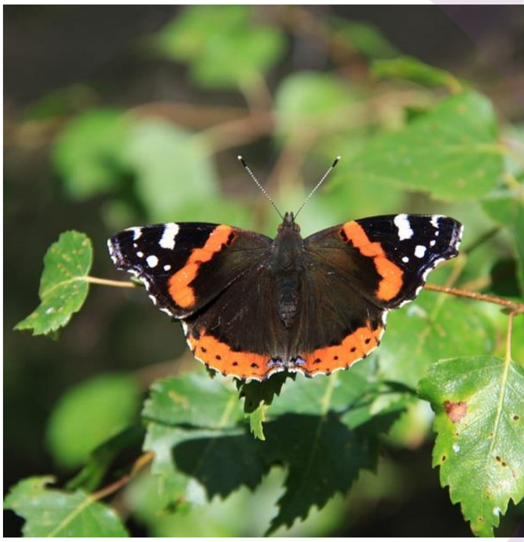
Study to identify potential measures to reduce future $PM_{2.5}$ concentrations to inform $PM_{2.5}$ Target Development

Report



Wood Group UK Limited – February 2022

Report for

Air Quality & Industrial Emissions (AQIE)
Department for Environment, Food and Rural Affairs (Defra)

Main contributors

Ben Warren
Matt Osund-Ireland
Christelle Escoffier
Martin Peirce
Ellenore Calas
Ian Keyte
Ben Croad

Issued by

....
Ian Keyte

Approved by

....
Ben Warren

Wood Group UK Limited

3rd Floor
11 Westferry Circus
Canary Wharf
London E14 4HD
United Kingdom

Doc Ref. 805608-WOOD-ZZ-XX-RP-OP-00014_S4_P01.01

H:\Projects\40575 PPAQ Defra MPMD 2018-2020\D Design\Spin-offs\PM2.5 Study\Deliver\Deliverables\Report

Copyright and non-disclosure notice

Third party disclaimer

Management systems

This document has been produced by Wood Group UK Limited in full compliance with our management systems, which have been certified to ISO 9001, ISO 14001 and ISO 45001 by Lloyd's Register.

Document revisions

No.	Details	Date
1	Draft v1	18/02/2021
2	Draft v2	11/03/2021
3	Draft v3 805608-WOOD-ZZ-XX-RP-OP-00002_S3_P01.01	27/04/2021
4	Draft v3 805608-WOOD-ZZ-XX-RP-OP-00002_S3_P02	29/10/2021
5	Draft v4 805608-WOOD-ZZ-XX-RP-OP-00013_S2_P01.01	28/02/2022
6	Final report	08/03/2022

Executive summary

Wood Group UK Ltd (Wood) has been commissioned by the Department for Environment, Food and Rural Affairs (Defra) to undertake this project to gather information on the potential for reducing emissions of fine particulate matter ($PM_{2.5}$) and its precursors in each sector. This information will be used, along with other information and analysis to inform the development of new $PM_{2.5}$ targets. **The measures and scenarios contained in this report do not in any way constitute government current or planned policy and were developed only to inform the target development process. Any views in the report reflect the opinions of the stakeholders and interpretation of the authors, they should not be taken to be the views of Defra or other government departments.**

As part of the Environment Act 2021, the government is required to set legally binding targets to improve air quality in England. These will focus on reducing concentrations of $PM_{2.5}$ as this is the pollutant of most harm to human health. Two $PM_{2.5}$ targets were proposed in the targets paper published in August 2020[1]; a maximum annual mean concentration in ambient air and a population exposure reduction in comparison to a baseline year.

This project involved identification of emerging technologies and behaviours that can be used to reduce $PM_{2.5}$ concentrations in future. A literature review and stakeholder engagement programme has been undertaken to collect data and information on the likely impact of technologies and behaviours on emissions of $PM_{2.5}$ and its precursors (e.g., nitrogen oxides (NO_X) and ammonia (NH_3)) and the likely uptake rates and implementation costs.

The stakeholder engagement programme took the form of an extensive series of interviews with experts followed by a series of workshops in January 2021, with each workshop covering a different work package. The work packages covered domestic/commercial combustion, urban mobility and traffic volume, road transport technology, shipping, rail, aviation, agriculture, industry and construction.

Following the programme of stakeholder engagement, a list of plausible measures to reduce future $PM_{2.5}$ concentrations was defined. For each measure, uptake rates and timescales have been varied to apply within each of three emission scenarios:

- Medium intervention – In this scenario measures based on proven technology and modest behaviour change are included, and the implementation dates and uptake rates are towards the lower end of estimates.
- High intervention – This scenario includes new technologies that are perceived as likely to be successful and a high degree of behaviour change. Implementation dates and uptake rates are toward the middle of estimates.
- Speculative – In this scenario the maximum feasible action is taken, all emerging technology is assumed to be successful and there is significant behaviour change. Optimistic (but still possible) implementation and uptake rates are used. This scenario represents the maximum technically feasible reduction in $PM_{2.5}$ concentrations.

The packages of measures under each scenario will be used to produce projections of emissions which will form the basis of air quality modelling inputs, The air quality modelling will be used to estimate future $PM_{2.5}$ concentrations, providing an understanding of which targets are achievable under different circumstances.

This report should not be taken as a record of exactly what was modelled. It describes the main evidence base that informed the scenarios; however some adjustments were required to enable individual

[1] 19 August 2020: Environment Bill - environmental targets - GOV.UK (www.gov.uk)

measures/sectors to be modelled and a small number of measures were updated following additional feedback.

The literature review and stakeholder engagement for this project has identified several areas where further research would be beneficial in order to better quantify $PM_{2.5}$ emissions and therefore better prioritise measures to reduce concentrations. Particular sources highlighted as requiring further research are as follows:

- Emissions from domestic, commercial and industrial wood combustion.
- Emissions from domestic and commercial cooking.

Non-Exhaust Emissions, including brake, tyre wear (road and aviation), road abrasion, the effective of heavier electric vehicles, and rail track, overhead line and brake wear. This is of particular importance as Non-Exhaust Emissions become the dominant source of emissions from road traffic.

Contents

1. Introduction

1.1 Overview

Clean air is recognised as a vital element in the health and wellbeing of people and the environments in which they live, as well as ensuring and improving economic prosperity.

As part of a wider range of measures to deliver cleaner air, the UK has agreed to international action, under the Gothenburg Protocol and National Emission Ceilings Directive (NECD; 2016/2284), to reduce national emissions of five air pollutants: ammonia (NH_3); nitrogen oxides (NO_X); non-methane volatile organic compounds (NMVOC); fine particulate matter ($PM_{2.5}$); and sulphur dioxide (SO_2). Following EU exit the NECD is implemented in UK law through the National Emissions Ceilings Regulations 2018.

Since 2013, the Multi-Pollutant Measures Database (MPMD) and associated tools have been used to develop policies to reduce emissions of these pollutants. These aid identification and assessment of technical options for reducing emissions, and prioritisation of cost-effective emissions control strategies to inform policy making.

As part of work required in relation to the Environment Act 2021, the government is required to set legally binding targets for air quality for England. As described in the targets policy paper[2] published by Defra in August 2020 these will focus on reducing concentrations of $PM_{2.5}$, as this is the pollutant of most harm to human health. Two targets are proposed; a maximum annual mean concentration in ambient air and a population exposure reduction in comparison to a baseline year.

The Environment Act 2021 requires that the Secretary of State is satisfied that the targets can be met. The range of targets which are achievable will be established through modelling of future $PM_{2.5}$ concentrations under different scenarios. These will consist of packages of abatement measures which vary from some improvements to business as usual to more speculative technology and significant behaviour change. The modelling will produce a range of target levels which are achievable, each associated with a different cost of implementation and health benefit.

This project is required to gather information on the potential for reducing emissions of $PM_{2.5}$ and its precursors in each sector. This involves identification of emerging technologies and behaviours, collecting data and expert opinion on uptake rates, implementation costs, impact on emissions on $PM_{2.5}$ and precursors (e.g. NO_X and NH_3), and gaining an understanding of what level of ambition uptake rates and emissions reductions represent. The information collected will be used in the MPMD and Scenario Modelling Tool (SMT) to provide projections of emissions which will then feed into the air quality modelling to estimate future $PM_{2.5}$ concentrations. The costs associated with implementing the measures will feed into the target impact assessment. **The abatement measures described in this report have been identified only for the purposes of developing plausible future scenarios. The measures contained in the scenarios should not in any way be construed as government policy or endorsement of particular measures.**

This study was the main basis for the scenarios modelled, however some adjustments were made by Imperial College London to enable individual measures/sectors to be represented in the modelling, and the details of some measures were updated following this study as a result of additional feedback. Therefore, this report

[2] https://www.gov.uk/government/publications/environment-bill-2020/august-2020-environment-bill-environmental-targets

should not be taken as a complete record of the final scenarios. Please see the Air Quality Target Evidence Report for details of the modelling carried out[3].

1.2 Report Structure

In addition to this Introduction, the report includes three sections:

- Section 2 describes the background of the study, including the total emissions of $PM_{2.5}$ and the sources of $PM_{2.5}$ where people are currently exposed to the highest concentrations.
- Section 3 describes the methodology framework of the study, including details of the approach that has been taken to ensure that the relevant measures have been identified and the relevant stakeholders within each sector have been engaged with to gather their expert opinion.
- Section 4 presents the results of the literature review and stakeholder engagement, representing the current state of knowledge. The results are discussed for each measure within each of the sectors.
- Section 5 summarises the findings and provides recommendations.

Details of the interviews undertaken and reports of each workshop held are included as appendices to this report.

[3] https://uk-air.defra.gov.uk/library/air-quality-targets

2. Background

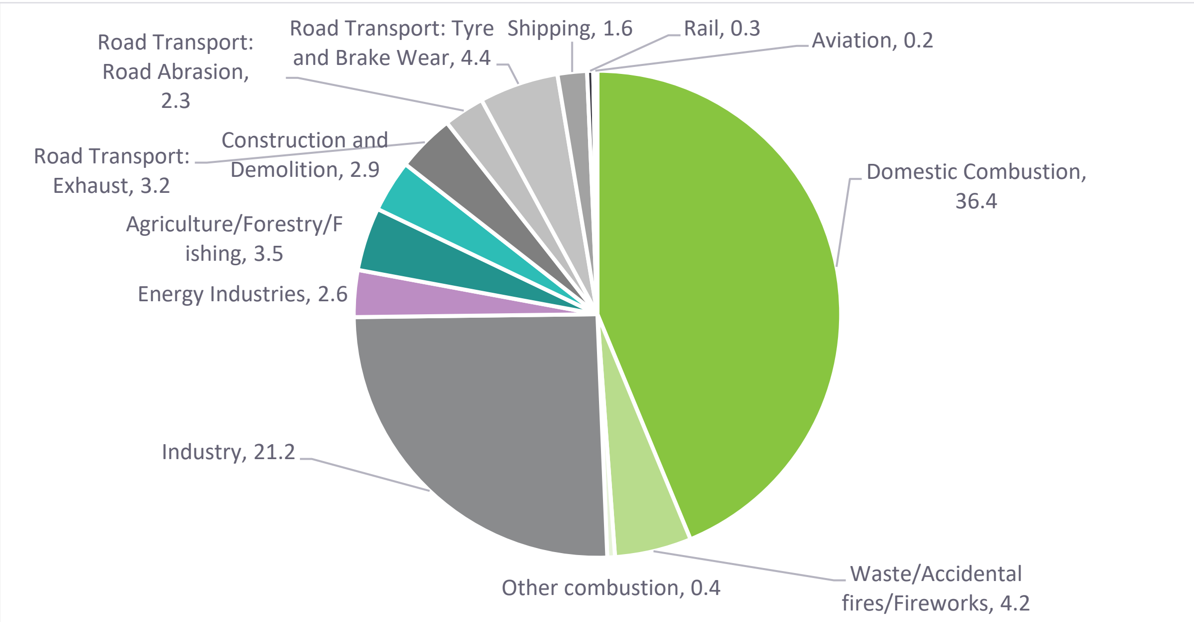
2.1 National Emissions

Particulate matter may be directly emitted into the atmosphere (termed primary particles) or formed by the reaction of atmospheric gases (secondary particles). Emissions of NH_3, NO_X and SO_2 from sources in the UK and Europe contribute to the formation of secondary PM over a large area. Secondary inorganic particulate matter is formed from these precursor gases is largely ammonium nitrate (NH_4NO_3) and ammonium sulphate ($(NH_4)_2SO_4$).

