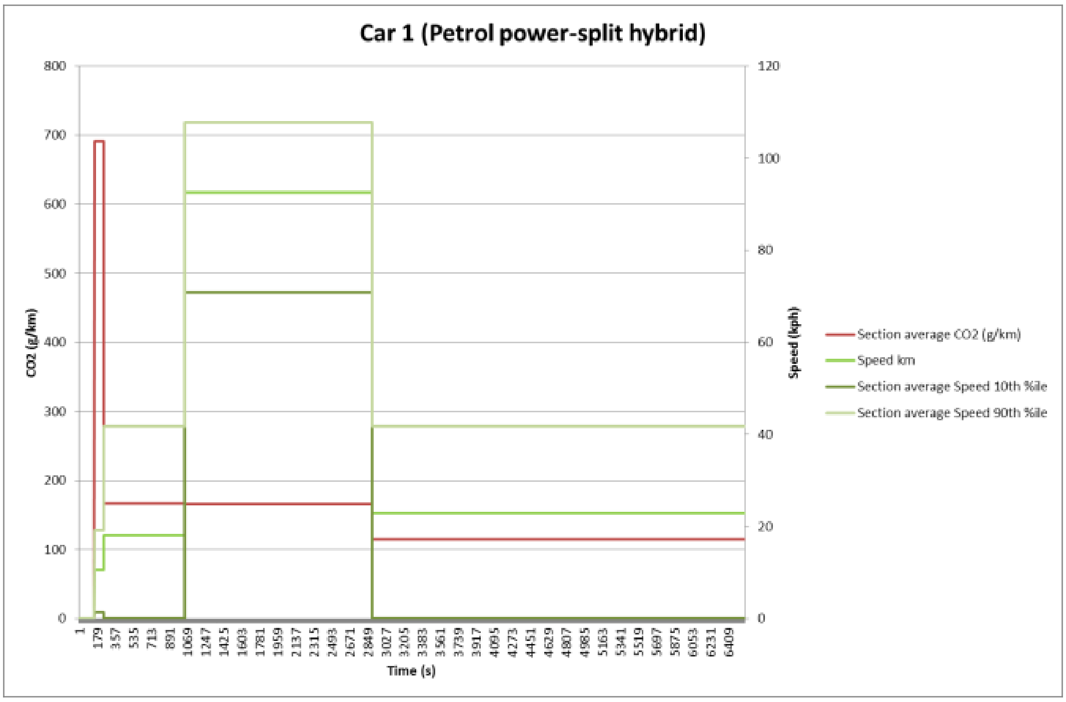


Figure C.2: Car 1 CO2 g/km with time

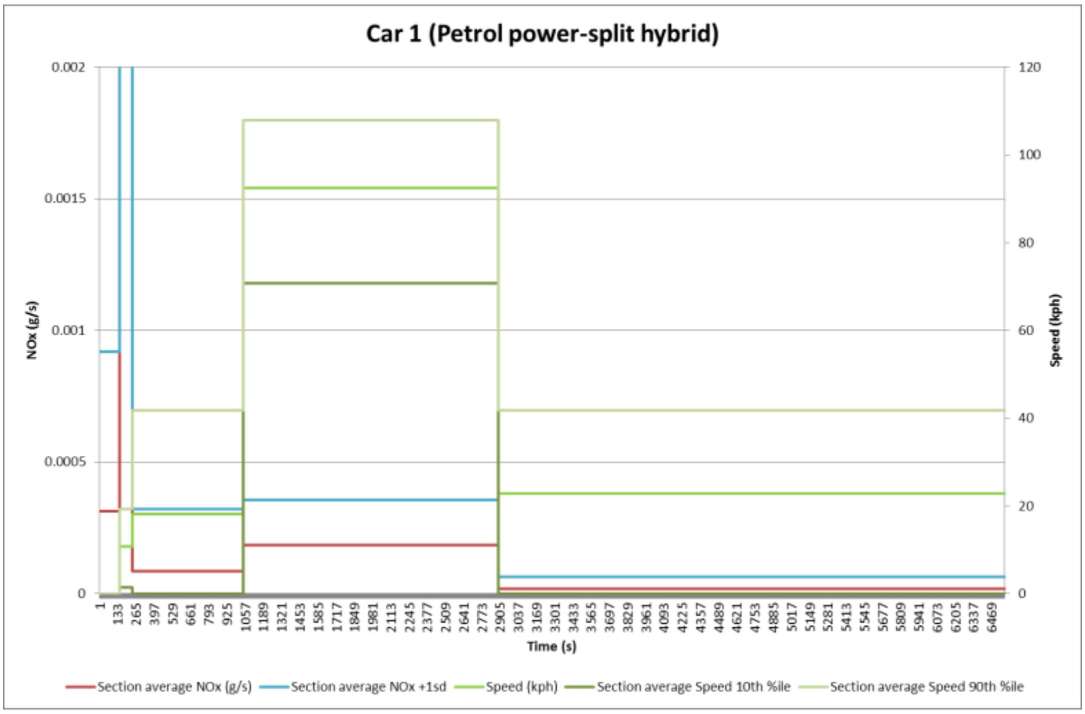


Figure C.3: Car 1 NOx g/s with time

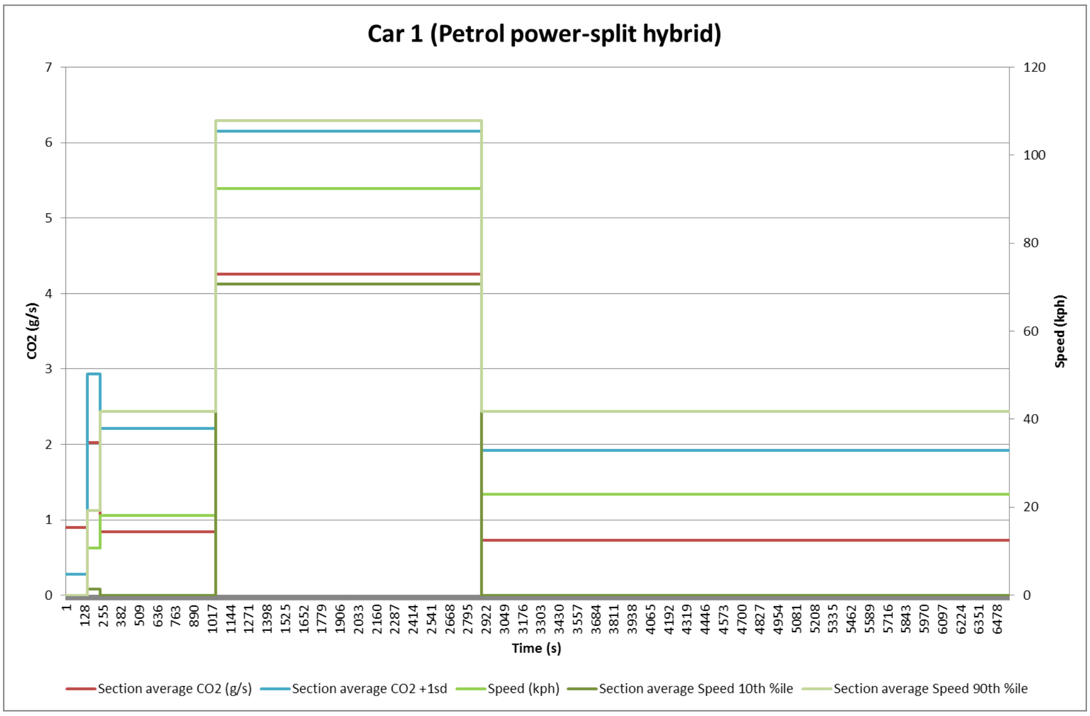


Figure C.4: Car 1 $CO_2$ g/s with time

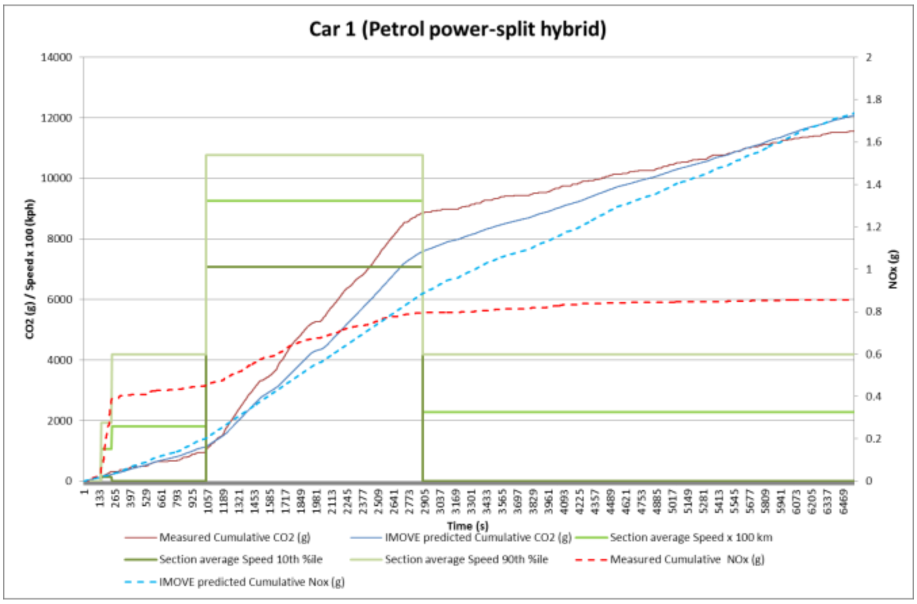


Figure C.5: Car 1 cumulative NOx and CO2 emissions with time, with equivalent predictions by iMOVE using COPERT 5.