The National Atmospheric Emissions Inventory (NAEI) produces estimates of emissions on an annual basis. The data for England (and the devolved administrations) are available from the NAEI website[4]. The 2018 emission totals for $PM_{2.5}$, NO_X and NH_3 divided by source groups are shown in Figure 2-1, Figure 2-2 and Figure 2-3.

The data for primary $PM_{2.5}$ emissions show that domestic combustion (44%) and industry (29% including energy industries) are the major sources of primary $PM_{2.5}$ emissions in England. Road transport contributes around 12% of total emissions, of which, tyre and brake wear (5%) is the largest source. For NO_X, road transport is the largest source (35%), followed by industry (19%) and energy industries (16%). The dominant source group for NH_3 is agriculture (84%).

Figure 2-1 Primary sources of $PM_{2.5}$ in England for the year 2018 (kilotonnes)[4]

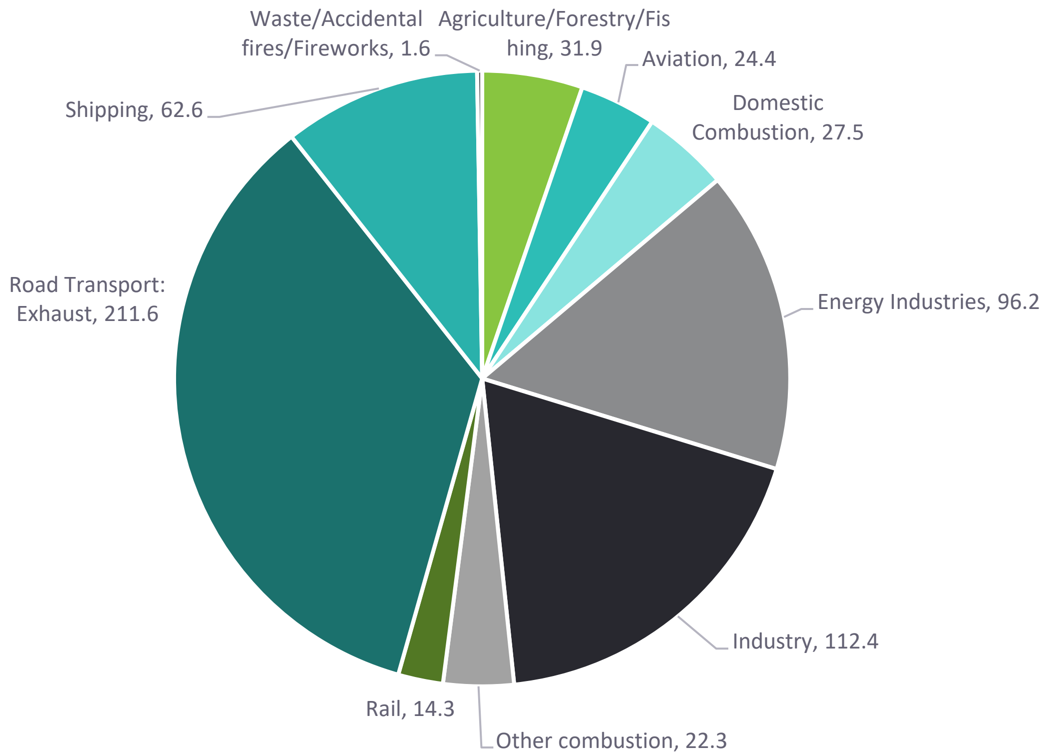


Pie chart showing primary sources of $PM_{2.5}$ in England for the year 2018. The pie chart shows that domestic combustion and industry are the major sources of primary $PM_{2.5}$ emissions in England. Domestic Combustion 36.4 kT, Waste/Accidental fires/Fireworks 4.2 kT, Other combustion 0.4 kT, Industry 21.2 kT, Energy Industries 2.6 kT, Agriculture/Forestry/Fishing 3.5 kT, Construction and Demolition 2.9 kT, Road Transport: Exhaust 3.2

[4] BEIS (2020) Report: Air Quality Pollutant Inventories for England, Scotland, Wales and Northern Ireland: 1990-2018. Online: https://naei.beis.gov.uk/reports/reports?report_id=1010

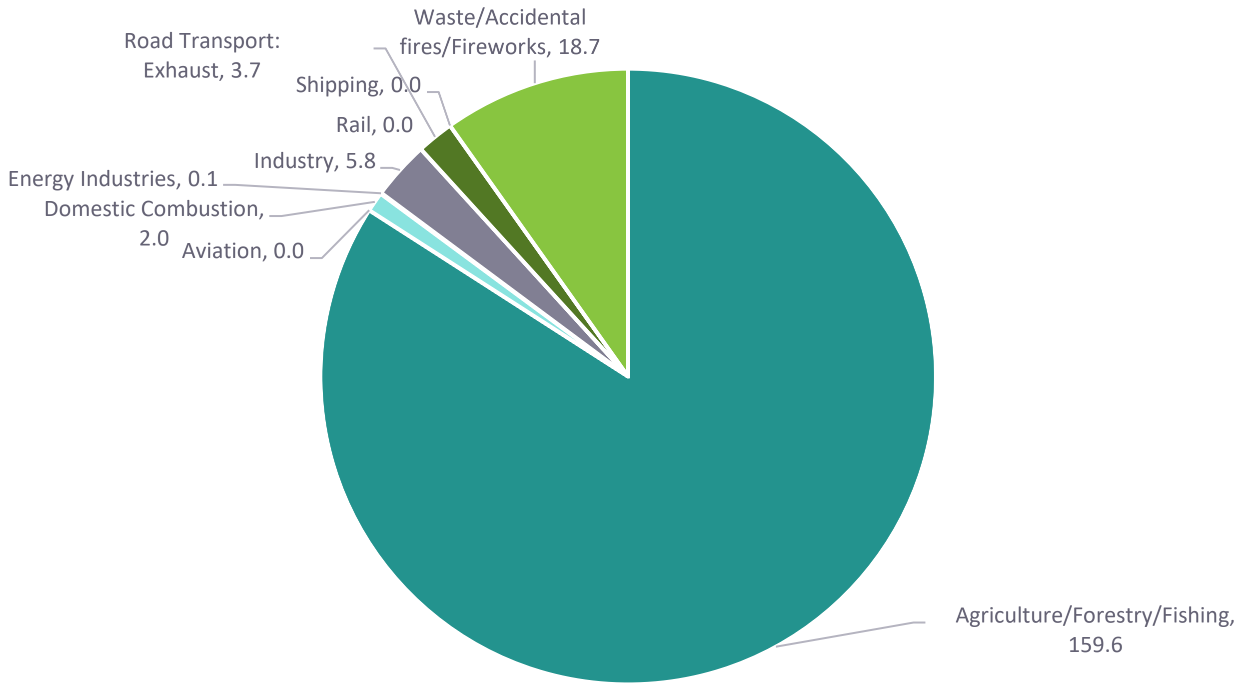
kT, Road Transport: Road Abrasion 2.3 kT, Road Transport: Tyre and Brake Wear 4.4 kT, Shipping 1.6 kT, Rail 0.3 kT, Aviation 0.2 kT.

Figure 2-2 Primary sources of NO_X in England for the year 2018 (kilotonnes) [4]



Pie chart showing primary sources of NO_X in England for the year 2018. The pie chart shows that road transport is the largest source, followed by industry and energy industries. Road Transport: Exhaust 211.5 kT, Industry 112.4 kT, Energy Industries 96.2 kT, Shipping 62.6 kT, Agriculture/Forestry/Fishing 31.9 kT, Domestic Combustion 27.5 kT, Aviation 24.4 kT, Other combustion 22.3 kT, Rail 14.3 kT, Waste/Accidental fires/Fireworks 1.6 kT.

Figure 2-3 Primary sources of NH_3 in England for the year 2018 (kilotonnes) [4]



Pie chart showing primary sources of NH_3 in England for the year 2018. The pie chart shows that agriculture is by far the largest source. Agriculture/Forestry/Fishing 159.6 kT, Waste/Accidental fires/Fireworks 18.7 kT, Industry 5.8 kT, Road Transport: Exhaust 3.7 kT, Domestic Combustion 2.0 kT, Energy Industries 0.1 kT, Shipping 0.0 kT, Rail 0.0 kT, Aviation 0.0 kT.

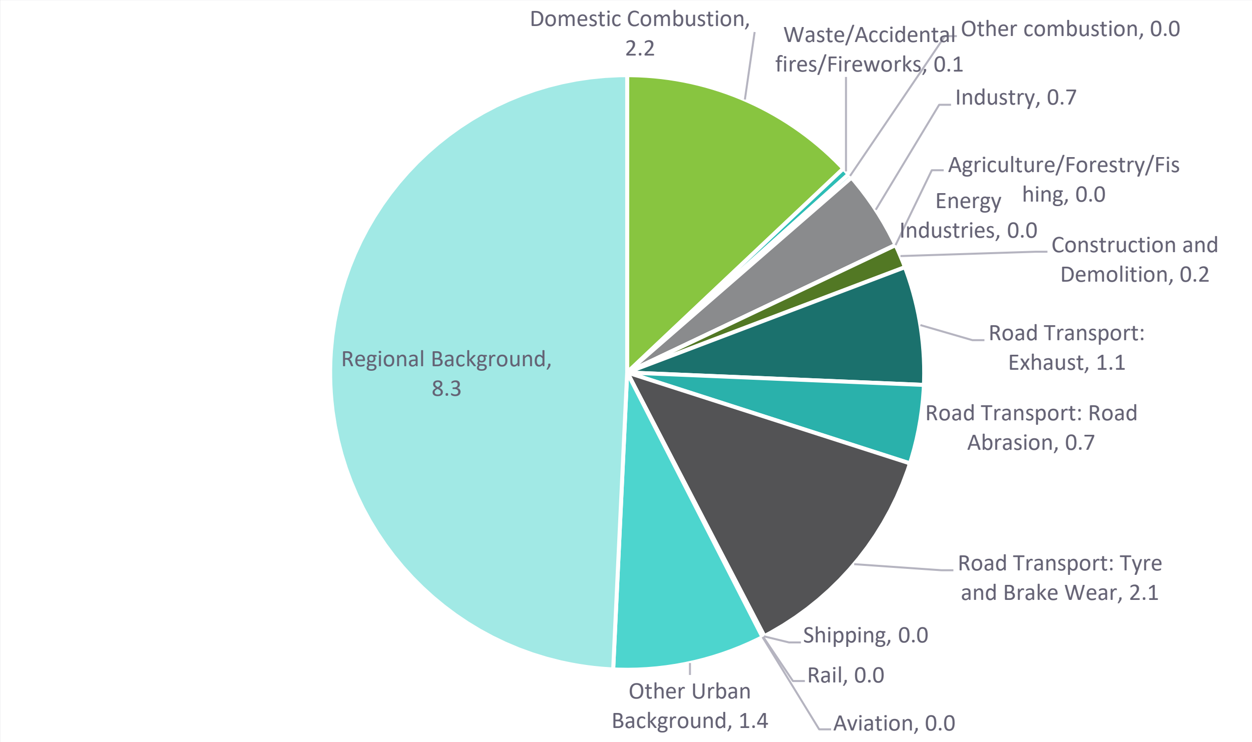
2.2 $PM_{2.5}$ Concentrations

As well as total emissions, the location of emission sources relative to the public is an important factor in determining the $PM_{2.5}$ concentrations that people are exposed to. Reducing exposure, and working towards achievement of concentration targets, requires understanding the relative contribution from each source (the *source apportionment*) to the ambient concentration at any particular location. $PM_{2.5}$ source apportionments for 2018 have been produced by the Pollution Climate Mapping (PCM) model[5]. In the PCM model, data on primary emissions from different sources from the NAEI and a combination of measurement data for secondary inorganic aerosol and models for sources not included in the emission inventory (including re-suspension of dusts) are used to estimate total concentrations.

As an illustrative example of the typical sources of $PM_{2.5}$ where concentrations are highest, the source apportionment for the PCM grid square with the highest concentration in 2018 (16.9 μg/m^3) is shown in Figure 2-4 (urban background and local contributions from a particular source have been combined). The proximity of any particular location to a local source, such as an industrial site, will determine the source apportionment for that location.

[5] Defra (2020) 2020 NO_2 and PM projections data (2018 reference year). Online: https://uk-air.defra.gov.uk/library/no2ten/2020-no2-pm-projections-from-2018-data

Figure 2-4 $PM_{2.5}$ Source Apportionment at a roadside urban location (µg/m^3)[5]



Pie chart showing $PM_{2.5}$ Source Apportionment at a roadside urban location. The results presented in the pie chart above are for the year 2018 and averaged for the 1 km grid square, grid reference (539922, 187824) located in the London Borough of Waltham Forest. Regional background is the largest source, followed by the combined contribution of road transport (tyre and brake wear, exhaust and road abrasion). Regional Background 8.3 µg/m^3, Domestic Combustion 2.2 µg/m^3, Road Transport: Tyre and Brake Wear 2.1 µg/m^3, Other Urban Background 1.4 µg/m^3, Road Transport: Exhaust 1.1 µg/m^3, Industry 0.7 µg/m^3, Road Transport: Road Abrasion 0.7 µg/m^3, Construction and Demolition 0.2 µg/m^3, Waste/Accidental fires/Fireworks 0.1 µg/m^3, Other combustion 0.0 µg/m^3, Rail 0.0 µg/m^3, Shipping 0.0 µg/m^3, Energy Industries 0.0 µg/m^3, Aviation 0.0 µg/m^3, Agriculture/Forestry/Fishing 0.0 µg/m^3.

Regional background pollution (49%) is the largest source of $PM_{2.5}$ at this location. Regional background pollution contributes up to 79% in other locations in London where concentrations are modelled, and up to 93% at other locations in the country. The regional background at this location is composed of:

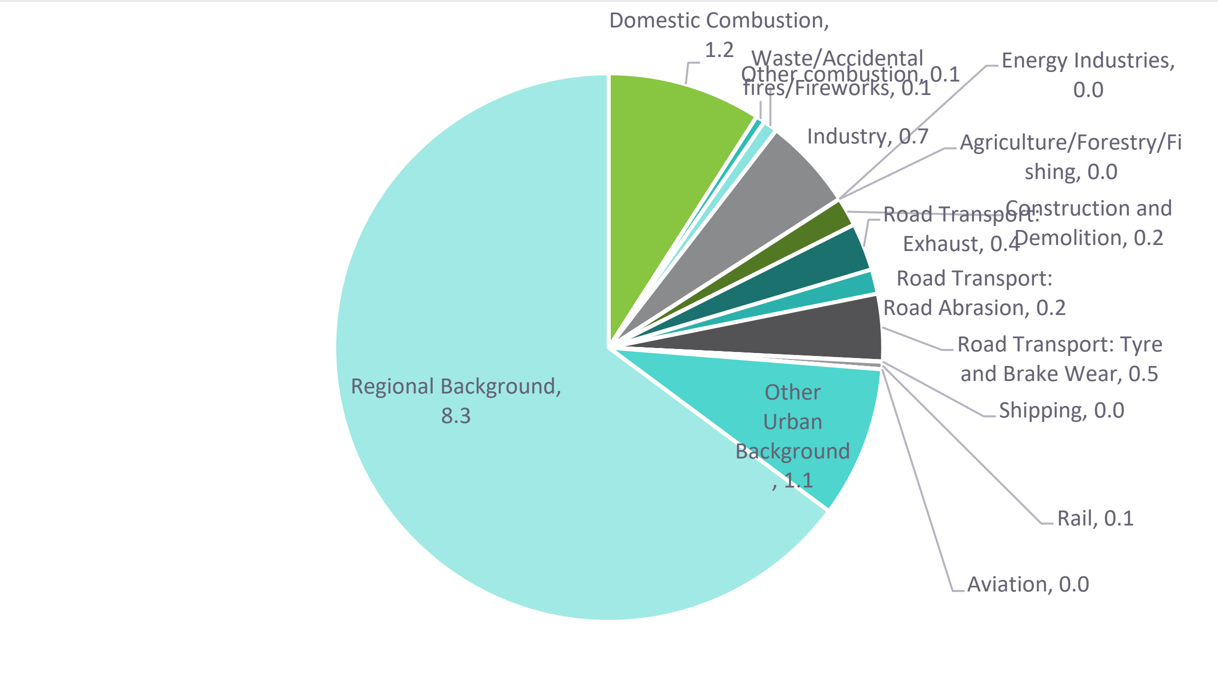
- Secondary Inorganic Aerosol (63% of regional background, 31% of total concentration).
- Sea Salt (6%, 3% of total concentration).
- Secondary Organic Aerosol (14%,7% of total concentration).
- Calcium rich dusts: fine (0%).
- Iron rich dusts (6%, 3% of total concentration).
- Long range transport Primary PM (11%, 5% of total concentration).

Ammonium sulphate and ammonium nitrate, the major contributors to secondary inorganic aerosol are formed by the atmospheric oxidation and reaction of precursor gases (SO_2, NO_X) and subsequent reaction with NH_3 and comprise a major component of $PM_{2.5}$[6]. This illustrates why emissions of NO_X and NH_3 emissions are an important part of this study. The proportion of the total concentration contributed by regional background sources is even greater at locations away from local sources of pollution (e.g., roads). This is why emissions of NO_X from other sources (e.g., ports and industry) are an important focus even though they may only contribute a small portion of the primary $PM_{2.5}$ at a particular location.

Road traffic contributes 24% of the $PM_{2.5}$ concentration at this modelled location. Tyre and brake wear alone contribute 13% of the concentration and they are now a larger source than exhaust emissions (which have reduced as a result of tighter vehicle emission standards).

Figure 2-5 and Figure 2-6 shown the same source apportionment for example urban background and rural locations respectively. These highlight the increasing importance of the regional background contribution when the influence of local sources is lower. The regional background contributes 65% of the total concentration at the urban background location and 80% of the total concentration at the rural location.

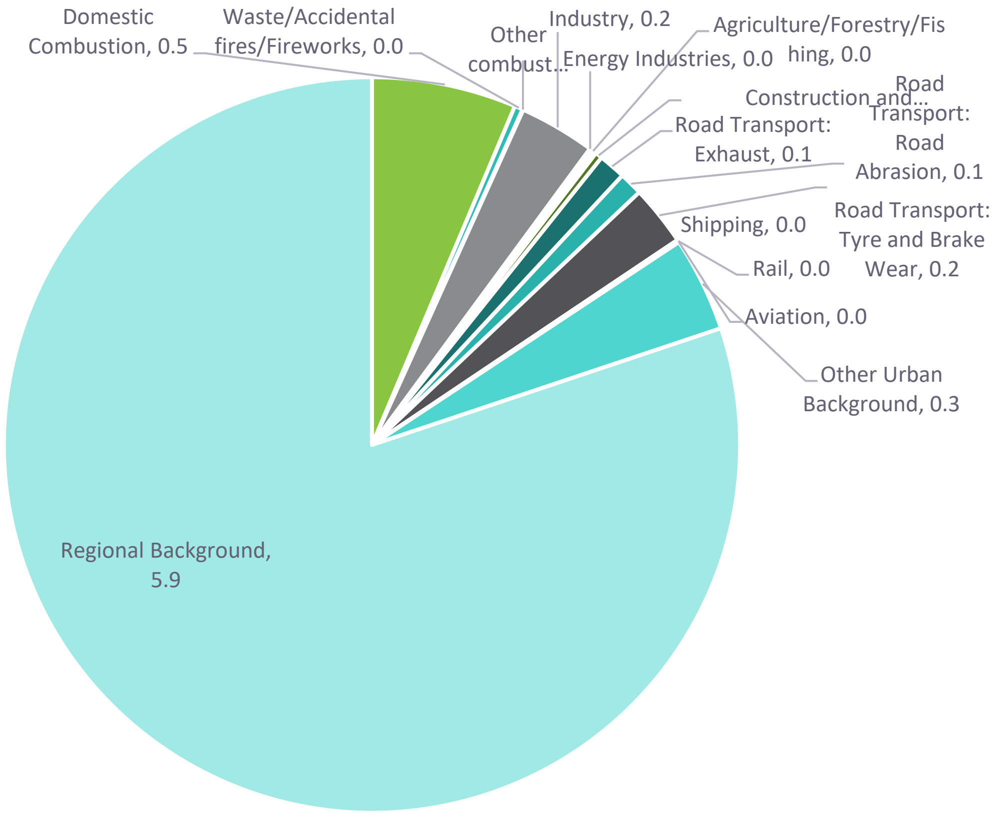
Figure 2-5 $PM_{2.5}$ Source Apportionment at an urban background location ($\mu g/m^3$)[5]



Pie chart showing $PM_{2.5}$ Source Apportionment at an urban background location. The results presented in the pie chart above are for the year 2018 and averaged for the 1 km grid square, grid reference (528830, 184000) located in the London Borough of Camden. Regional background is by far the largest source. Regional Background 8.3 $\mu g/m^3$, Domestic Combustion 1.2 $\mu g/m^3$, Road Transport: Tyre and Brake Wear 0.5 $\mu g/m^3$, Other Urban Background 1.1 $\mu g/m^3$, Road Transport: Exhaust 0.4 $\mu g/m^3$, Industry 0.7 $\mu g/m^3$, Road Transport: Road Abrasion 0.2 $\mu g/m^3$, Construction and Demolition 0.2 $\mu g/m^3$, Waste/Accidental fires/Fireworks 0.1 $\mu g/m^3$, Other combustion 0.1 $\mu g/m^3$, Rail 0.1 $\mu g/m^3$, Shipping 0.0 $\mu g/m^3$, Energy Industries 0.0 $\mu g/m^3$, Aviation 0.0 $\mu g/m^3$, Agriculture/Forestry/Fishing 0.0 $\mu g/m^3$.

[6] McFiggans, Alfarra, Allan, Coe, Hamilton, Harrison, Jenkin, Lewis, Moller, Topping, and Williams (2015) A review of the state-of-the-science relating to secondary particulate matter of relevance to the composition of the UK atmosphere – Report for Defra. Online: https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1511251442_AQ0732_Understanding_secondary_inorganic_and_organic_aerosol.pdf

Figure 2-6 $PM_{2.5}$ Source Apportionment at a rural location (µg/m³)[5]



Pie chart showing $PM_{2.5}$ Source Apportionment at a rural location. The results presented in the pie chart above are for the year 2018 and averaged for the 1 km grid square, grid reference (396002, 341030) located in the administrative area of Staffordshire Moorlands District Council. Regional background is by far the largest source. Regional Background 5.9 µg/m³, Domestic Combustion 0.5 µg/m³, Road Transport: Tyre and Brake Wear 0.2 µg/m³, Other Urban Background 0.3 µg/m³, Road Transport: Exhaust 0.1 µg/m³, Industry 0.2 µg/m³, Road Transport: Road Abrasion 0.1 µg/m³, Construction and Demolition 0.0 µg/m³, Waste/Accidental fires/Fireworks 0.0 µg/m³, Other combustion 0.0 µg/m³, Rail 0.0 µg/m³, Shipping 0.0 µg/m³, Energy Industries 0.0 µg/m³, Aviation 0.0 µg/m³, Agriculture/Forestry/Fishing 0.0 µg/m³.