## Car 2 – Petrol power-split hybrid

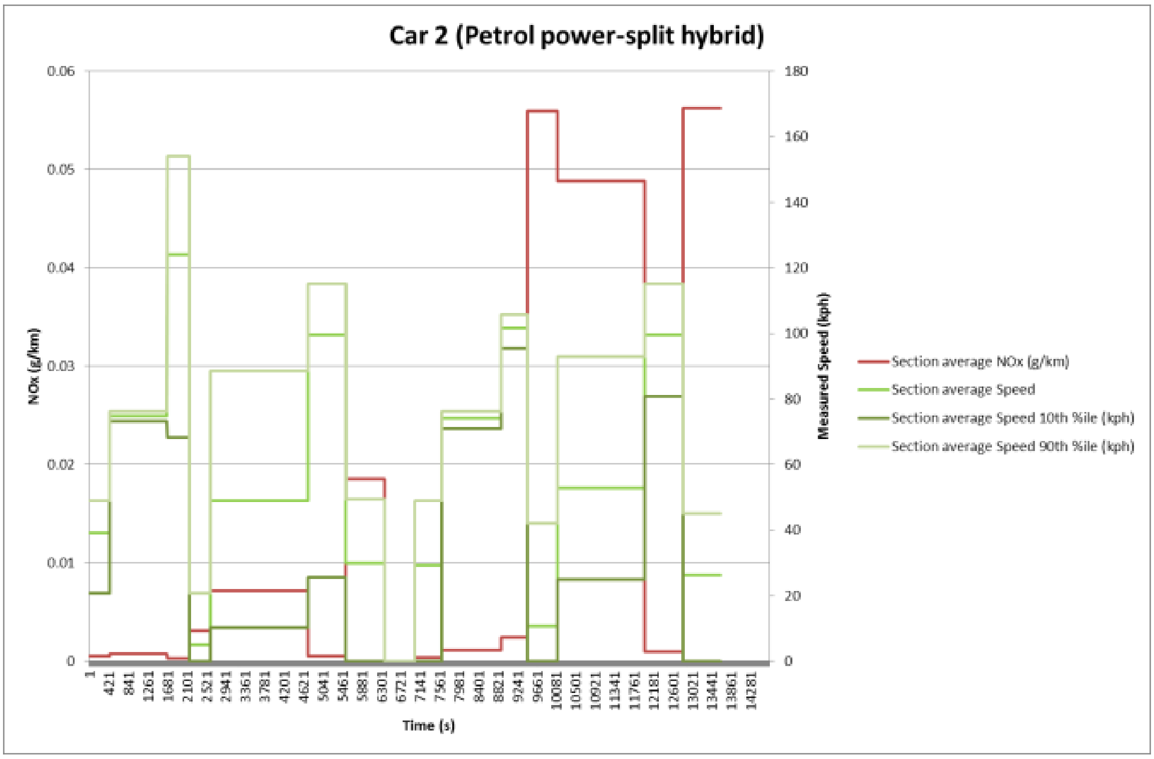


Figure C.6: Car 2 $NO_x$ g/km with time

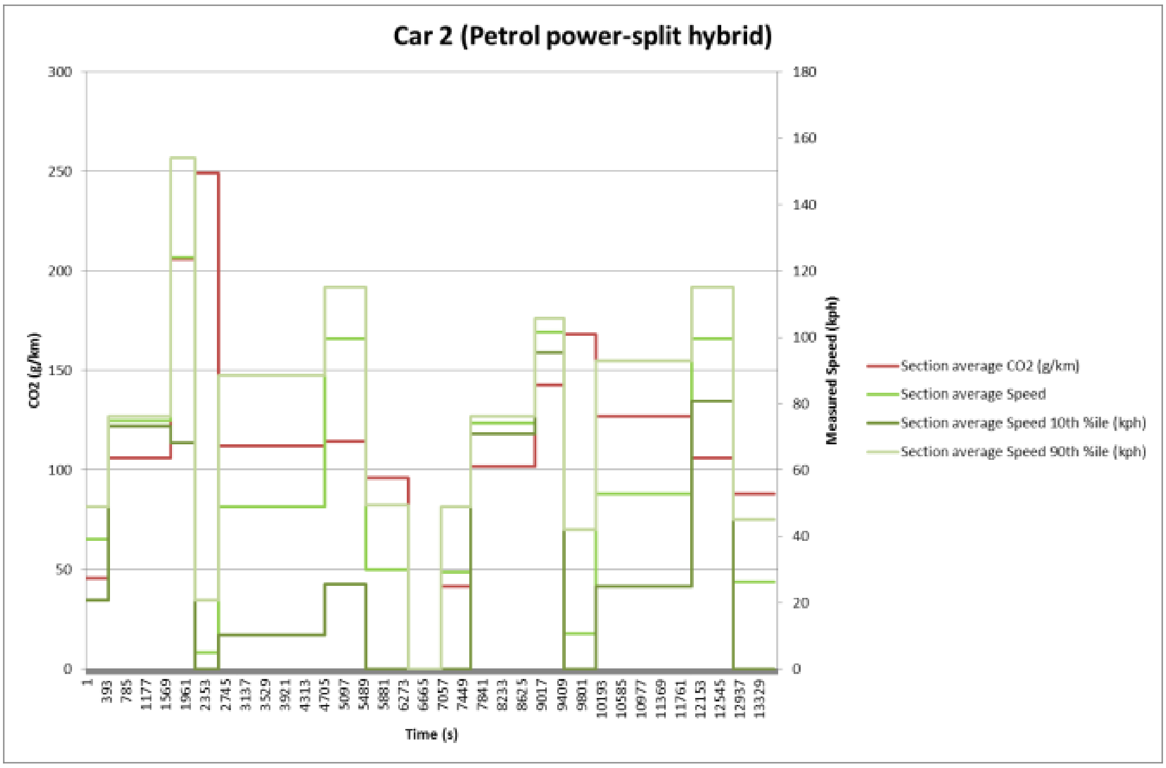


Figure C.7: Car 2 $CO_2$ g/km with time

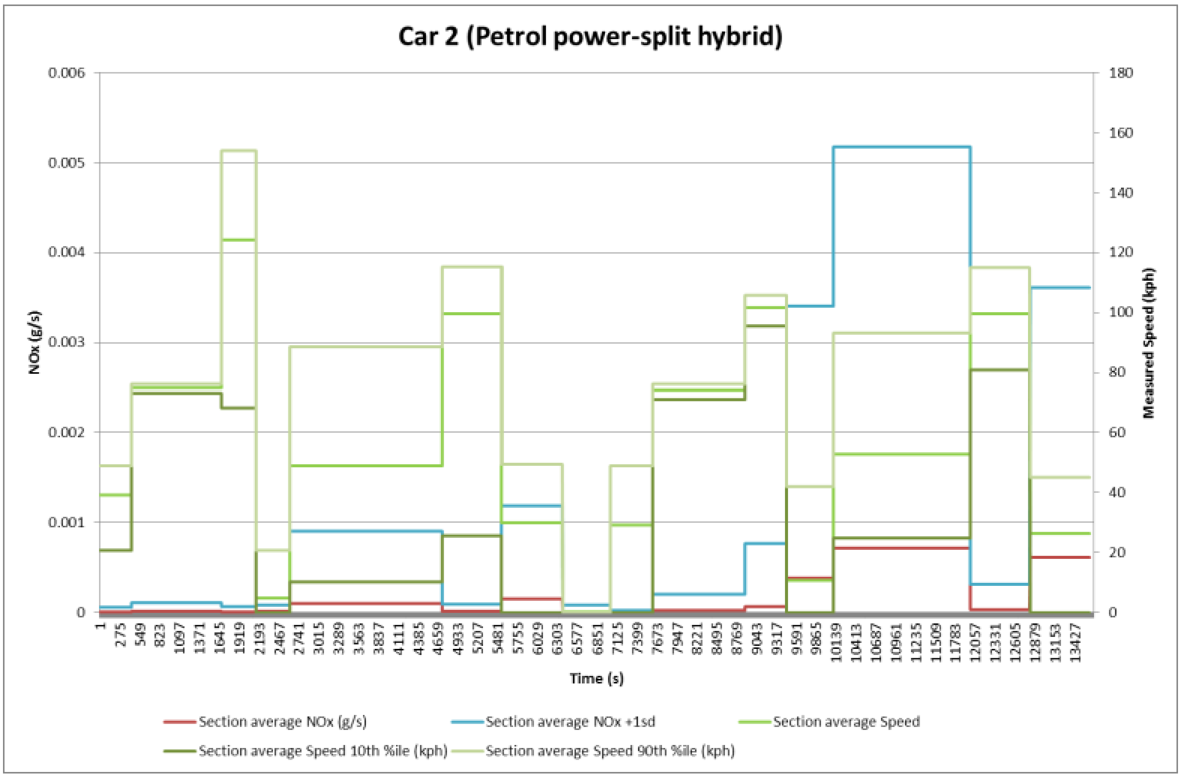


**Figure C.8: Car 2 NO$_x$ g/s with time**

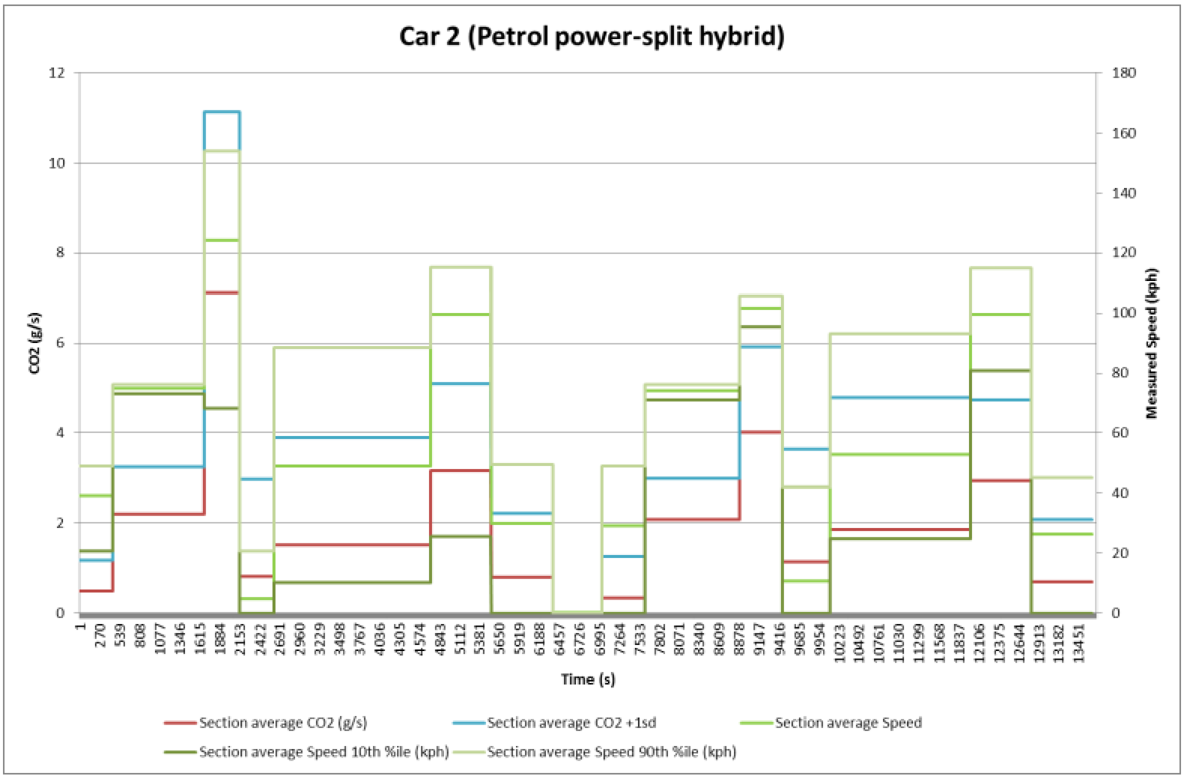


**Figure C.9: Car 2 CO$_2$ g/s with time**

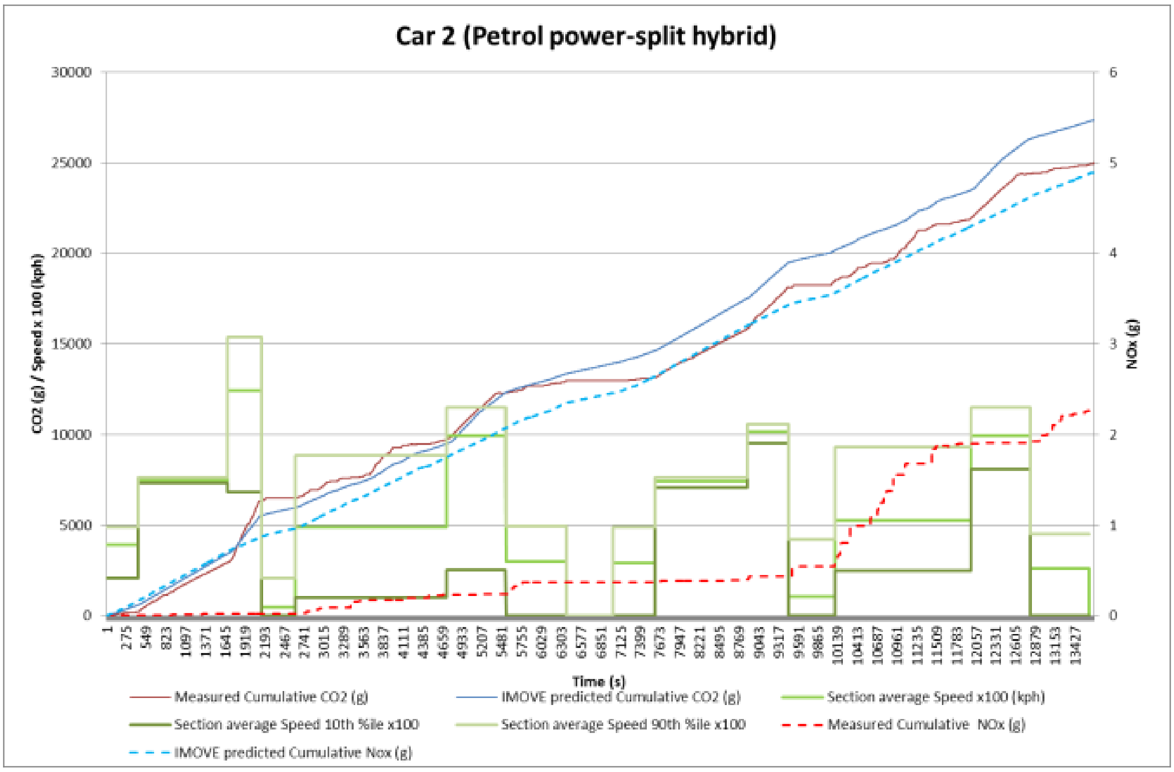


**Figure C.10: Car 2 cumulative $NO_x$ and $CO_2$ emissions with time, with equivalent predictions by iMOVE using COPERT 5.**