3. Methods

3.1 Overview

To enable focussed research and stakeholder engagement, the project was divided into different Work Packages (WPs) on the basis of emissions sources and/or management approaches. The WPs are detailed in Table 3-1.

Table 3-1 Work Packages

Category	Work Package
Urban Air Quality	Urban Traffic Management (inc. planning, modal shift and behavioural change to active travel)
	Other Urban Combustion (Domestic/Commercial combustion and commercial cooking)
Transport	Road Transport Technology
	Shipping
	Aviation
	Rail
Agriculture	Agriculture
Industry	Industrial (regulators/Operators/Original Equipment Manufacturers (OEMs)
	Construction

The project was conducted through a series of feedback processes to maximise stakeholder input. The available literature was reviewed to develop initial lists of measures within each sector and to identify key stakeholders. Interviews with key stakeholders were used to identify additional relevant literature and further stakeholders to be interviewed. Through this cyclical process stakeholders were identified to invite to the workshops. The workshops were used to provide confirmation of the general conclusions drawn from the literature review and interview process. The workshop summaries were issued to attendees to gather further comment on the measures presented and to help finalise the list of measures.

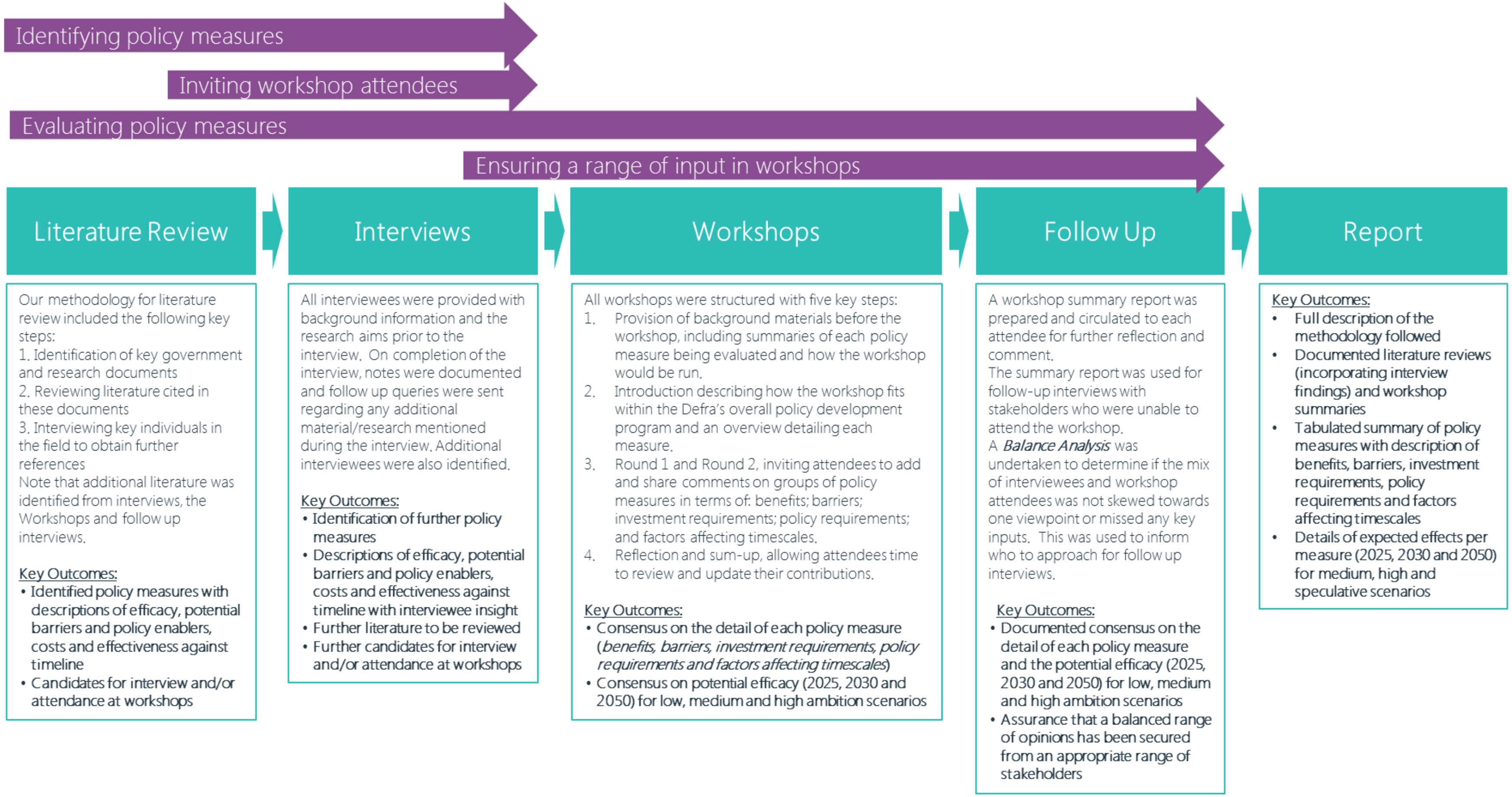
The literature review and engagement with stakeholders enabled development of a long list of options for reducing $PM_{2.5}$. The information on the potential of each measure to reduce emissions alongside the costs and feasibility of each option, and the potential scale of use (individual site, local, regional, national) was detailed.

The long list was then refined to provide a shorter list of measures that are suitable for use in the modelling process. The shortlist was determined based on whether there was stakeholder consensus that the measure could help to reduce $PM_{2.5}$ concentrations and whether there was sufficient data/information to draw suitably robust assumptions for modelling.

The process flow for gathering evidence to support this project is summarised in Figure 3-1.

wood.

Figure 3-1 Process flow for gathering evidence



This Figure presents the process flow for gathering evidence. The first step is identifying policy measures, which included the literature review and interviews with stakeholders and experts. The next step was to invite workshop attendees. This started during the literature review and was completed with the interviews. The interviews were followed by the workshops and follow up discussions with stakeholders and experts. These four activities (literature review, interviews, workshops and follow up) made up the next step in the process flow which is evaluation of the policies. Having completed these flows, the final action was to provide the report.

3.2 Literature Review

The researchers reviewed the available literature relevant to each sector. Different search terms were used for each work package, reflecting the wide variety of emission sources considered, with keywords related to relevant pollutants, the industry, the emission source, and particular technologies.

The literature review began with "grey" literature produced by organisations and commercial publishers identified through searches into the relevant emission sources. Grey literature sources produced by organisations and commercial publishers provides sector intelligence and case studies that may not be available within the academic literature. Sources used included white papers, government documents, conference proceedings, reports by research funders and campaign organisations, and working papers. Key references were identified in relation to their relevance to the research questions, recommendations by expert stakeholders and through consideration of the relative age of reports. Where possible, the most recent available literature has been used to draw conclusions.

The literature reviewed extended to peer-reviewed academic literature when required to answer particular aspects highlighted in the initial research questions detailed below, when grey literature referred to other sources and when directed by stakeholders. Academic literature from peer-reviewed sources were obtained from online electronic libraries and databases.

The following general research questions were defined at the outset of the review:

- What activity or technology is the source of emissions (e.g., engine, industrial process, waste processing etc.)?
- What measures (technological, behavioural or policy) are there available to reduce the emissions from the sources identified through the first question?
- What are the timescales for implementation of the measure (e.g., short-term 0-5 years, medium term 5-15 years or long term 15-30 years)?
- Where possible, what are the costs of the measure (CAPEX and OPEX)?
- What is the likely availability of the measure (considering technological readiness, market penetration etc.)?
- What are the barriers to implementation (e.g., financial, technological or policy)?
- What is the likely level of uptake (e.g., limited, common or ubiquitous)?
- What is the effect on particulate emissions (and other relevant emissions)?

3.3 Interviews

Engagement with experts relevant to each sector enabled further exploration into the emerging and potential future measures identified that could reduce emissions of $PM_{2.5}$ and its precursors (technologies, behaviours and policies), developed an understanding of the likelihood and requirements for implementing each measure, and identified what best practice could consist of in future. Experts were identified from initial knowledge of the experts in each sector, and through contacts in various government departments.

The engagement process was also informed by the initial stages of the literature review. Where key references regarding particular measures were identified, this was used to determine the appropriate organisations or individuals to contact. This included authors of key reports. Contact was established as soon as possible to enable meaningful engagement with stakeholders.

These interviews supported the appraisal of information provided in the literature review and filled gaps in knowledge where published literature does not exist.

The interviews targeted a cross section of academics, practitioners and policy makers to seek a range of views from within each sector. Interviews were conducted via video conference over the period December 2020 to February 2021 with each interview lasting approximately 30 – 45 minutes. The list of stakeholder organisations interviewed is provided in Appendix A.

To ensure consistency, and to capture relevant details for the project, the framework of research questions detailed above was used to highlight key themes that were explored within the interviews. The interviews followed a semi-structured format based around these questions. Additional questions were posed that were relevant to the specific area of expertise and knowledge of the interviewee and to fill gaps in the literature review or follow-up on relevant points.

Each interview started with the interviewer providing an overview of the project and its purpose before then stating the goals of the interview were to: (1) capture insight and knowledge based on practical experience; (2) guide the literature review with additional sources of information, reports, policy papers etc.; (3) supplement the results of the literature review; and (4) assist with the critical appraisal of information obtained from the published literature.

Each interview was minuted and a record sent to each interviewee for review and further comment.

3.4 Workshops

Workshops were held in January 2021. Some of the stakeholders already interviewed attended these workshops alongside additional attendees. The workshops were used to confirm the findings to-date, develop an understanding of the level of consensus regarding the details of each measure, within each sector, and identify additional measures that had yet to be identified.

The workshops took place over video conference and each was scheduled for two and a half hours. The format of the workshops was a combination of presenting the initial findings and targeted discussion sessions around each measure. Each workshop included:

- Introduction to the project.
- Presentation on the literature review findings and suggested measures for the sector.
- Discussion of each measure or group of measures, focusing on the likely benefits of the measure, the barriers to implementation, the investment and policy requirements for the measure to be implemented and the factors that are likely to affect implementation timescales. The aim of the discussion was to capture views on the level of ambition, the potential rate of implementation and levels of uncertainty associated with different measures.

The workshops included the use of a digital notice board to enable attendees to add notes to the board recording their views as the discussions progressed. The write-up of these workshops is provided in Appendix B.

As part of the interview and workshop process, stakeholders were mapped to different organisation types to enable a range of opinions to be collected. When the mix of stakeholders attending a workshop was considered to give disproportionate influence a particular stakeholder group, efforts to contact stakeholders from under-represented organisation types were increased to redress the balance of attendance. When key organisations were unable to attend workshops, they were contacted to ensure that their views had been captured. The stakeholder organisation types involved in the interviews and workshops are presented in Table 3-2.

Table 3-2 Types of Organisation Involved in Interviews and Workshops

	Organisation Type	Agriculture	Aviation	Construction	Industrial	Other Urban Combustion	Road Traffic	Shipping	Urban AQ
Interviews	Charity/Campaign Group						1		3
	Consultancy	1	2				3		4
	Government	2			9	4	7	2	6
	Manufacturer (Equipment, Vehicle, Technology)		1	1	1		6	1	
	Operator		2	2					
	Science/Research/Innovation (University)	4	1	1		2	5		5
	Trade Association	1		3	14	4	1	1	2
	Grand Total	**8**	**6**	**7**	**24**	**10**	**23**	**4**	**20**
Workshops	Charity/Campaign Group	2		1		1	1		1
	Consultancy	1	1	3			3		7
	Government	11	5	1	19	4	13	1	4
	Manufacturer (Equipment, Vehicle, Technology)		3	3	6	2	3	3	
	Operator		6	3	3	1		5	
	Science/Research/Innovation (University)	4	2	6	0	2	3	3	3
	Trade Association	11		6	10	5	1	5	1
	Grand Total	**29**	**17**	**23**	**42**	**15**	**24**	**17**	**16**

wood.

3.5 Process Flow for each WP

A summary of the process flow for evidence gathering, given in Figure 3-1, is provided for each of the WPs in Table 3-3.

Table 3-3 Work Package Process Flow

Sector	Literature Sources	Interviews	Workshop Date	Workshop Attendees
Agriculture	22	8	29/01/2021	29
Aviation	16	6	26/01/2021	17
Construction	31	7	27/01/201	23
Industry	48	20	28/01/2021	42
Other Urban Combustion	46	10	25/01/2021	15
Rail	13	7	See Note	
Road Traffic Technology	53	23	21/01/2021	24
Shipping	29	4	27/01/2021	17
Urban Mobility	58	20	20/01/2021	16
Grand Total	316	105		183

Note: No workshop was held for rail as interviews with key stakeholders were considered sufficient due to the high degree of centralisation within the industry with DfT, Network Rail, RSSB, RIAGB and RDG representing industry consensus.

4. Measures

4.1 Overview

The measures identified are described in this section. For each measure, a description of the measure is provided, followed by a description of the evidence base, including consideration of depth of the research basis and the consensus regarding the evidence. The evidence regarding the measure is then summarised, in terms of benefits, barriers, investment requirements, policy requirements and factors affecting timescale for implementation (where information was available). A tabular summary is provided for each measure.

The summary table also describes how the measures are incorporated into the scenarios. There are four main scenarios being modelled:

- **Baseline** – This scenario is based on NAEI 2018 projections with some adjustments to include more recent evidence and legislation. The baseline includes emission reductions as a result of legislation already introduced and new lower emitting technology replacing older technology e.g. road vehicle fleet turnover.
- **Medium** – In this scenario additional action is taken to reduce $PM_{2.5}$ concentrations. The measures tend to be based on proven technology and modest behaviour change, with moderate implementation times and uptakes.
- **High** – In this scenario additional measures are employed to reduce $PM_{2.5}$ concentrations, and implementation times and uptakes are more rapid
- **Speculative** – In this scenario the maximum possible action is taken, it includes the implementation of technology still in development and more significant behaviour change. Implementation times and uptakes are the most ambitious stakeholders thought feasible.

The baseline therefore defines the lower boundary of emissions reductions and the speculative the upper. In addition to the scenarios based on this study, two comparison scenarios were modelled. A net zero scenario based on the core carbon budget 6 pathway, and a scenario in which the NECR 2030 targets are met for all air pollutants. Some measures taken to meet net zero by 2050, will also reduce $PM_{2.5}$ emissions and a small number that may be taken such as additional use of biomass combustion would increase it.

The way in which each measure is applied in each scenario is described in the summary table. Implementation dates and uptake rates vary between the medium, high and speculative scenarios and have been informed by the literature review and stakeholder engagement. For example, the speculative scenario generally includes the earliest feasible uptake of a particular measure and the maximum reduction in emissions identified. Measures have been discussed with stakeholders within each sector to provide an informed view of what a speculative level of implementation (i.e. where the maximum possible action is taken) would look like. High and medium levels of effectiveness have then been informed by this. In some cases, where different measures act on the same emissions source, the measures considered most likely to be implemented have been applied in the medium or high intervention scenarios, with the measures that requires greater policy change or technological development being employed in the speculative scenario.

4.2 Domestic/Commercial Combustion

Introduction

As illustrated in Section 2, domestic combustion is currently estimated to contribute 44% of total $PM_{2.5}$ emissions in England, 5% of NO_X emissions and 1% of NH_3 emissions. Whilst estimates of the amount of wood combustion carried out in England vary, it is generally accepted that use of wood is the largest contributor to total $PM_{2.5}$ emissions in the sector. The combustion of gaseous fuels emits much less particulate matter.

Measures in this work package therefore relate to reducing the amount of solid fuel combusted, reducing the amount of fuel combusted by improving energy efficiency and finally, shifting heating away from technologies that require fuel combustion.

Phase Out the Sale of Highly Polluting Solid Fuels

Measure Description

Coal and wet wood emit far more $PM_{2.5}$ than low sulphur smokeless fuels or dried wood and regulations to regulate the sale of house coal and wet wood (>20% moisture) and introduce limits on sulphur content of smokeless fuels have already been introduced. In accordance with The Air Quality (Domestic Solid Fuels Standards) (England) Regulations 2020[1], the sale of small quantities of wet wood and house coal for domestic use will be phased out in England over the period 2021 to 2023.

This existing measure is included in the baseline scenario but described here to reflect the importance of this policy as highlighted by stakeholders.

Evidence Base and assessment of evidence

Domestic burning of solid fuels including wood and coal is recognised as a large source of $PM_{2.5}$ emissions in England. However, estimates of solid fuel use, from which total emissions are calculated, vary significantly.

Estimates from the National Atmospheric Emission Inventory (NAEI)[2] suggests that domestic burning of wood contributes 38% to the total UK $PM_{2.5}$ emissions, which is the value used in the Government's Clean Air Strategy[3]. This value is based on a Department for Business, Energy and Industrial Strategy (BEIS) survey[4]. that estimated 4.4 million tonnes of wood were burnt in domestic premises per year[5]. A report published by HETAS in 2019[5] reported an annual tonnage of wood burnt indoors in the domestic sector of 1.9 million tonnes in the UK based on an industry led survey undertaken by the Stove Industry Alliance (SIA) in 2019. The report suggests that domestic wood consumption may have been overestimated in the BEIS survey by a factor of 2.4. Another recent estimate made by Defra[6], using data from a survey undertaken by Kantar on behalf of Defra[7] is a total of 2.4 million tonnes of wood burnt indoors and outdoors in the domestic sector over the period April 2018 to March 2019 in the UK. There is also high uncertainty in the emission factor. Higher moisture levels in the wood being burnt greatly increase the emissions generated and emissions from different appliances are highly variable.

Looking at the NAEI domestic combustion sector specifically (1A4bi), the total $PM_{2.5}$ emitted in the sector in 2018 is estimated at 46.8 kilotonnes (kT) for the UK as a whole. Emissions from wood burning are estimated at 40.7 kT, representing 87% of total $PM_{2.5}$ emissions from this sector.

In England, the NAEI estimate for the 1A4bi sector is 36.4 kT of $PM_{2.5}$ overall. Applying the above UK factors suggests 31.6 kT of $PM_{2.5}$ is emitted from wood burning.

Summary of evidence

Defra consulted on the cleaner domestic burning of solid fuels and wood in 2018[8]. The Air Quality (Domestic Solid Fuels Standards) (England) Regulations 2020 apply to wood, bituminous coal and manufactured fuel, as detailed below.

Regulation on wood:

- *All wood sold for the purpose of domestic combustion in volumes under $2m^3$ must go through a certification scheme or the supplier must demonstrate that the fuel meets the required moisture levels.*
- *All wet wood sold for the purpose of domestic combustion over $2m^3$ must be sold with relevant advice on how to season the wood to make it suitable as a fuel.*
- *Small foresters producing 600 m^3 or less per year will be exempt for the first year, prior to 2021 only.*

Regulation on bituminous house coal:

- *All bituminous house coal will be phased out from sale for domestic heating purposes.*
- *Direct sales of loose coal will have a longer transition period to 2022 to enable those who currently rely on house coal for their primary heat source to identify a cost-effective alternative.*

Manufactured solid manufactured fuels:

- *All manufactured solid mineral fuels sold will need to be labelled to confirm they contain less than 2% sulphur and have less than 5g/h smoke emissions.*
- *Suppliers will need to get their products tested to confirm they comply.*

Defra published an Impact Assessment[9] as part of the consultation, which included a projected reduction in $PM_{2.5}$ emissions compared to a baseline scenario with no ban introduced. In 2025 a reduction of 8.8 kT of $PM_{2.5}$ emissions was estimated, and in 2030 a reduction of 9.4 kT of $PM_{2.5}$ emissions (with no projections beyond 2030).

Looking at the total $PM_{2.5}$ emissions in the domestic combustion sector (1A4bi), as estimated in the NAEI, this leads to a reduction of 24% and 26% of a total 36.4 kT, in 2025 and 2030, respectively.

The Impact Assessment estimates a total cost for businesses, households, and the Government of £19.5m for the 2020-2030 period. This includes a total cost for businesses of £123.8m (loss of profit, investments in drying equipment, monitoring and administrative costs). For households, a benefit of £105m over the 11-year period is estimated from switching fuels. For government, the cost is estimated at £1.4m over the 11-year period, to cover the costs of an information campaign to promote safer and cleaner fuels burning habits and local authorities' enforcement costs.

Summary - Phase Out Sale of Highly Polluting Solid Fuels

Factor	Summary		
Benefits	**2025** Reduction of 8.8 kT of $PM_{2.5}$ emissions. Reduction of 24% - 49% of the 1A4bi sector. **2030** Reduction of 9.4 kT of $PM_{2.5}$ emissions. Reduction of 26% - 52% of the 1A4bi sector. % Reduction depends on baseline total emissions from wood used.		
Barriers	Difficulty in enforcing regulation especially with smaller suppliers. Some risk of negative impact associated with seasoning wood in kiln, but the production could be regulated and emissions controlled. Environmental permits could be required. Concern that displacement of these fuels will be transferred from domestic to commercial uses. Could disadvantage households in fuel poverty.		
Investment Requirements	Education campaign building on the existing grassroots Burnright campaign. Education from local authorities on the environmental issues. This includes factors such as seasoning of wood.		
Policy Requirements	Contribution of outdoor burning needs to be better quantified and policies developed accordingly. The Renewable Heat Incentive (RHI) requires people to buy a Biomass Suppliers List (BSL) registered fuel to demonstrate sustainability. BSL is to be adapted to include fuel quality as well. This will help to ensure that the fuel used is the right fuel for the boiler. Introduce regulations for outdoor burning (potentially included under domestic burning at present in emission inventories). Need for a sustainable biomass policy covering all aspects of biomass use to take account of all environmental impact. These include sustainable production, land use, carbon neutrality and offsetting and air quality from combustion. There is need to bring more non-domestic burning into regulations.		
Factors Affecting Timescales	Delivery of benefits will depend upon both education of consumers and enforcement of policies. The policy will be implemented in 2021 but a transition period of one year is given to small foresters (producers of less than 600m^3 of wood annually), and an extra two years for the delivery of loose coal through direct sales.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	Not modelled for $PM_{2.5}$ specific scenarios, included as an adjustment to the baseline		
Justification	The baseline scenario includes a 9.7kT reduction in $PM_{2.5}$ emissions (24%) in 2030 as a result of "Baseline Adjustment - Regulating the sale of wet wood and traditional coal in England"		

Reduce Emissions from Domestic Combustion of Solid Fuels

Measure Description

The use of modern appliances to burn solid fuels can significantly reduce particulate emissions. Emissions can be reduced through measures such as:

- Education on good practice for existing appliances with, and communication on benefit of retrofitting to newer appliances building on the Burnright campaign[10].
- Retrofitting older appliances to Ecodesign standards and replacing open fires with Ecodesign appliances. All new indoor solid fuel burning appliances sold in the UK to meet Ecodesign standards including limits on PM emissions. Ecodesign has been implemented since 2020 for independent boilers and will be implemented in 2022 for room heater stoves[11].

- Installation of new wood burning stoves in urban areas to be banned and existing stoves to be phased out (this is considered a highly ambitious measure).
- Reducing the amount of wood burnt by switching homes heated with wood to other sources (e.g. heat pumps and gas boilers).
- Regulating or banning outdoor wood burning.