## Car 3 – Petrol parallel hybrid

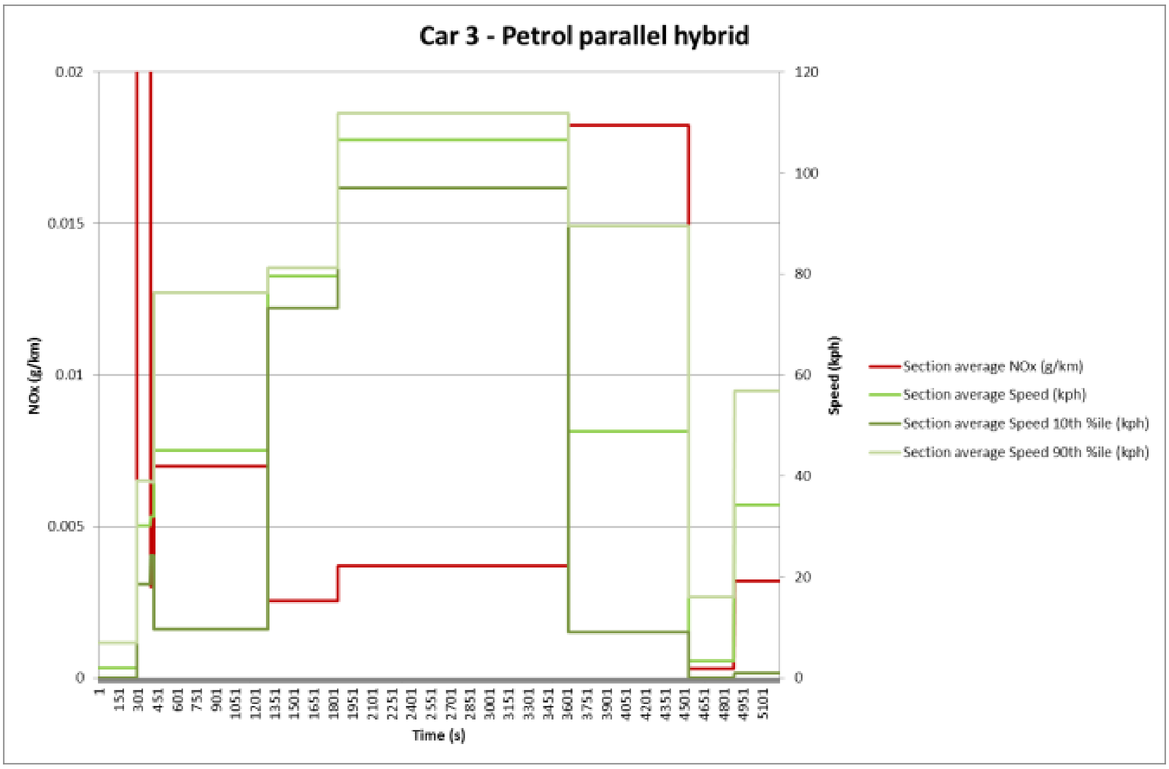


Figure C.11: Car 3 $NO_x$ g/km with time

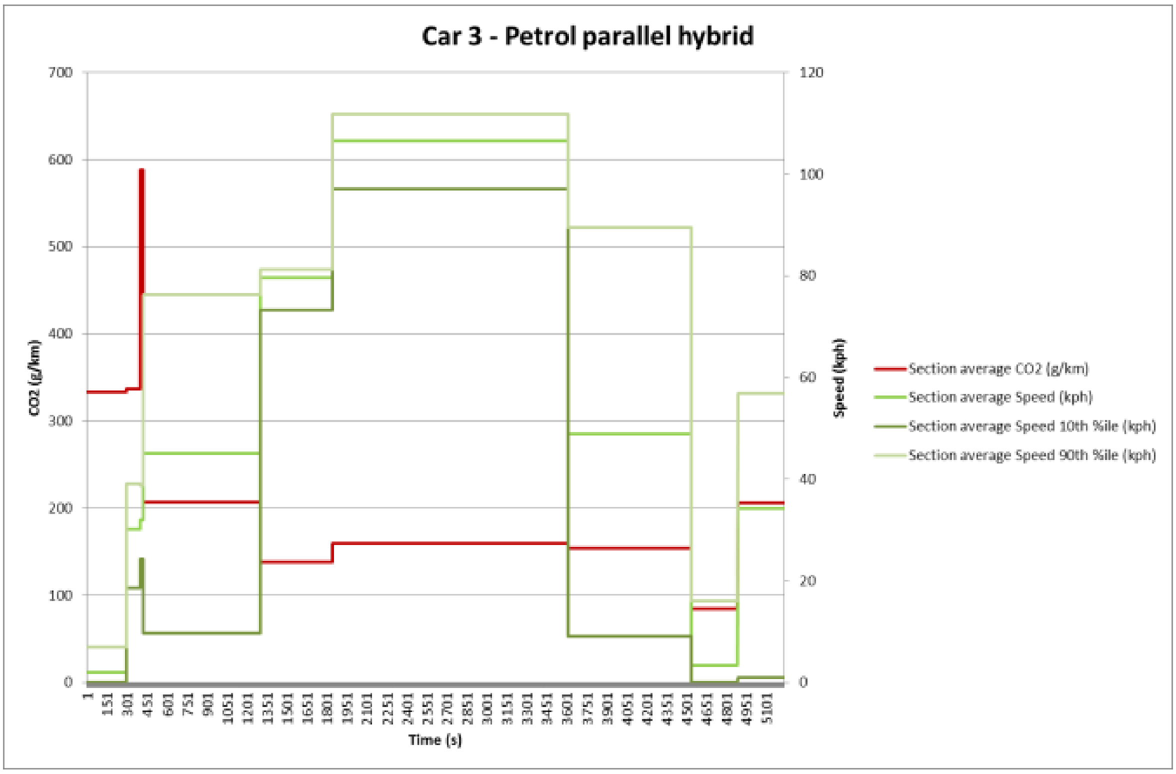


Figure C.12: Car 3 $CO_2$ g/km with time

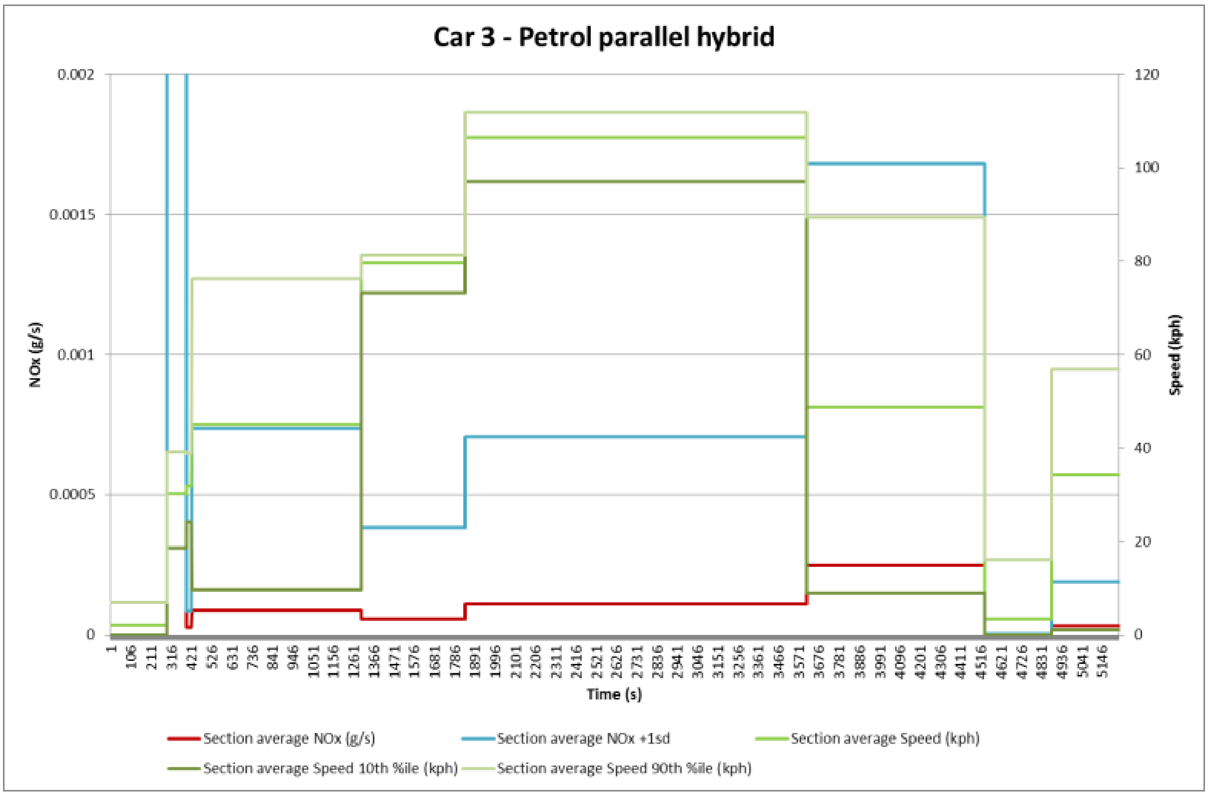


Figure C.13: Car 3 $NO_x$ g/s with time

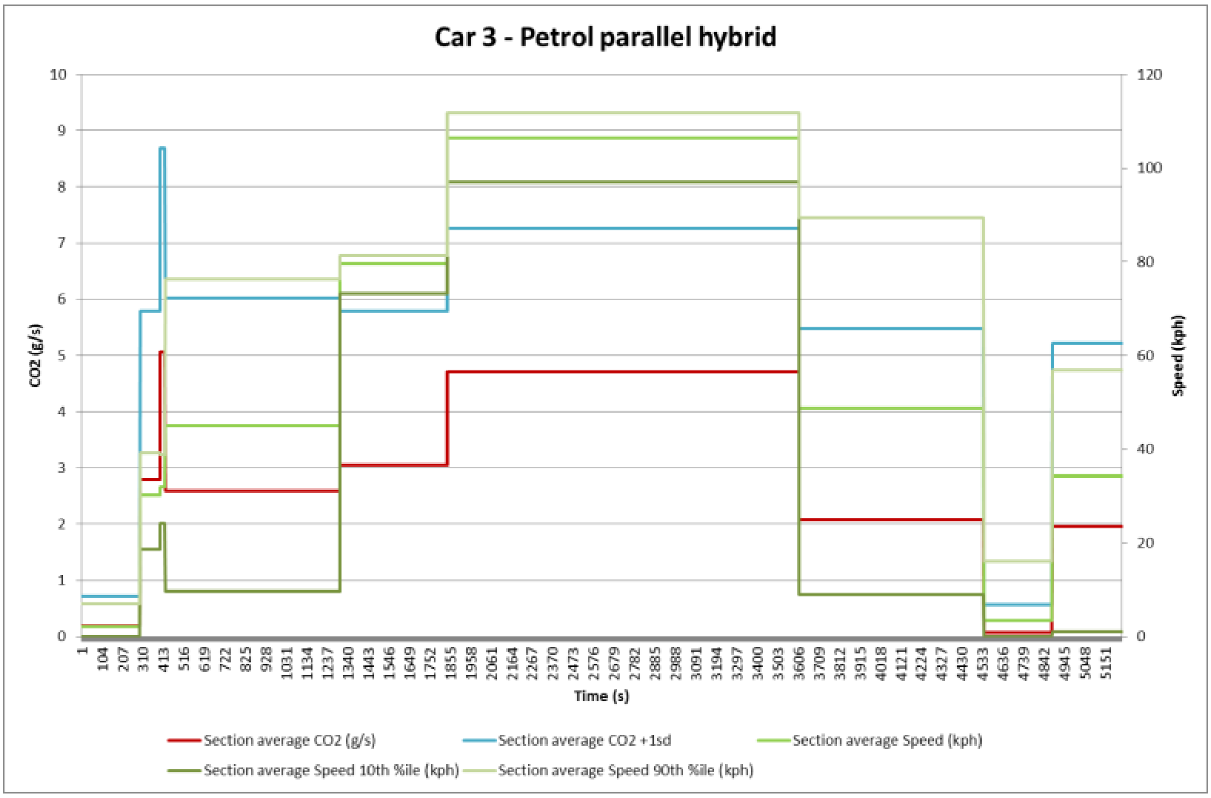


Figure C.14: Car 3 $CO_2$ g/s with time

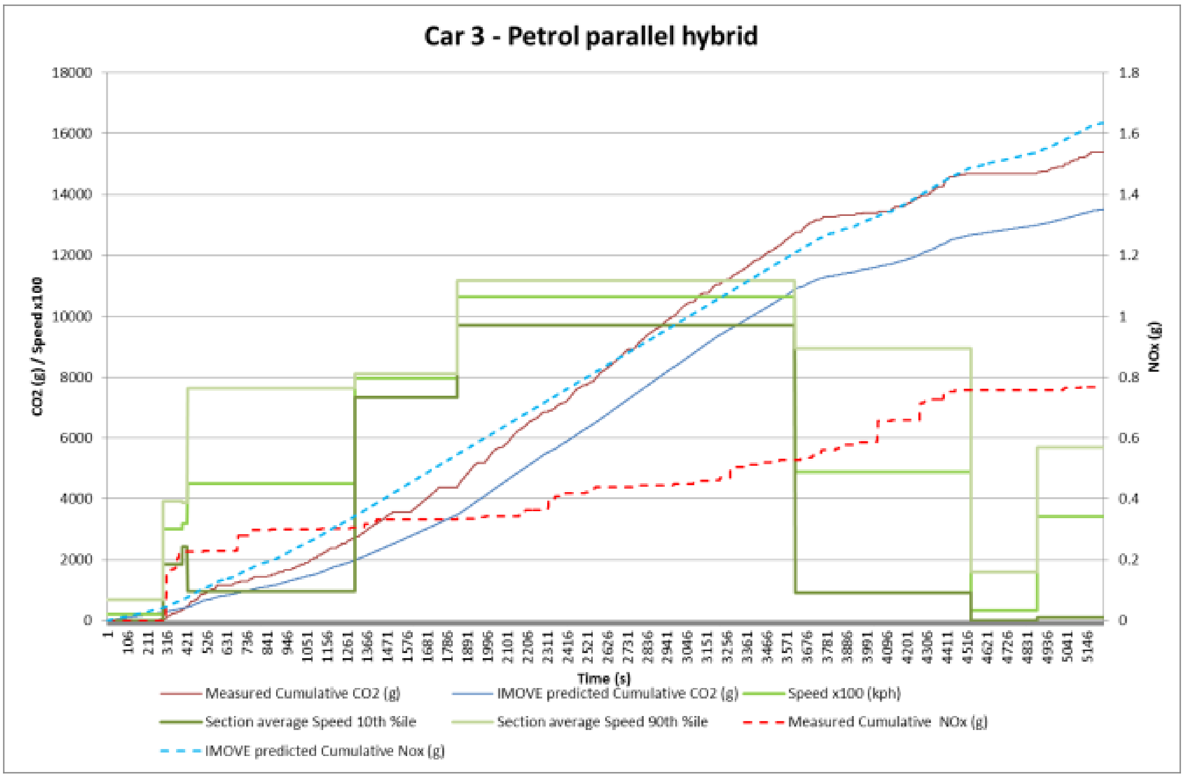


**Figure C.15: Car 3 cumulative $NO_x$ and $CO_2$ emissions with time, with equivalent predictions by iMOVE using COPERT 5.**