Evidence Base and assessment of evidence

These is a consensus in the literature, interviews and workshop that newer Ecodesign stoves emit far less $PM_{2.5}$ than older stoves and open fire appliances. The Stove Industry Alliance (SIA) has developed the clearSkies label[12] which shows that labelled appliances have been independently certified, confirming that they meet or exceed the forthcoming Ecodesign Regulations.

There is uncertainty in real-world emissions compared to emission limits. As reported in a review of the potential air quality impacts from biomass combustion published by Defra's AQEG[13], several studies have compared laboratory and real-world emissions of the same appliances and found large variability. Many factors affect actual emission rates, including user behaviour, the quality of the fuel and the installation of the appliance. A study in New Zealand compared emissions from the same appliances within a laboratory and under real world conditions where the wood burners were operated normally by the householder. The results suggested that real world emissions may be up to 4-5 times higher than those achieved within laboratory studies[14]. This was discussed in the workshop.

In the UK context, a report from EPUK[15] based on work undertaken by Brighton and Hove City Council, highlights an increasing number of gross pollution and nuisance cases associated with solid fuel appliances being dealt with by Local Authorities. These are commonly linked to appliances which are poorly installed, being misused, or burning inappropriate fuels.

Summary of evidence

Research undertaken by Kantar on behalf of Defra[7] reported trends on household ownership of solid fuel burning appliance in England, using data from the English Housing Survey (EHS). Analysis of the EHS data indicated an increase in the presence of solid fuel burning secondary heating systems (stove and open fire) between 2003 and 2016 from 11.5% to 14.1%. The data also indicates a rise in households with a stove from 2.3% to 7.2%, and a decrease in households with an open fire from 9.1% to 6.9%. As a result, by 2016, there were more households in England with stoves than with open fires.

Defra used data from the domestic combustion core activity survey[16], undertaken by Kantar in the period April 2018 - March 2019 in the UK, to estimate that of the total wood burnt indoors in England, 24% was on open fires, and 76% in stoves. The research also highlights that a large proportion of people did not know which kind of appliance they had installed. Table 3.12 of the report[7] shows that 46% of UK respondents did not know what type of appliance they had, 35% said their appliance was Defra exempt and 9% said their appliance was Ecodesign. In urban smoke control areas (SCA), 34% of respondents did not know what type of appliance they had, 53% said their appliance was Defra exempt and 7% said their appliance was Ecodesign.

In laboratory settings, Ecodesign appliances have been reported to emit 90% less PM than open fires and 80% less than older stoves. $PM_{2.5}$ emissions range from around 2,660 g/MWh for conventional stoves to 335 g/MWh for an Ecodesign stove[17]. They also have PM emission limits 55% lower than Defra exempt stoves[18]. There was general agreement regarding the effectiveness of these stoves at the workshop.

Based on the estimate that 24% of wood burnt in England is burnt on open fires, and that they emit 10% more than older stoves, wood burning on open fires is estimated to account for around 24% of $PM_{2.5}$ emissions from the domestic combustion sector (1A4bi), with wood burning on stoves accounting for around 76%. Using these assumptions, and assuming that 9% of wood is burnt on Ecodesign stoves, replacing all open fires with Ecodesign appliances could result in a reduction of 28% of $PM_{2.5}$ emissions from domestic wood burning. Replacing all existing stoves with Ecodesign appliances would result in a reduction of 57% of $PM_{2.5}$ emissions.

There is uncertainty on this value as the total amount of wood burnt on older or newer (Defra exempt, or Ecodesign) stoves is not known. As discussed for the previous measure, there is also uncertainty in the total amount of $PM_{2.5}$ emissions from wood burning.

There was a general consensus at the workshop on the need to educate the public on good burning practices. Educational resources such as the Burnright website[10], and the Defra Burn Better campaign[19] are important tools the public should be referred to.

Domestic solid fuel combustion is important in terms of public health. Although the focus of this study is on ambient air, a recent study[20] also demonstrated that people inside homes with a residential stove are at risk of exposure to high intensities of indoor $PM_{2.5}$ within a short period of time through normal use, with peak pollution events referred as 'flooding' events correlated with the opening of the stove door. Reducing domestic wood combustion could therefore reduce health impacts. The Institute of Health Equity suggests that low Greenhouse Gas (GHG) scenarios that rely on increased use of domestic biofuels and biomass to replace fossil fuels will bring lesser health gains than if these fuels play a smaller role[21]. They recommend setting a target date to eliminate home installations of wood burning stoves, prioritising elimination in urban areas, and set a further target date to eliminate/remove all existing wood burning stoves in urban areas. In the workshop, some stakeholders suggested that the future role of biomass for domestic heating could be limited to rural areas and those buildings that are not suitable for heat pumps. The Kantar survey[7] suggests that 68% of indoor burners lived in urban areas in the UK with 32% in rural areas.

The importance of outdoor burning as a source of $PM_{2.5}$ emissions was also highlighted in the stakeholder engagement, and it was agreed that there is a high level of uncertainty regarding the extent of these emissions. Outdoor burning is done for a number of reasons, including: cooking; creating a fun or homely atmosphere outside; outdoor heating; and waste disposal. The NAEI estimates that small-scale waste burning (5C2) accounts for 1% of total UK primary $PM_{2.5}$ emissions.

The recent Kantar survey for Defra, provided data on the extent of outdoor burning practices in the period April 2018 - March 2019 in the UK. A greater proportion of the UK population engaged at least occasionally in outdoor burning compared to the proportion that engaged in indoor burning. 14.3% of the survey respondent in England said they had burnt outdoors in the period. However, respondents tended to burn outdoors less frequently than indoors. The seasonal pattern for outdoor burning was inverse to indoor burning. People burning material outdoors were more likely to live in urban areas (82%) than people burning indoors. The main purposes for choosing to burn outdoors were for cooking (73%), waste disposal (28%), to create a fun or homely atmosphere outside (21%), and outdoor heating (14%).

Summary – Reduce Emissions from Solid Fuels Domestic Combustion

Factor	Summary		
Benefits	Retrofitting all open fires to Ecodesign appliances could lead to a reduction of $PM_{2.5}$ emissions of ~25% from the 1A4bi sector. Retrofitting all stoves to Ecodesign appliances could lead to a reduction of $PM_{2.5}$ emissions of up to ~60% from the 1A4bi sector. This could also have a positive impact on indoor air quality depending on how stoves are used.		
Barriers	Lack of commonly agreed data on the scale of wood burning and therefore total emissions. Preferences for open fires despite effect on air quality and heat and cost efficiency issues. Wood may be an important heating source for those experiencing fuel poverty. Real world emissions are strongly dependant on correct use and maintenance of the appliance. There could be a rise in the second-hand market for older appliances.		
Investment Requirements	Educate burners on good burning practice involving installers, servicing companies, fuel retailers. Educate the public on health benefits and fuel savings with switching to newer appliances. Tax rebates or grant systems to encourage purchase of modern appliances.		
Policy Requirements	Mandate regular maintenance and chimney sweepings (as already in place in other countries). Policies to halt the sale of unsuitable appliances is required. Scrappage scheme for replacement of unsuitable appliances.		
Factors Affecting Timescales	Development of policies needs further research into the sources of PM from wood burning (e.g. determine contribution from unregulated outdoor burning - bonfires, incinerators, barbeques, outdoor pizza ovens, etc.).		
	Retrofitting all open fires to Ecodesign appliances		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	25% reduction in emissions from domestic wood combustion by 2050	25% reduction in emissions from domestic wood combustion by 2040	N/A
Justification	Only included in high scenario based on stakeholder opinions around likelihood of uptake	Based on differences between open fire and modern stove emission rates and stakeholder input on uptake/benefits. All open fires retrofit to Ecodesign	Not included as this scenario includes the more speculative measure of reductions in domestic wood burning associated with a switch to other heating sources
	Retrofitting all older stoves to Ecodesign appliances		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	Not modelled for $PM_{2.5}$ specific scenarios, included in the modelled baseline		
Justification	"Replace old secondary units with new stoves" included in the modelled baseline (~51% reduction in emissions from domestic wood combustion from 2025)		
	Ban installation and phase out stove/open fires in urban areas		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	Non included.	5% uptake in 2025 15% uptake in 2030, 2040 and 2050	30% uptake in 2025 60% uptake in 2030 65% uptake in 2040 68% uptake in 2050

Factor	Summary		
Justification	Important policy changes would be required to significantly reduce domestic wood burning. Based on stakeholder engagement around the uncertainty of emissions, and the benefits that can be achieved using Ecodesign stoves, this measure is only applied in high and speculative scenarios	Relatively low uptake based on the assumption that domestic combustion of wood is reduced in a very targeted way in the urban areas with the highest $PM_{2.5}$ concentrations	Policy change to seek a major reduction in domestic wood combustion associated with a switch to alternative sources (e.g. heat pumps and gas boilers). Uptake at a maximum of 68% reflecting the proportion of wood burner living in urban areas
	Regulate/Ban outdoor burning		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	50% reduction in $PM_{2.5}$ emissions from small scale waste burning in 2050	50% reduction in $PM_{2.5}$ emissions from small scale waste burning in 2040
Justification	Considered to be fairly ambitious by some stakeholders in terms of enforcement and behavioural change therefore only included in High and Speculative scenarios.	Based on stakeholder engagement and discussion around better education on the issue, particularly for urban areas. Slower uptake. Outdoor burning is recognised for other reasons in addition to waste burning but this source enables emission adjustment in the model.	Based on stakeholder engagement and discussion around better education on the issue, particularly for urban areas. Faster uptake. Outdoor burning is recognised for other reasons in addition to waste burning but this source enables emission adjustment in the model.

Reduce Emissions from Cooking

Measure Description

Introduce legislation on $PM_{2.5}$ emissions limits from domestic and commercial cooking. Emission reductions could be achieved by phasing out gas hobs to reduce emissions from combustion and the installation of filters such as Electrostatic Precipitators (ESP) to reduce emissions from the cooking process.

Evidence Base and assessment of evidence

The cooking sector (domestic and commercial) has been shown to be a large contributor to $PM_{2.5}$ emissions especially in the urban environment. However, there is a lack of consensus on the scale of total emissions from the sector. This was reflected in the discussion at the workshop.

Summary of evidence

Cooking has been shown to be a large contributor to $PM_{2.5}$ emissions especially in urban environments. The London Atmospheric Emission Inventory (LAEI) estimates that cooking (including commercial cooking) accounts for 13% of $PM_{2.5}$ emissions[22], as reported in the GLA Roadmap to meeting World Health Organization (WHO) guidelines by 2030[23].

A recent unpublished study reviewed several estimates of total $PM_{2.5}$ emission from cooking in the UK and used UKIAM[24] to model the different scenarios of the contribution of cooking to $PM_{2.5}$ concentrations and population exposure. The study used estimates of total $PM_{2.5}$ emissions ranging from 2 kT to 7.4 kT.

- 2 kT of $PM_{2.5}$ per year in the UK, assuming an emission of 80 mg/day per person of $PM_{2.5}$ from cooking[25], based on findings from studies in Paris[26].
- 7.4 kT of $PM_{2.5}$ per year, based on measurements campaigns in London which estimated emissions of cooking organic aerosol to be 320 mg/day[27].

ESP can remove over 90% of $PM_{2.5}$ from kitchen exhausts[28]. The cost of an ESP for kitchen extract systems (excluding installation and maintenance) is estimated be in the range £2,500[29] to £3,550[30].

Summary – Reduce Emissions from Cooking

Factor	Summary		
Benefits	ESP can remove >90% of $PM_{2.5}$. There is anecdotal evidence that some restaurants have an ESP installed but no data on the total number. Installing ESP in all restaurants in London could lead to an 11% reduction in total $PM_{2.5}$ emissions in London Benefit for indoor quality.		
Barriers	Lack of evidence on the scale of the issue. Difficulty in regulating numerous small businesses. Wood-fired restaurants and takeaways are not always required to have filters as this may have not been considered in the planning/approval process. ESP costs are prohibitive for small businesses.		
Investment Requirements	Research into the scale of emissions from commercial cooking. This could involve use of aetholometers[1] to trace wood combustion. Investment in filters/ESP by commercial cooking facilities. Investment in enforcement by government/local authorities.		
Policy Requirements	Policies to require commercial cooking facilities to use filters/ESP.		
Factors Affecting Timescales	Research on the scale of the issue. Benefits will also be determined by the enforcement regime developed and funding provided.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Not modelled as this is not represented as a source in the NAEI, therefore baseline emissions cannot be reduced. Further research in the magnitude of this source is required.		

[1] An aethalometer uses optical analysis to determine the concentration of black carbon particles in air.

Reduce Fuel Combustion by Improving Energy Efficiency

Improving energy efficiency standards of buildings has the potential to reduce the heating demand, and therefore the quantity of fuel used. Energy efficiency measures are discussed by type of buildings (future homes, existing homes, non-domestic buildings) in the following sections.

As stated in the recent government Impact Assessment (IA) on Future building Standards[31], domestic and non-domestic buildings have been estimated to account for 40% of the UK's total energy use. The UK has set in law a target to bring its GHG emissions to net zero by 2050. Building work carried out in England must comply with the Building Regulations. The Government is currently consulting on proposed changes to Part L (conservation of fuel and power) and Part F (ventilation) of the Building Regulations, as well as addressing overheating in residential buildings.

The Climate Change Committee (CCC) recommends in its 6th Carbon budget that energy efficiency is improved in all UK buildings[32]. Approximately 74% of the UK's heating and hot water demand in buildings is met by natural gas, 10% by petroleum, and smaller amounts of other fuels such as coal and biomass[33]. Energy efficiency measures in the CCC Balanced Pathway scenario deliver a 12% reduction in heat demand to 2050 which is considered a conservative estimation.

As stated in the Buildings summary report[34], in 2019, direct greenhouse gas (GHG) emissions from buildings accounted for 17% of the UK total. Direct building CO_2 emissions were split between homes (77%), commercial buildings (14%) and public buildings (9%)[35]. Direct emissions result primarily from the use of fossil fuels for heating.

Future Homes - Reduce Fuel Combustion by Improving Energy Efficiency

Measure Description

Improving energy efficiency standards of future homes has the potential to reduce the heating demand and therefore the quantity of fuel used.

Evidence Base and assessment of evidence

The benefit of improving energy efficiency of future homes, has been largely discussed and recommended in carbon saving and net zero policy reports. The benefits are related to energy and fuel savings. Reduction in quantity of fuel burned will lead to improvement in air quality. However, there is large uncertainty over the energy and heat savings which can be achieved.

Summary of evidence

For fabric energy efficiency in new homes, the CCC recommends ultra-high standards of energy efficiency in new homes from 2025 at the latest, delivered through measures such as triple glazing and high levels of airtightness.

The Government consulted in 2019-2020 on the Future Homes Standard[36]. This was the first stage of the consultation on changes to Part L (conservation of fuel and power) and Part F (ventilation) of the Building Regulations, and related to future homes. The Government's response to the consultation was published in January 2021[37]. The legislation will be introduced in 2024 ahead of implementation in 2025. From 2025, the Future Homes Standard will deliver homes that produce 75% less CO_2 emissions compared to current standards and are zero-carbon ready.

- New homes will not be built with fossil fuel heating, such as natural gas boilers.
- New homes will be future-proofed with low carbon heating and high levels of energy efficiency.
- No further energy efficiency retrofit work will be necessary to enable them to become zero-carbon as the electricity grid continues to decarbonise.

Additionally, an interim uplift in Part L standards will be implemented in 2022 (delayed due to Covid-19), before meeting the Future Homes standard in 2025. In the interim, these homes are expected to produce 31% less CO_2 emissions compared to current standards.

An Impact Assessment on the interim uplift of the standard was published along the consultation[38]. The IA did not consider the costs and benefits of the Future Homes Standard. Before its introduction in 2025, the government will consult on the full technical details and produce an associated Impact Assessment.

The Impact Assessment estimated a total amount of gas saved of 93,932 GWh (calculated over 10 years of policy and 60-year life of buildings) which represents approximately 1,342 GWh saved a year. Based on

England domestic gas consumption of 280,953 GWh in 2019[39] this represents an approximate reduction of 0.5% per year. The cost benefit analysis undertaken in the IA uses gas boilers as main heating. The gas consumption reduction of 0.5% per year is therefore solely related to the improved energy efficiency. A larger reduction is expected from 2025 when the Future Homes Standard is fully implemented as new homes will not be built with fossil fuel heating.

The Impact Assessment estimates an incremental cost of £10,454m plus transition costs of £3.2m for new domestic buildings. For new buildings, the initial capital costs will be borne by developers, but these costs may ultimately be passed to landowners. Maintenance and replacement costs will be borne by the building owners/occupiers. For works to existing buildings, costs will be borne by the building owners/occupiers. The IA also estimates a total energy saving of £7,738m, leading to a total financial cost of £2,179m.

Summary – Future Homes - Reduce Fuel Combustion by Improving Energy Efficiency

Factor	Summary		
Benefits	From 2022, 0.5% reduction in domestic gas consumption.		
Barriers	Uncertainty over the energy savings which can be achieved. Costs of higher specifications.		
Investment Requirements	Industry R&D into new materials and construction approaches. Homebuilder investment into meeting higher standards.		
Policy Requirements	Future Homes Standards to be implemented in 2025. Interim uplift from 2022.		
Factors Affecting Timescales	Implementation of policy.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	8% uptake by 2030 and maintained thereafter	14% uptake by 2030 and maintained thereafter	19% uptake by 2030 and maintained thereafter
Justification	Uptake rates for cavity/solid wall insulation to reduce emissions of pollutants (up to 8% reduction in $PM_{2.5}$ emissions) from domestic heating taken from MPMD. This covers the combined effect of new homes and energy efficiency improvements for existing homes.		

Existing Homes - Reduce Fuel Combustion by Improving Energy Efficiency

Measure Description

Improving energy efficiency standards of existing homes has the potential to reduce the heating demand and therefore the quantity of fuel used.

Evidence Base and assessment of evidence

The benefit of improving energy efficiency of existing homes, has been largely discussed and recommended in carbon saving and net zero policy reports. The benefits are related to energy and fuel savings. Reduction in quantity of fuel burned will lead to improvement in air quality. However, there is large uncertainty over the energy and heat savings which can be achieved.

Summary of evidence

As stated in the government's Energy White Paper[40], Around 16 million homes in England, 66% of the total, are at Energy Performance Certificate (EPC) D or worse[41]. In the private rental sector, existing legislation requires that buildings have a minimum standard of energy performance only of Band E.

The CCC 6th carbon budget[32] recommends establishing targets to retrofit and upgrade existing homes to be energy efficient:

- All rented homes and homes for sale to achieve EPC C by 2028.
- Homes with mortgages achieve EPC C by 2033.

Following on the Future Homes Standard, the Future Buildings Standard consultation has now opened. This is the second stage of the consultation on changes to Part L (conservation of fuel and power) and Part F (ventilation) of the Building Regulations, and relates to existing homes and non-domestic buildings. The consultation proposes uplifted standards for existing homes, as well as non-domestic buildings (discussed in the next section). The main goal is to ensure that work done to existing homes and non-domestic buildings is to a high standard of energy efficiency. The proposal includes significant uplifts to minimum standards of new elements, including walls, floors, roofs, windows and doors which will apply most commonly when building an extension or replacing windows. The consultation also proposes to mandate Self-Regulating Devices (SRDs) when replacing boilers, to prevent overheating. Changes to Part L and Part F are expected to be fully implemented by 2025.

The initial Impact Assessment estimated a total of almost 62,894 GWh of gas saved over 10 years of policy and 60 year life of the building[31] which represents approximately 898 GWh saved a year. Based on England domestic gas consumption of 280,953 GWh in 2019[39] this represents an approximate reduction of 0.3% per year.

The Impact Assessment estimates an incremental cost of £1,384m for existing domestic buildings. For works to existing buildings, costs will be borne by the building owners/occupiers. The Impact Assessment also estimates a total energy saving of £739m, leading to a total financial cost of £645m (albeit the effect of phasing out of high carbon fossil fuels is not incorporated).

Summary – Existing Homes - Reduce Fuel Combustion by Improving Energy Efficiency

Factor	Summary		
Benefits	From 2022 0.3% reduction in domestic gas consumption per year.		
Barriers	Uncertainty over the energy savings which can be achieved. Costs for retrofit. Inconvenience to householders.		
Investment Requirements	R&D and innovation into approaches to improve the energy efficiency of existing homes. Investment by homeowners.		
Policy Requirements	Future Buildings Standards to be implemented in 2025. Interim uplift from 2022.		
Factors Affecting Timescales	Implementation of policy.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	8% uptake by 2030 and maintained thereafter	14% uptake by 2030 and maintained thereafter	19% uptake by 2030 and maintained thereafter
Justification	Uptake rates for cavity/solid wall insulation to reduce emissions of pollutants (up to 8% reduction in $PM_{2.5}$ emissions) from domestic heating taken from MPMD. This covers the combined effect of new homes and energy efficiency improvements for existing homes.		

Non-Domestic Buildings - Reduce Fuel Combustion by Improving Energy Efficiency

Measure Description

Improving energy efficiency standards of non-domestic buildings has the potential to reduce the heating demand and therefore the quantity of fuel used.

Evidence Base and assessment of evidence

The benefit of improving energy efficiency of non-domestic buildings, has been largely discussed and recommended in carbon saving and net zero policy reports. The benefits are related to energy and fuel savings. Reduction in quantity of fuel burned will lead to improvement in air quality. However, there is large uncertainty over the energy and heat savings which can be achieved.

Summary of evidence

As stated in the Government's Energy White Paper[40], there are approximately 1.8 million non-domestic properties in England and Wales. Buildings in the commercial and public sectors account for around a third of the total final energy consumed for buildings purposes (i.e., excluding industrial, agricultural or transport). The Government has committed to all rented non-domestic buildings being EPC Band B by 2030, where cost effective.

The Future Building Standards currently in consultation proposes to:

- Uplift the minimum fabric standards of new non-domestic buildings.
- Uplifts the minimum standards for new and replacement thermal elements in existing non-domestic buildings.

The Impact Assessment[31] published with the Future building standards consultation suggests a large energy saving albeit with an estimated additional gas consumption of 11,184 GWh overall in non-domestic buildings. This is mainly due to more efficient lighting releasing less heat energy and consequently a need for additional heating from the main heating plant.

The Impact Assessment estimates an incremental cost of £3,602m for non-domestic buildings. For new buildings, the initial capital costs will be borne by developers, but these costs may ultimately be passed to landowners. Maintenance and replacement costs will be borne by the building owners/occupiers. For works to existing buildings, costs will be borne by the building owners/occupiers. The Impact Assessment also estimates a total energy saving of £3,124m, leading to a total financial cost of £479m.

Summary – Non-Domestic Buildings - Reduce Fuel Combustion by Improving Energy Efficiency

Factor	Summary		
Benefits	The Future Buildings Standard may not have benefits due to increased gas consumption relating to more efficient lighting.		
Barriers	Uncertainty over the energy savings which can be achieved. Costs.		
Investment Requirements	Industry R&D into new materials and construction approaches. Innovation into approaches to improve the energy efficiency of existing buildings. Operator investment into meeting higher standards.		
Policy Requirements	Future Buildings Standards to be implemented in 2025. Interim uplift from 2022.		
Factors Affecting Timescales	Implementation of policy.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A

Justification	Not enough information to enable quantification

Transformation of Heating Away from Combustion of Fuels

Combustion of fuels in buildings, mainly for heating purpose, accounts for a large proportion of $PM_{2.5}$ emissions. Table 4-1 details the percentage of total UK emissions by fuel and building types as estimated in the NAEI[2].