## Car 4 – Diesel parallel "through-the-road" hybrid

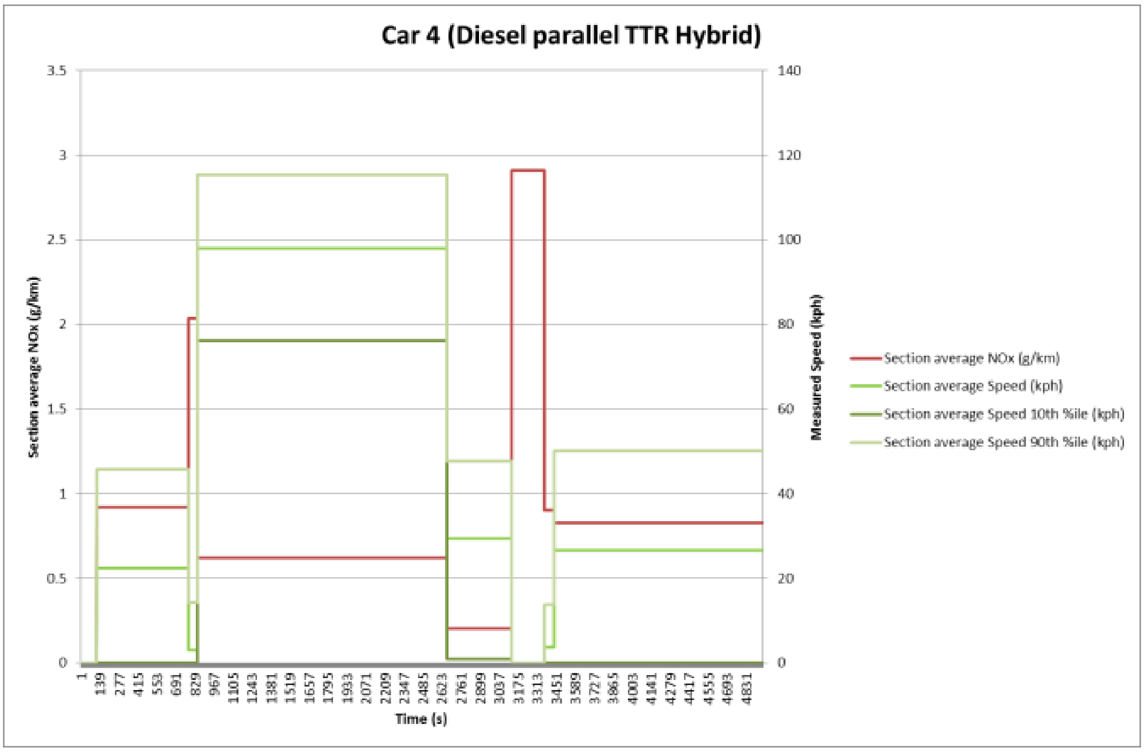


Figure C.16: Car 4 $NO_x$ g/km with time

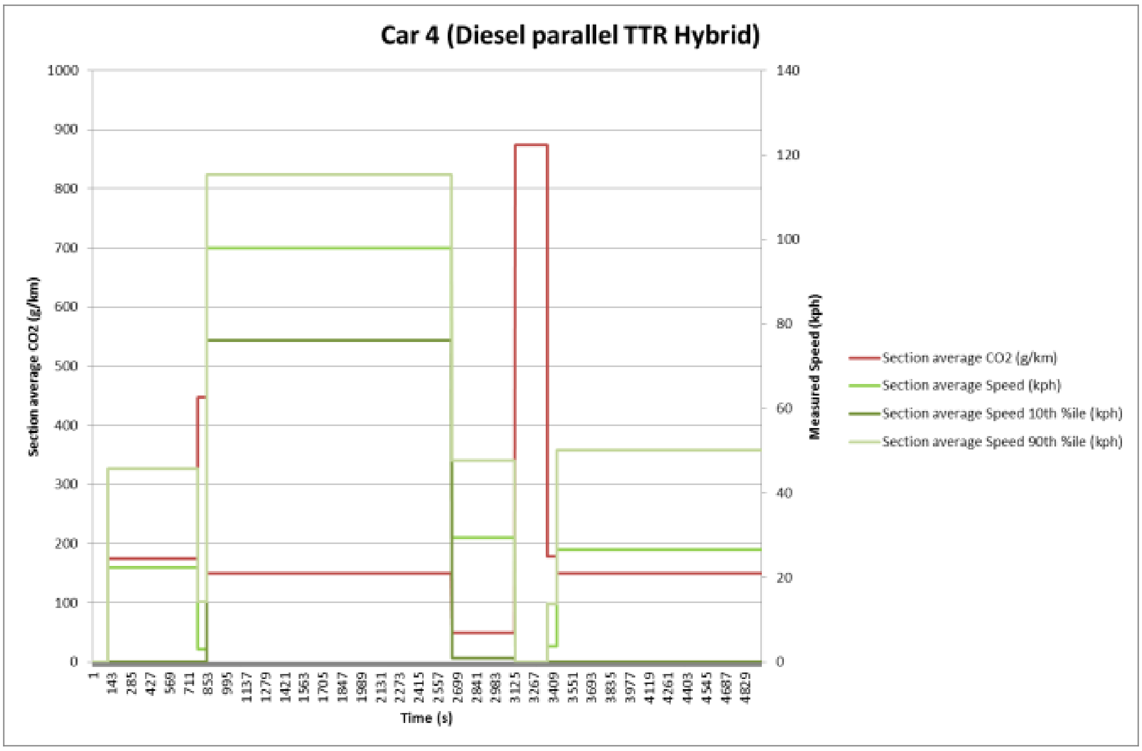


Figure C.17: Car 4 $CO_2$ g/km with time

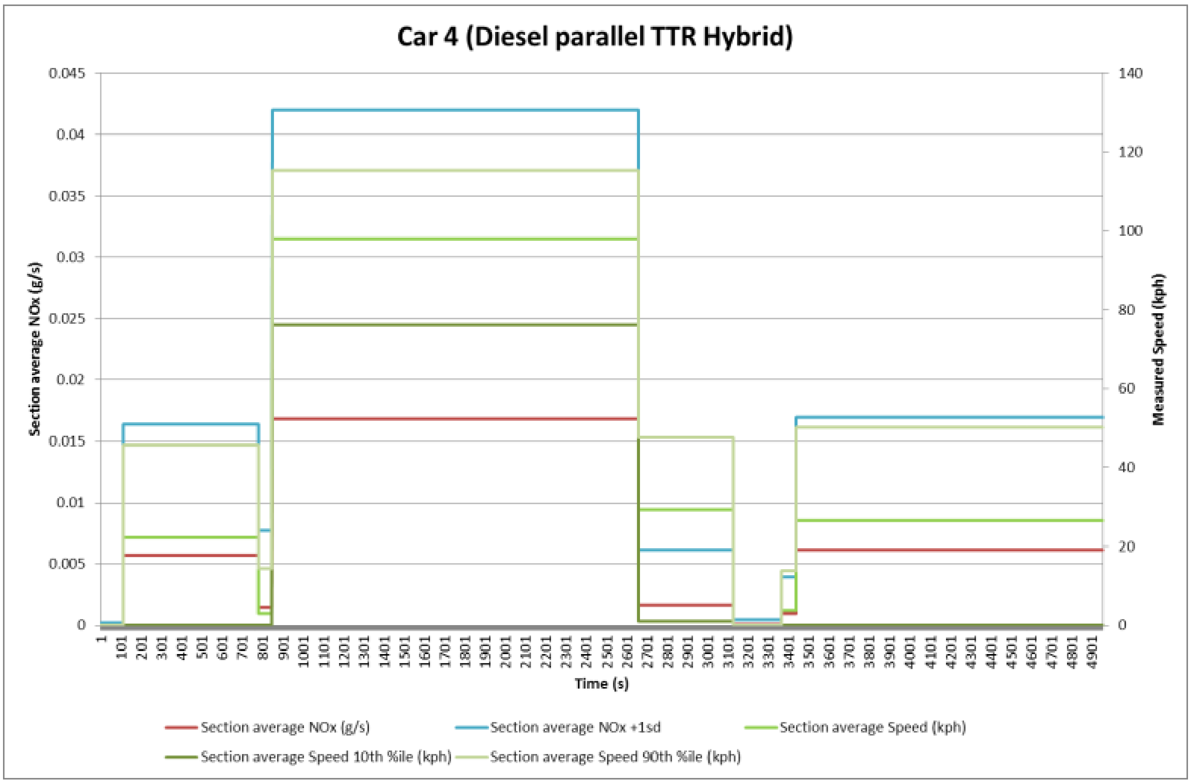


Figure C.18: Car 4 $NO_x$ g/s with time

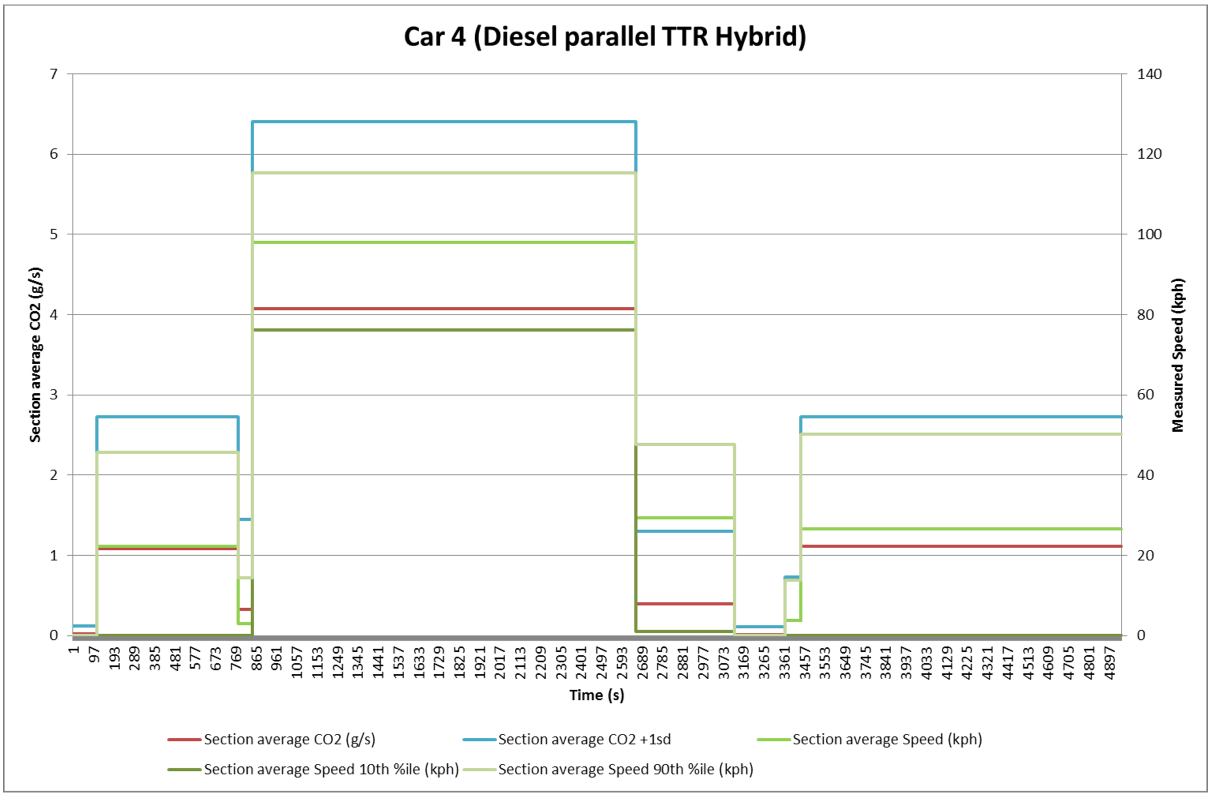


Figure C.19: Car 4 $CO_2$ g/s with time

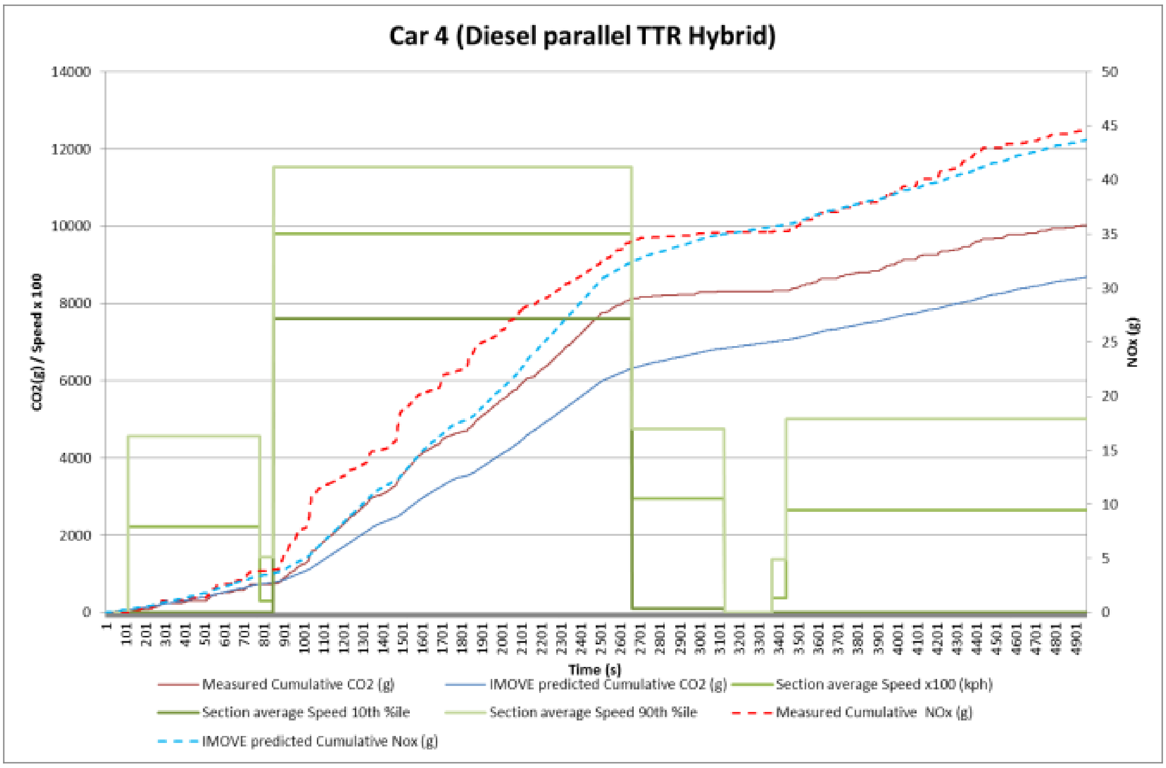


**Figure C.20: Car 4 cumulative $NO_x$ and $CO_2$ emissions with time, with equivalent predictions by iMOVE using COPERT 5.**

## Car 5 – Diesel parallel “through-the-road” hybrid

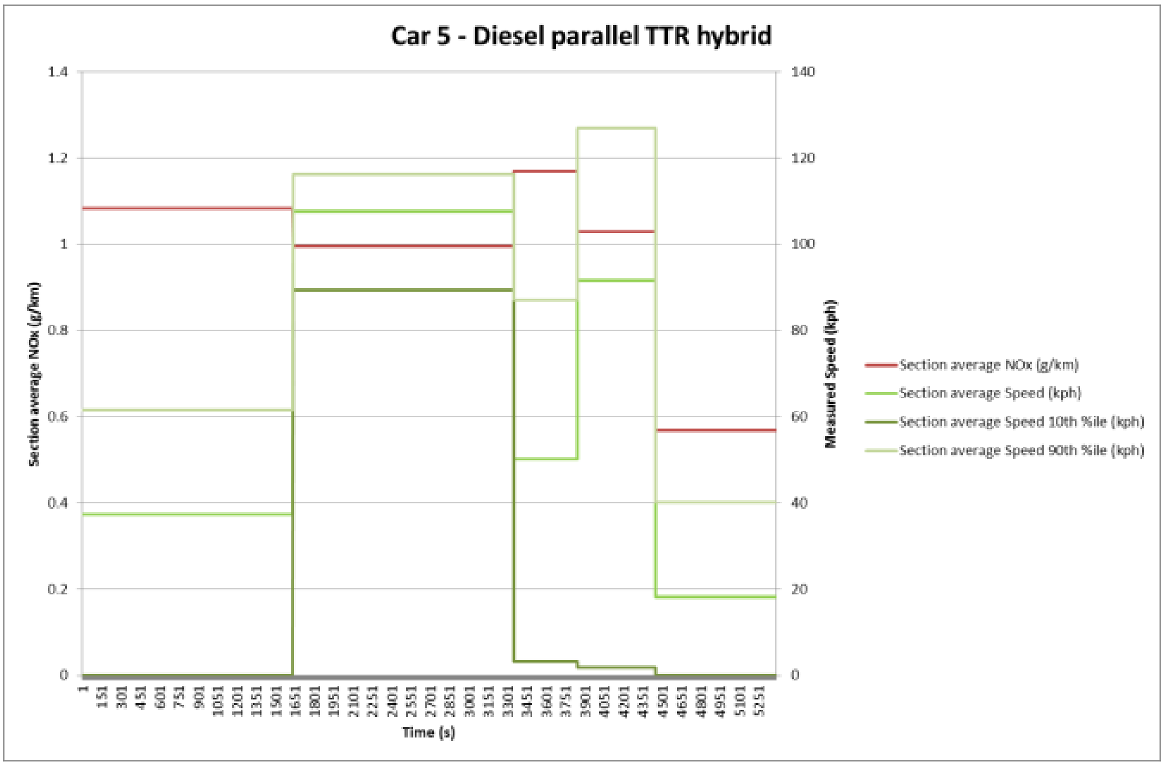


Figure C.21: Car 5 $NO_x$ g/km with time

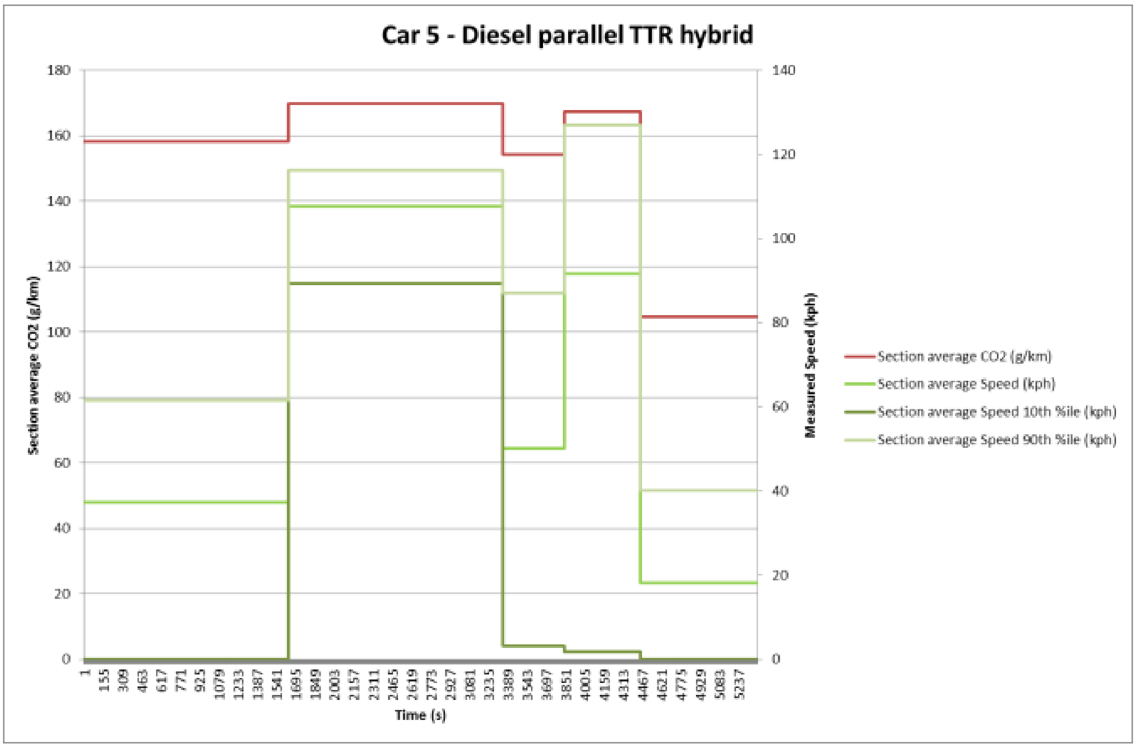


Figure C.22: Car 5 $CO_2$ g/km with time

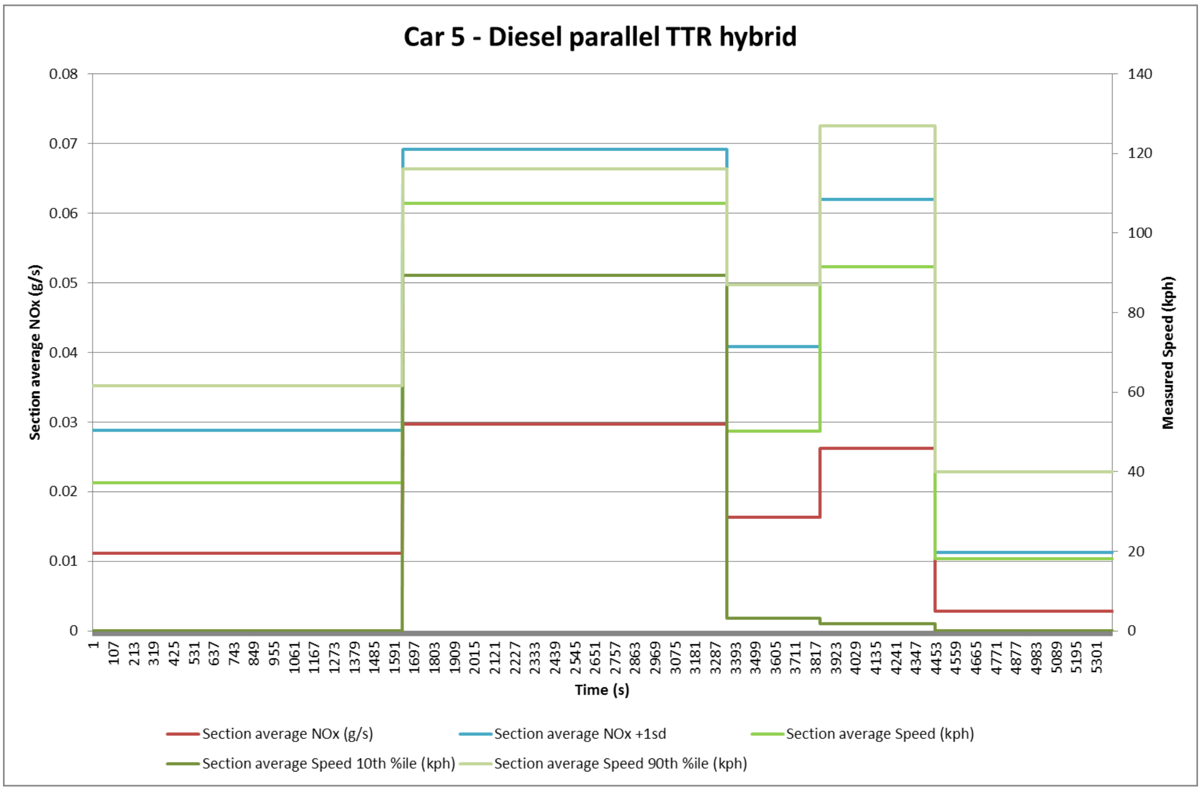


Figure C.23: Car 5 NO$_x$ g/s with time

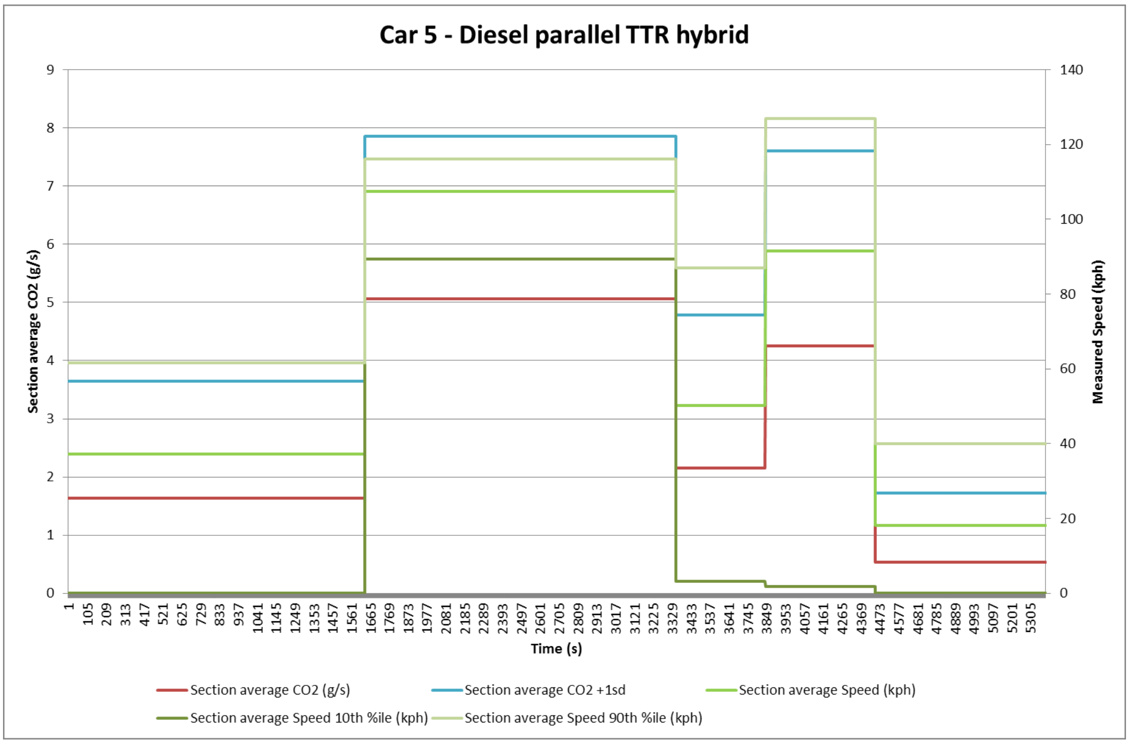


Figure C.24: Car 5 CO$_2$ g/s with time

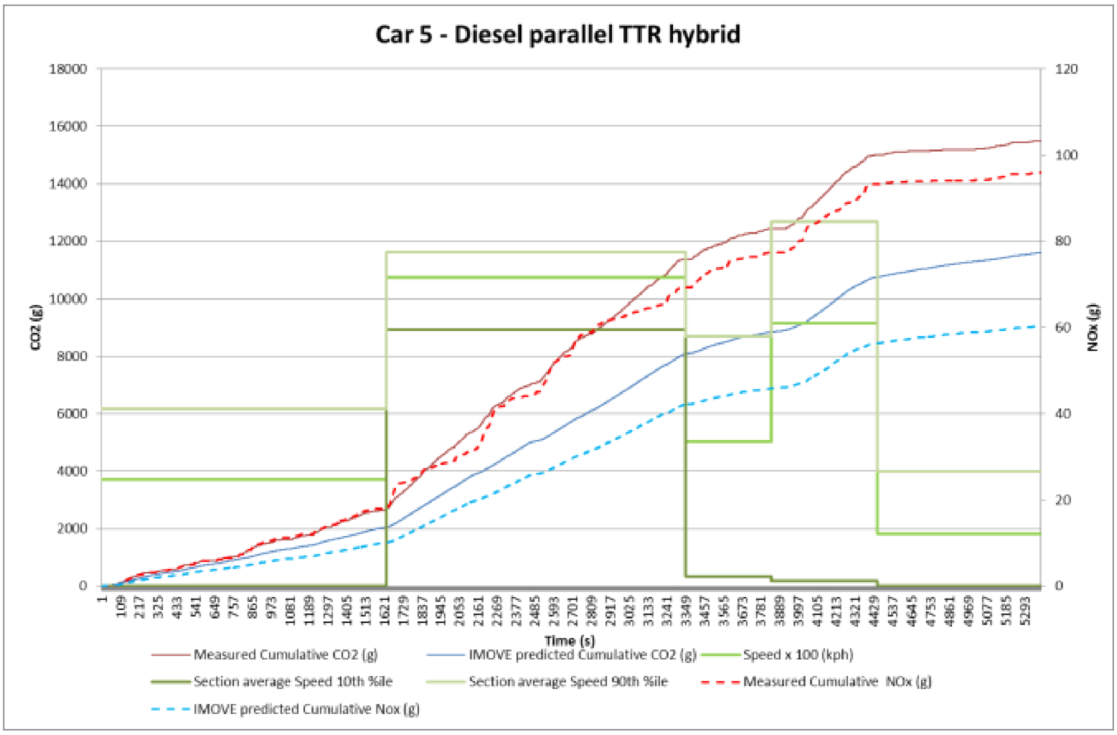


Figure C.25: Car 5 cumulative $NO_x$ and $CO_2$ emissions with time, with equivalent predictions by iMOVE using COPERT 5.

# Car 6 – Diesel plug-in hybrid

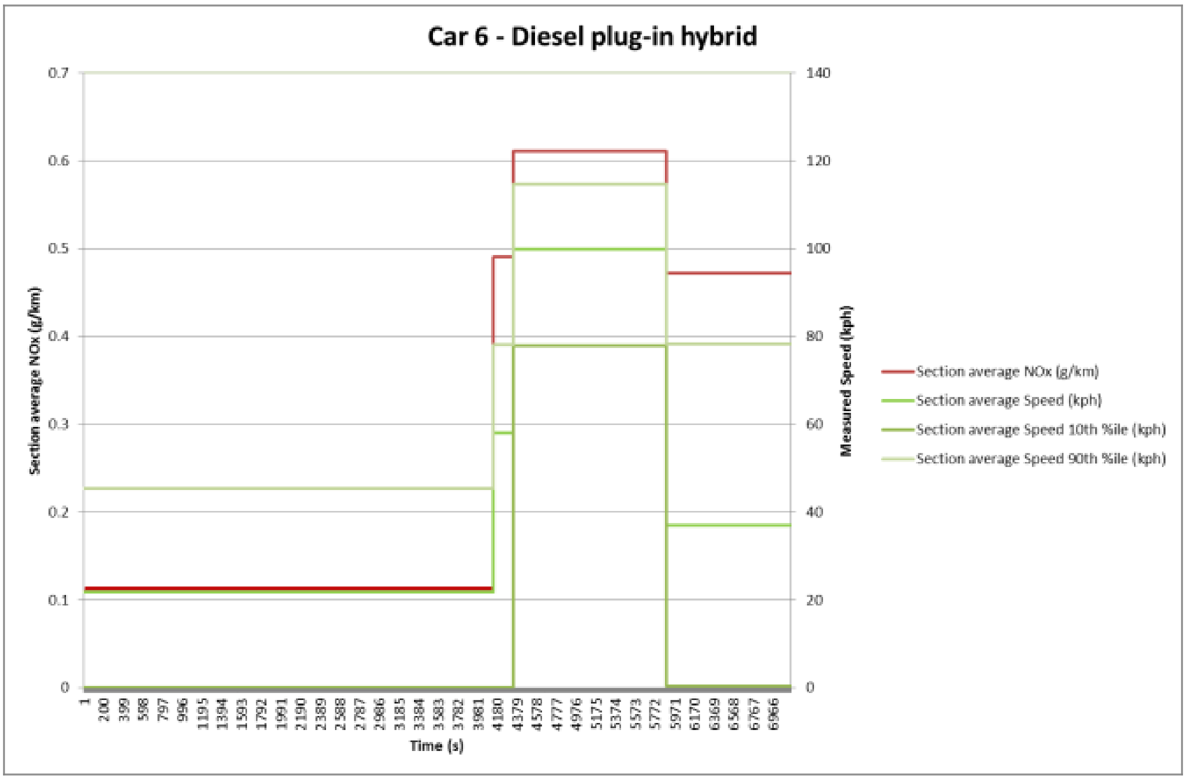


**Figure C.26: Car 6 $NO_x$ g/km with time**

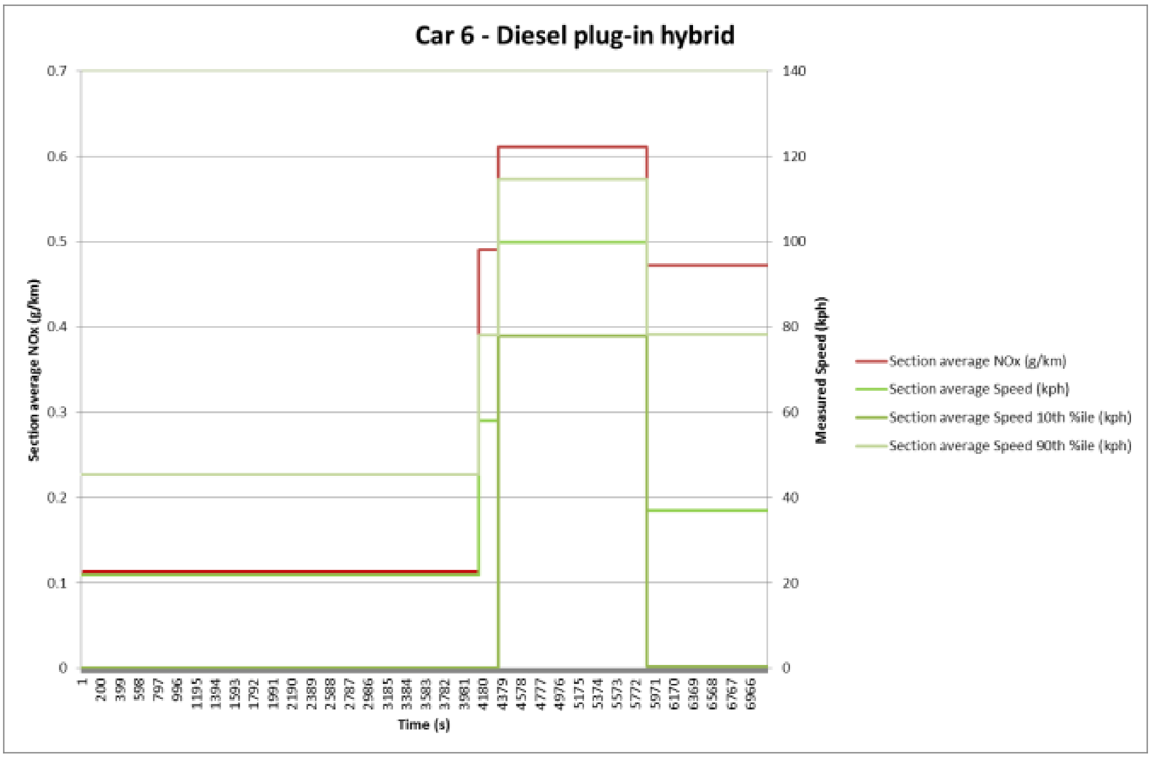


**Figure C.27: Car 6 $CO_2$ g/km with time**

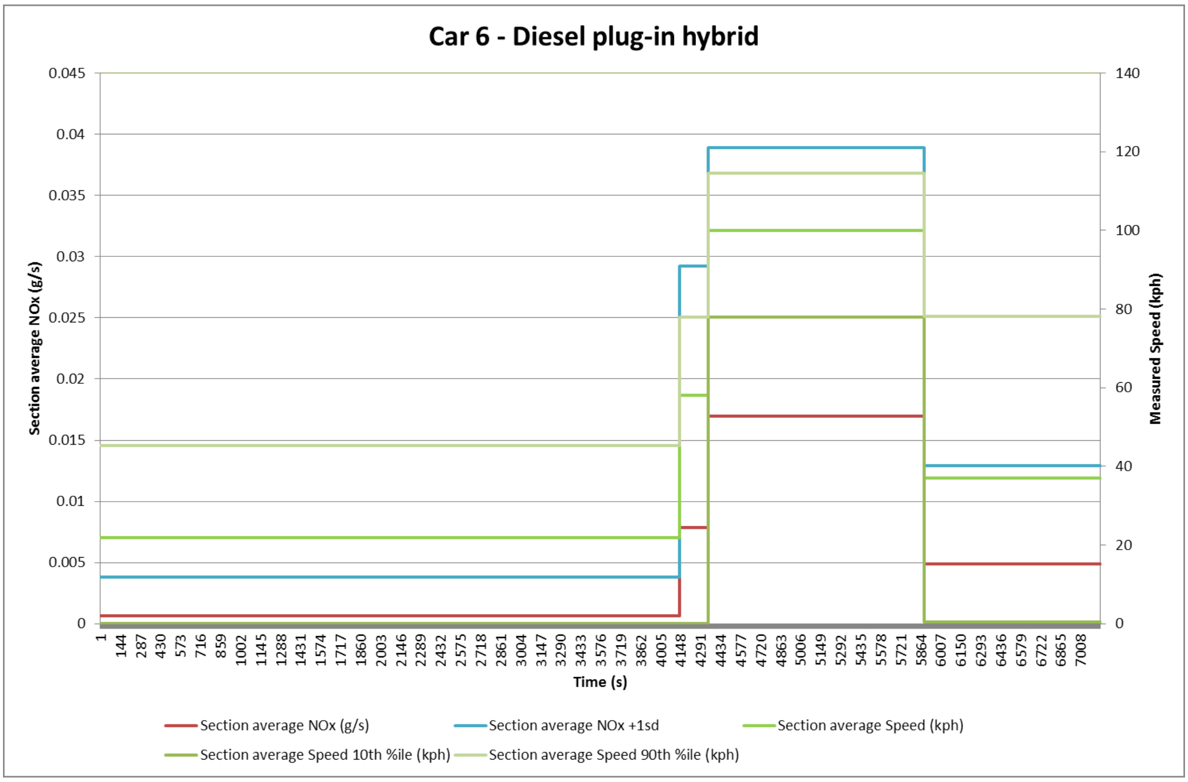


Figure C.28: Car 6 $NO_x$ g/s with time

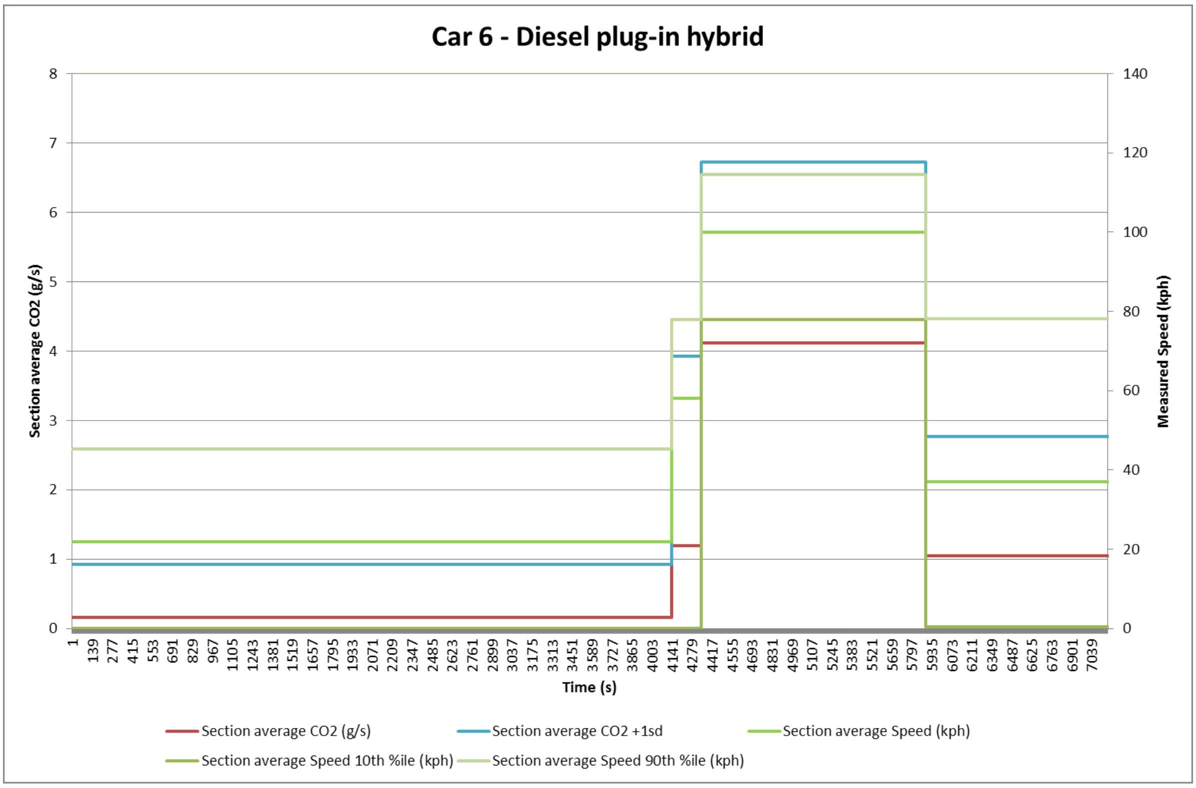


Figure C.29: Car 6 $CO_2$ g/s with time

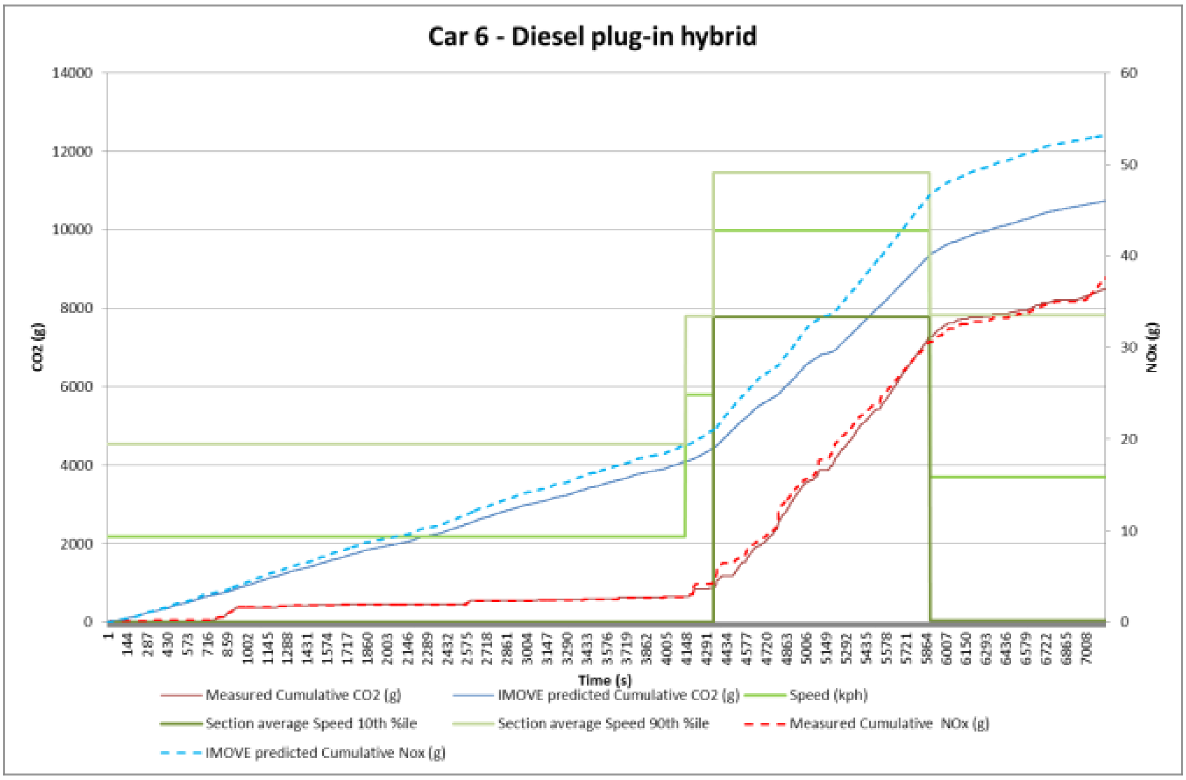


**Figure C.30: Car 6 cumulative $NO_x$ and $CO_2$ emissions with time, with equivalent predictions by iMOVE using COPERT 5.**

## Car 7 – Diesel internal combustion

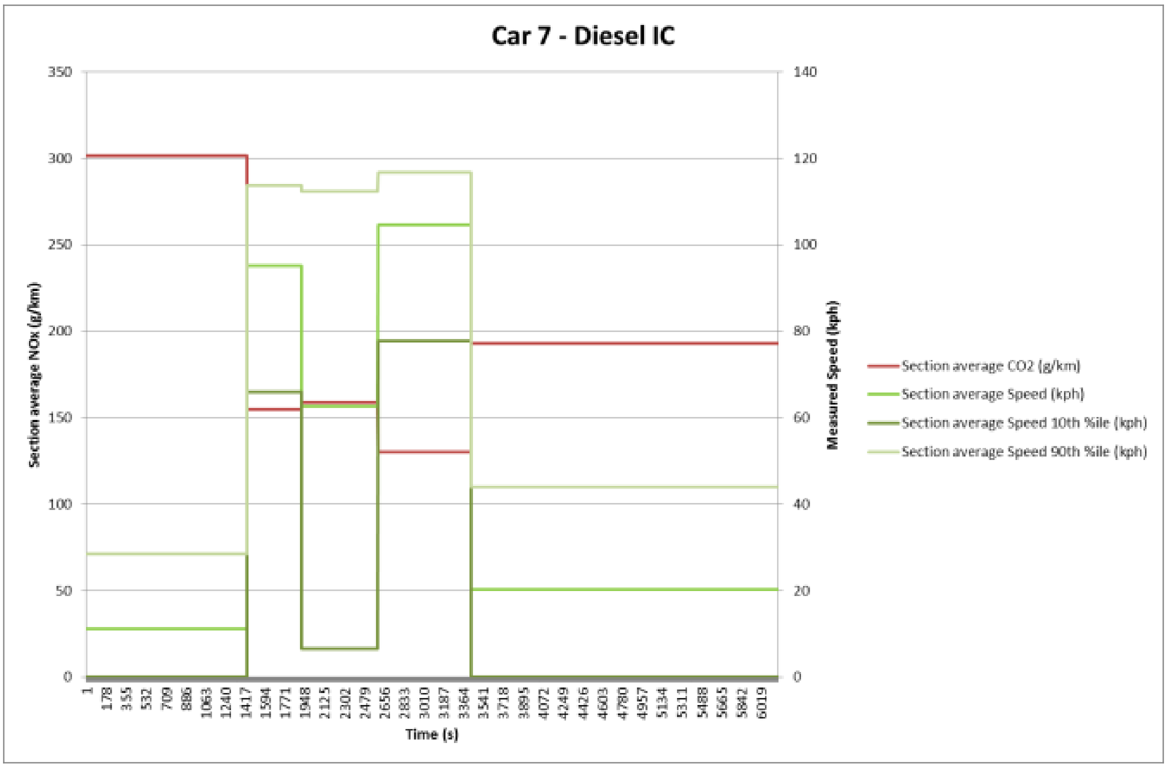


Figure C.31: Car 7 $NO_x$ g/km with time

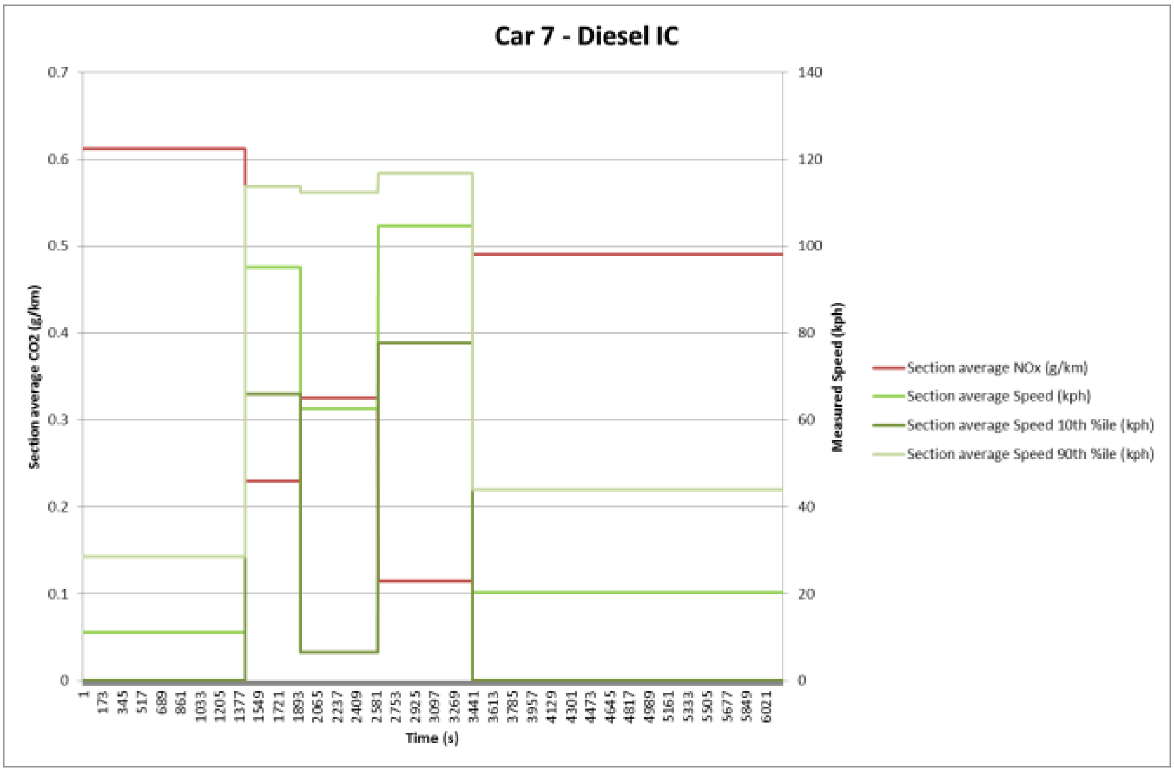


Figure C.32: Car 7 $CO_2$ g/km with time

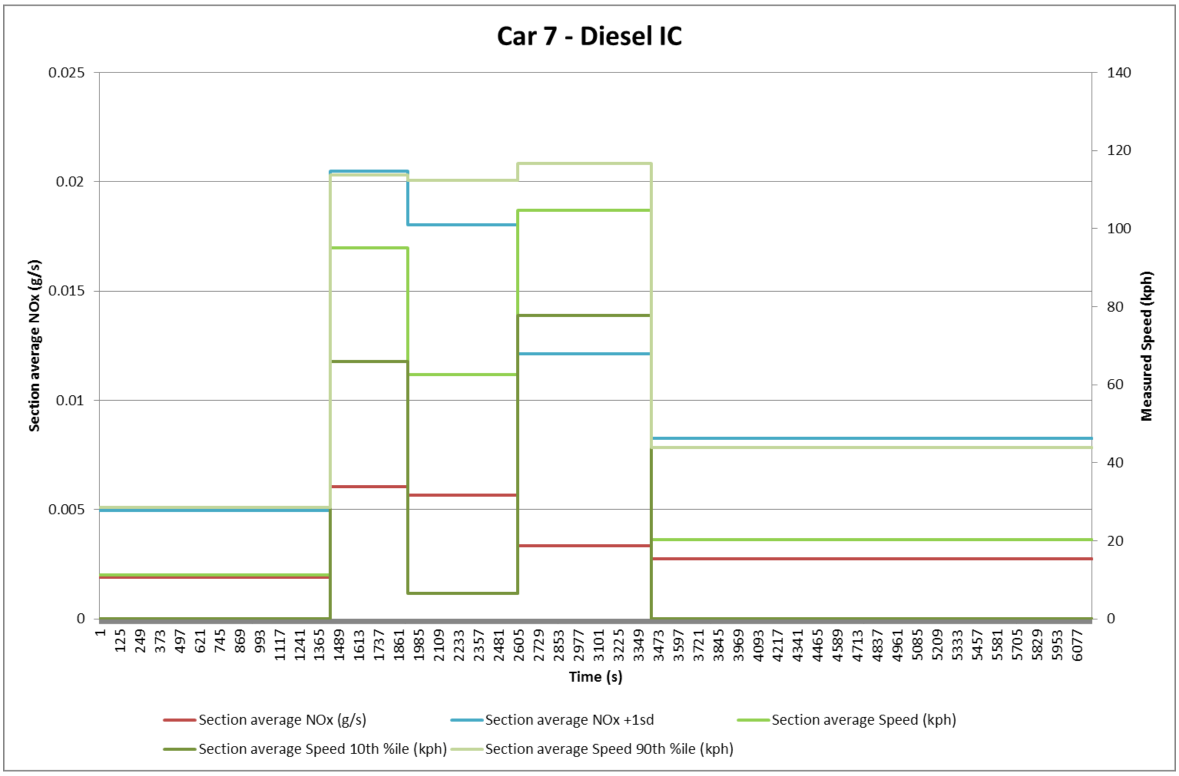


**Figure C.33: Car 7 NO$_x$ g/s with time**

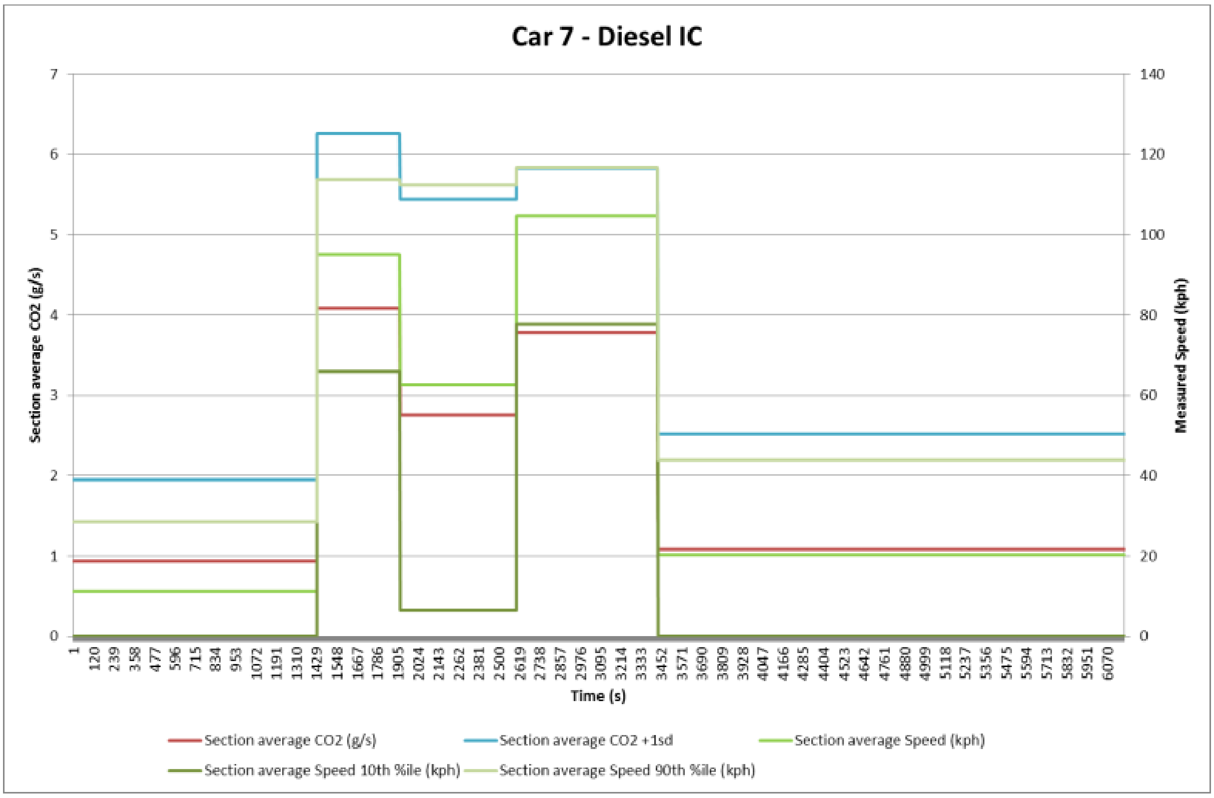


**Figure C.34: Car 7 CO$_2$ g/s with time**

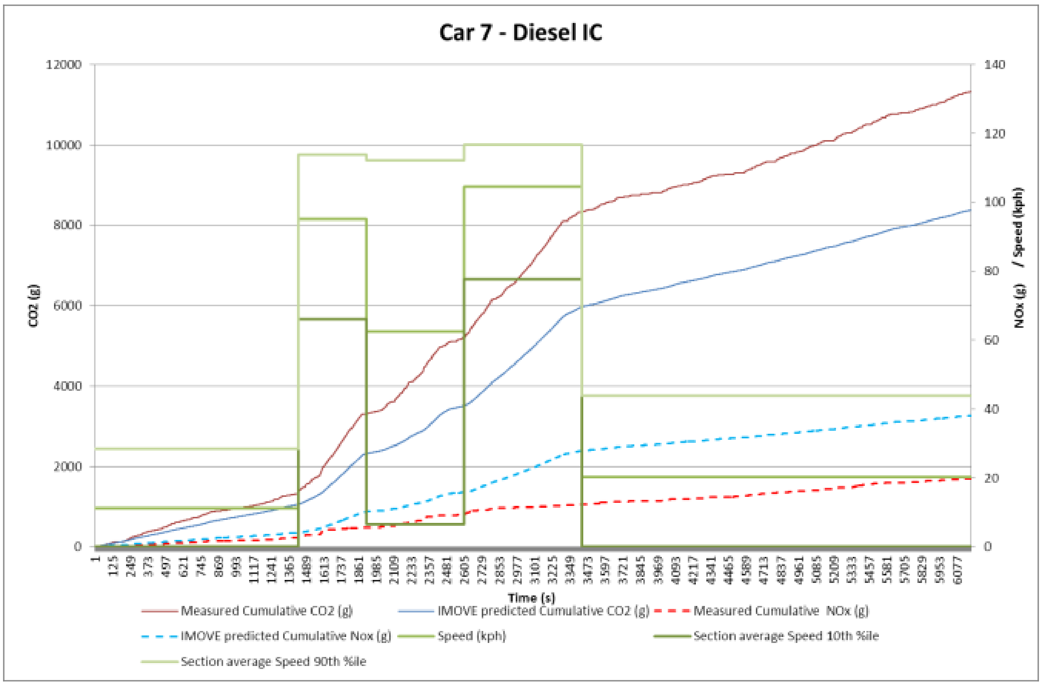


**Figure C.35: Car 7 cumulative $NO_x$ and $CO_2$ emissions with time, with equivalent predictions by iMOVE using COPERT 5.**

## Car 8 - Diesel internal combustion

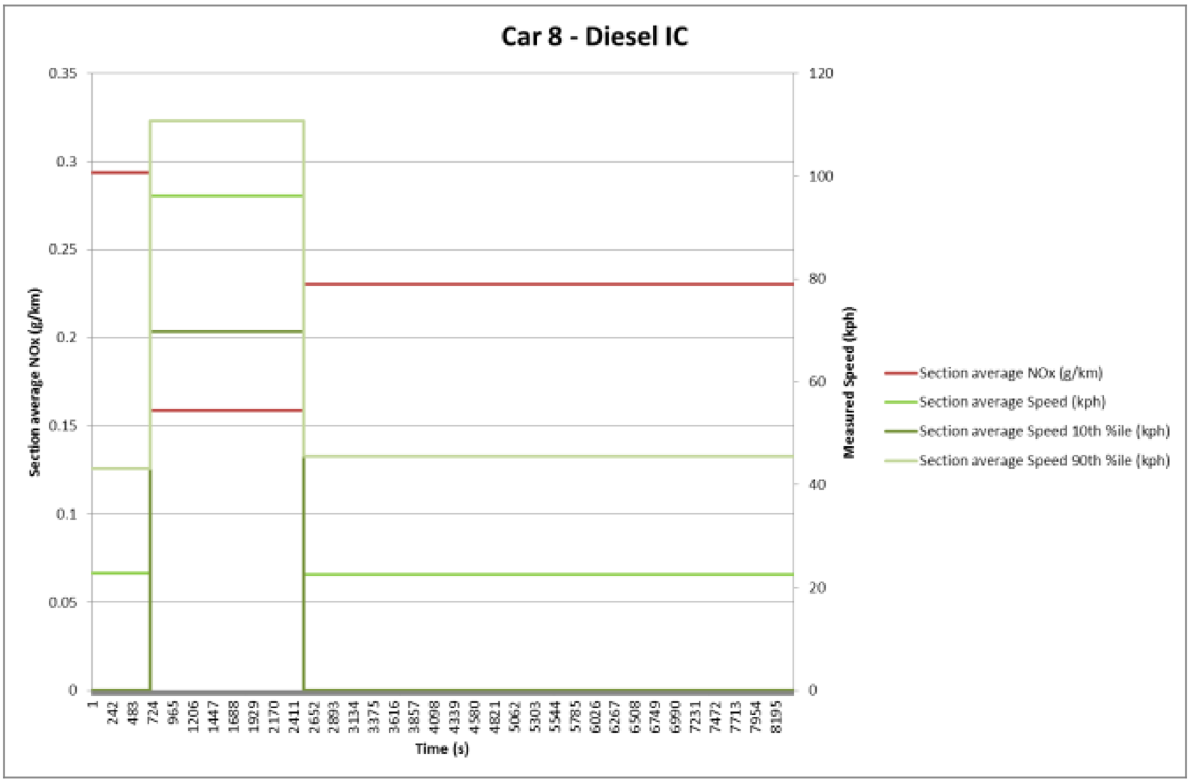


Figure C.36: Car 8 $NO_x$ g/km with time

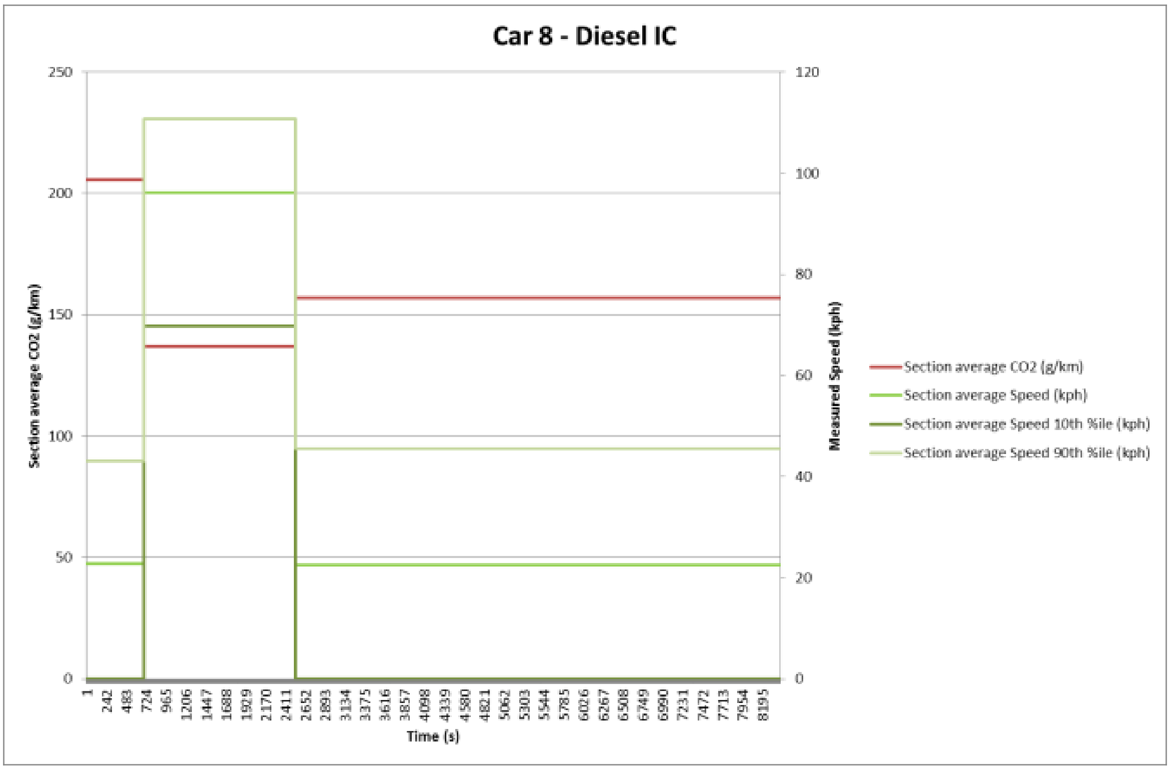


Figure C.37: Car 8 $CO_2$ g/km with time

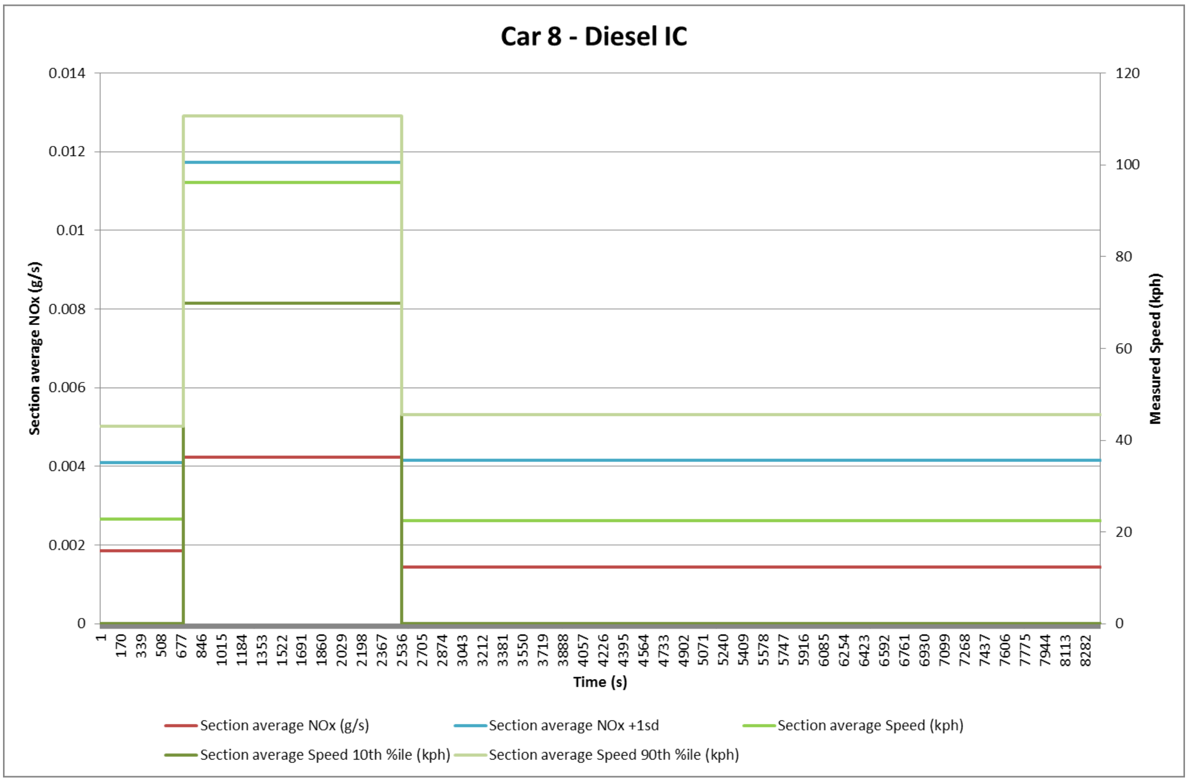


Figure C.38: Car 8 $NO_x$ g/s with time

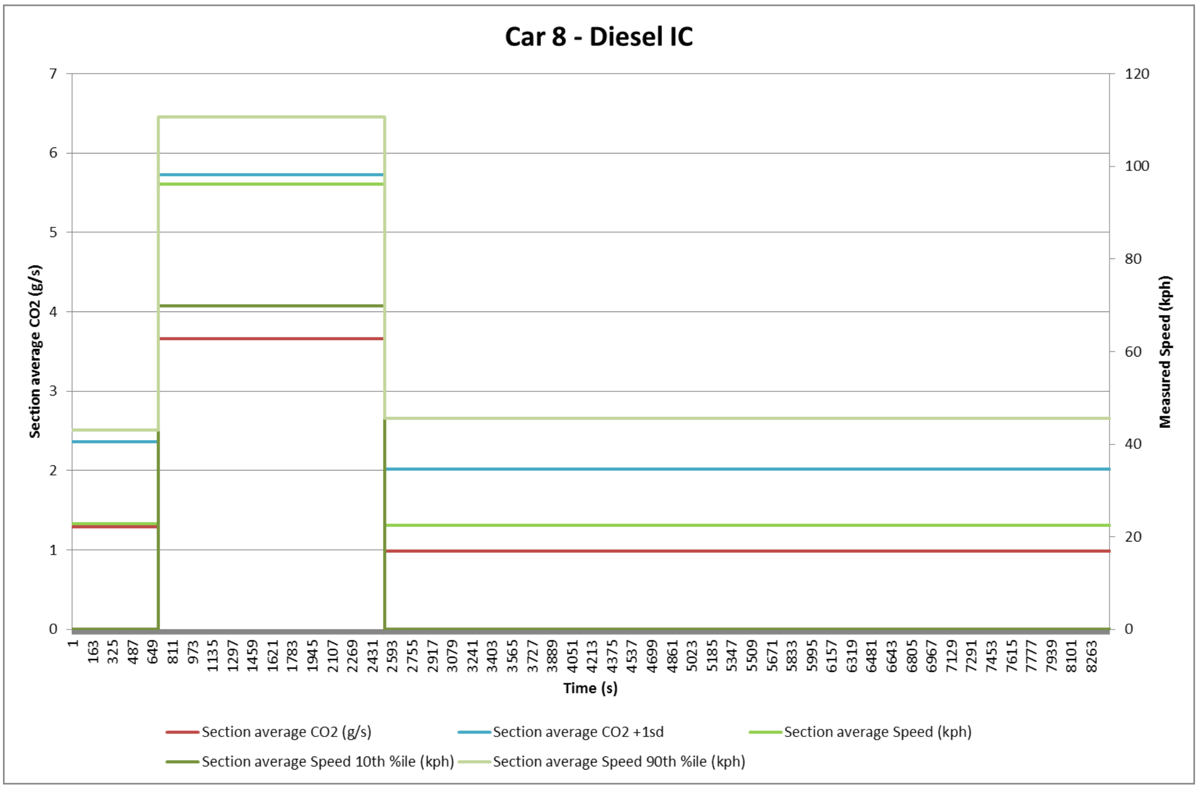


Figure C.39: Car 8 $CO_2$ g/s with time

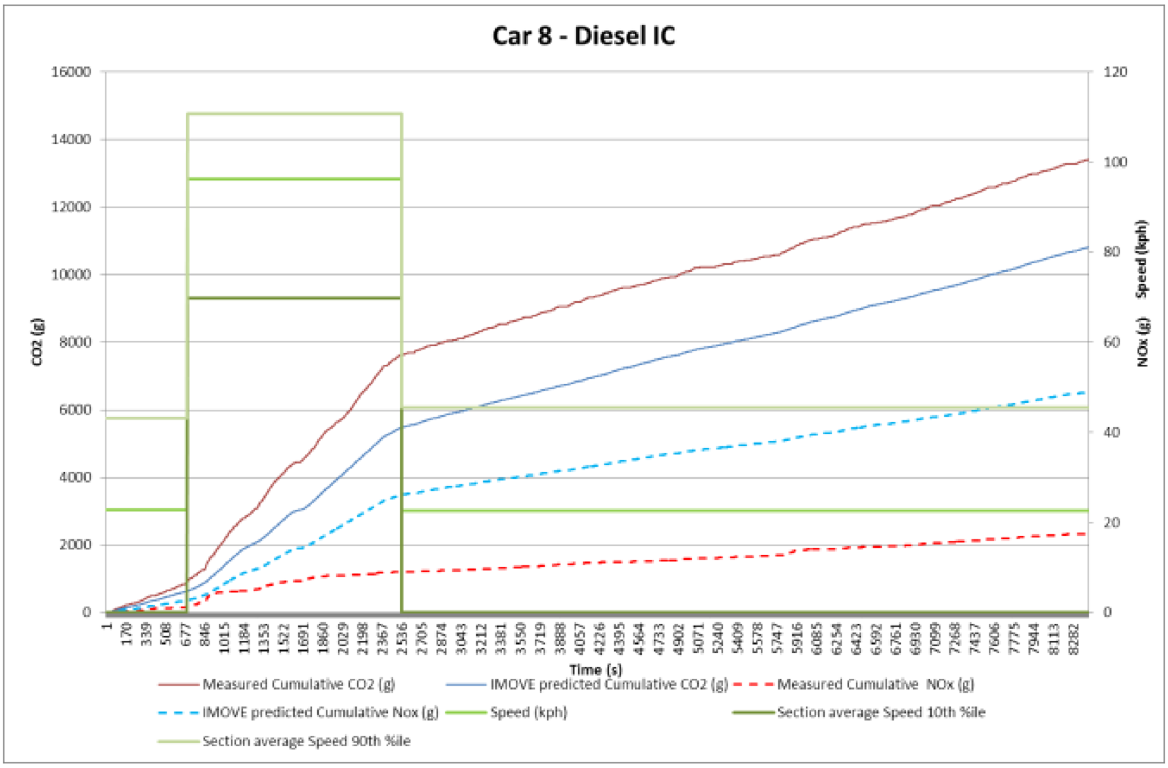


**Figure C.40: Car 7 cumulative NO$_x$ and CO$_2$ emissions with time, with equivalent predictions by iMOVE using COPERT 5.**

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