As the UK has set in law a target to bring its GHG emissions to net zero by 2050, decarbonising the heating sector is a priority. Phasing out fossil fuels heating has been largely discussed and recommended in carbon saving policies. This would also reduce $PM_{2.5}$ emissions. However, some replacement fuels recommended for reducing GHG emissions, such as biomass, will have negative impacts on air quality. The air quality implications of widespread use of other fuels such as hydrogen are not yet fully understood.

As discussed in the workshop, there is unlikely to be a one-size-fits-all solution for all homes. There was consensus that heat pumps have zero $PM_{2.5}$ emissions, however there was agreement that heat pumps are unlikely to me*et all* heating needs and other systems would be required. Ground source heat pumps would be the preferred solution for houses with gardens. Discussions during the workshop highlighted that district heating (and economies of scale) has potential to support the transition away from fossil fuel use.

Table 4-1 NAEI estimated $PM_{2.5}$ emissions (%) in the combustion sector by type of fuel (UK, 2018)

Fuel	Domestic combustion (1A4bi)	Miscellaneous industrial/commercial combustion (1Aai)	Public sector combustion (1Aai)
Anthracite	0.7%	N/a	N/a
Burning oil	0.3%	N/a	0.0%
Coal	6.3%	0.1%	0.2%
Fuel oil	0.0%	0.1%	<0.1%
Gas oil	<0.1%	0.1%	<0.1%
Liquefied Petroleum Gas (LPG)	<0.1%	<0.1%	N/a
Natural gas	2.5%	0.3%	0.2%
Petroleum coke	0.5%	N/A	N/A
Secondary Solid Fuel (SSF)	0.9%	0.0%	N/A
Wood	86.0%	N/a	N/a
Charcoal	1.5%	N/a	N/a
Total %	98.9%	0.6%	0.5%
Total $PM_{2.5}$ emissions (kT)	**46.8 kT**	**0.3 kT**	**0.2 kT**

Homes – Transformation of Heating Away from Combustion of Fuels

Measure Description

Transformation of heating away from fuel combustion, through electrification (mainly heat pumps) and district heat networks.

Evidence Base and assessment of evidence

Transformation of heating away from fossil fuels to low carbon heating has been largely discussed and recommended in carbon saving and net zero policy reports. However, some fuels recommended for reducing GHG emissions, such as biomass, could have negative impacts on air quality. The success of the measure is therefore dependent on a transition to electrification of heating. The air quality implications of widespread use of other fuels such as hydrogen are not yet fully understood.

Summary of evidence

There are estimated to be 1.7 million fossil fuel boilers installed every year in the UK[42]. This highlights the reliance of the current domestic heating market on fossil fuels and emphasises the significant change required to move away from this reliance.

The percentage of $PM_{2.5}$ emissions in the domestic combustion sector are detailed by type of fuel in Table 4-1 using data from the NAEI for 2018. $PM_{2.5}$ emissions from domestic oil and gas combustion account for 3.4% of emissions from the 1A4bi sector. Wood burning accounts for 86.9% of emissions. The remaining 9.6% are from combustion of other solid fuels (coal, anthracite, SSF, charcoal)

The CCC has recommended phasing out the installation of oil boilers in 2028 in residential homes, and phasing out installation of gas boilers in 2033[34]. These phase out dates have been brought earlier with the government committing to set the performance standard of the Future Homes Standard at a level which means that new homes will not be built with fossil fuel heating from 2025[37]. Based on an average 15 years of life of boilers appliances, this ban on new installations from 2025 would lead to the cut of oil and gas domestic combustions emissions from around 2040. Outputs from the UK TIMES model[43] developed by UCL and BEIS for the "core run" (considered to be the best estimate available for the central case for future fuel usage) have been used to determine factors to adjust natural gas combustion emission totals in the Domestic Combustion sector.

The CCC has recommended the installation of 5.5 million heat pumps by 2030 including 2.2 million in new homes. Additionally, the Government has committed in its Ten Point Plan to reach 600,000 heat pumps installations by 2028[44].

The National Grid's Future Energy Scenario (FES)[45] (Consumer Transformation and Leading the Way scenarios) assumes that to help manage peak heat demand, 40% of homes with heat pumps could have thermal storage that supports heating. The storage capacity per home could be between two and four hours of heat demand on a peak winter day in winter. These homes will require much less electricity for heating at peak times, reducing demand on the local and national network. The FES also estimates that energy required for residential heating in a net zero world could be over 50% lower by using high levels of insulation and electric heat pumps (Consumer Transformation scenario). Better insulation would contribute one-third of the reduction, heat pumps uptake would contribute two-thirds.

Summary – Homes – Transformation of Heating Away from Combustion of Fuels

Factor	Summary		
Benefits	Oil and gas ban: ~3% $PM_{2.5}$ emissions in the domestic combustion (1A4bi) sector from natural gas and oil Natural gas and oil combustion in the domestic sector expected to end between 2040 and 2050		
Barriers	Cost for new appliances. Disruption for installation of new appliances, convenience, trust in other types of technology, noise of alternatives (e.g., air pumps) and perceived attractiveness of alternatives. The space required for heat pumps may limit applicability. Gaps in the supply chain for non-fossil fuel systems were mentioned by several stakeholders. Lack of consumer awareness/acceptance around that issue, and that the transition to low carbon heating will require some disruption.		
Investment Requirements	Industry R&D to create innovative systems that can be applied widely. Need for the scaling up of manufacturing and significant increase in the number of trained installers. Distribution network to be more gas tight than for methane and significant upgrade might be needed. Homeowners will bear the costs of new equipment.		
Policy Requirements	Introduction of regulations are needed to give a clear signal to supply chain to invest in retraining installers and increase awareness of low carbon heating technologies. Introduction of regulations to phase out fossil fuel heating in existing buildings off the gas grid i.e. oil/LPG from 2025 (forthcoming BEIS consultation expected Spring 2021). Clarity is required regarding zoning policies and place-based deployment of low carbon heating solutions (~2025).		
Factors Affecting Timescales	Development of the manufacturing base and supply chain. Rates of constructing new homes. Timing of introduction of regulations to phase out fossil fuel heating off the gas grid. Development of technology for hydrogen boilers rather than gas boilers. If gas disappears as a utility, the infrastructure could be used to some extent for hydrogen if it is invested in and improved. Hydrogen is a very small molecule and will leak much more easily than methane which is a key public safety issue. Trigger points relating to the awareness of the existing high carbon system to drive uptake of low carbon solutions.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	Domestic combustion of natural gas: 27% reduction by 2030 58% reduction by 2040 100% reduction by 2050	As for medium	As for medium
Justification	UK TIMES Outputs	UK TIMES Outputs	UK TIMES Outputs

Non-Domestic Buildings – Transformation of Heating Away from Combustion of Fuels

Measure Description

Transformation of heating away from fuel combustion, through electrification (mainly heat pumps) and district heating.

Evidence Base and assessment of evidence

Transformation of heating away from fossil fuels to low carbon heating has been largely discussed and recommended in carbon saving and net zero policy reports. However, some replacement fuels recommended for reducing GHG emissions, such as biomass, could have negative impacts on air quality. The success of the measure is therefore dependent on a transition to electrification of heating. The air quality impacts of other fuels such as hydrogen are not fully understood.

Summary of evidence

The percentage of $PM_{2.5}$ emissions in the non-domestic combustion sector (1Aai) are detailed by type of fuel in Table 4-1 using data from the NAEI for 2018. Overall emissions from the non-domestic combustion sector are minimal (0.5 kT) compared to the domestic sector (46.8 kT). Within the 1Aai sector, oil and gas combustion accounts for 76% of emissions, and the remaining 24% is from coal combustion.

The CCC has recommended to phase out the installation of oil boilers in 2025 in public buildings and 2026 in commercial buildings, and to phase out the installation of gas boilers in 2030 in public buildings, and 2033 in commercial buildings.

Additionally, the Future Building Standards consultation document[31] states that buildings constructed to the Future Buildings Standard will need to use low-carbon heating. The standard is expected to be fully implemented from 2025. Based on an average 15 years of life of boilers appliances, this ban on new installations from 2025 would lead to the cut of oil and gas domestic combustions emissions from 2040.

Summary – Non Domestic Buildings – Transformation of Heating Away from Combustion of Fuels

Factor	Summary
Benefits	Oil and gas ban: 76% reduction of the 1A4ai sector from 2040
Barriers	Cost for new appliances. Disruption for installation of new appliances, convenience, trust in other types of technology, noise of alternatives (e.g., air pumps) and perceived attractiveness of alternatives. Gaps in the supply chain for non-fossil fuel systems were mentioned by several stakeholders. Lack of consumer awareness/acceptance around that issue, and that the transition to low carbon heating will require some disruption.
Investment Requirements	Industry R&D to create innovative systems that can be applied widely. Need for the scaling up of manufacturing and significant increase in the number of trained installers. Distribution network to be more gas tight than for methane and significant upgrade might be needed. Operators will bear the costs of new equipment.
Policy Requirements	Introduction of regulations are needed to give a clear signal to supply chain to invest in retraining installers and increase awareness of low carbon heating technologies. Introduction of regulations to phase out fossil fuel heating in existing buildings off the gas grid i.e. oil/LPG from 2025 (forthcoming BEIS consultation expected Spring 2021). Clarity is required regarding zoning policies and place-based deployment of low carbon heating solutions (~2025).
Factors Affecting Timescales	Development of the manufacturing base and supply chain. Timing of introduction of regulations to phase out fossil fuel heating off the gas grid. Development of technology for hydrogen boilers rather than gas boilers. If gas disappears as a utility, the infrastructure could be used to some extent for hydrogen if it is invested in and improved. Hydrogen is a very small molecule and will leak much more easily than methane. This will be a greater public safety issue with higher hydrogen proportions in the fuel mix. To some extent, implementation may relate to the awareness of the issues with the existing high carbon system, which could drive uptake of low carbon solutions.

Ambition Scenario	Medium	High	Speculative
Input for emissions modelling	70% reduction in emissions from non-domestic combustion by 2040	70% reduction in emissions from of non-domestic combustion by 2035	70% reduction in emissions from of non-domestic combustion by 2030
Justification	Assuming phase out of oil and gas boilers in 2025 and 15 years life of appliances.	Assuming earlier phase out date	Assuming earlier phase out date, whilst also considering the time required for implementation

4.3 Transport

Road Transport

Introduction

As illustrated in Section 2, road transport is estimated to contribute around 12% of total $PM_{2.5}$ emissions in England. Road transport is the largest source of NO_X (35%) and contributes around 2% of NH_3 emissions. As shown in Figure 2-4, emissions from road traffic are a more important contributor (>20%) at the roadside locations where $PM_{2.5}$ concentrations are likely to be highest. Measures to reduce road traffic emissions are therefore likely to play an important role in achieving the proposed $PM_{2.5}$ targets.

Exhaust emissions contribute all of the NO_X emissions and around a third (4% of the national total) of $PM_{2.5}$ emissions. The ongoing replacement of older vehicles with newer models that meet tighter emission standards will have a significant effect on exhaust emissions in future. The newest Euro 6 cars (and policies that encourage their uptake) are delivering significant benefits and improvements in air quality have been observed[46].

This process of reducing tailpipe emissions will be supported by the uptake of electric vehicles with no exhaust emissions. Sales of new standard Internal Combustion Engine (ICE) cars and vans (which do not have the capability of driving a significant distance with zero emissions) will end by 2030. This transition be accounted for in all the scenarios, based on DfT projections of vehicle sales. As exhaust emissions reduce, Non-Exhaust Emissions (NEE) of particulates will become more important as a proportion (increasing from ~8% of $PM_{2.5}$ emissions; 3% from road abrasion and 5% from brake and tyre wear). Measures that can reduce traffic volumes as well as how technology changes will reduce emissions per vehicle need to be considered.

Measures related to road traffic have been considered in two groups: (1) mobility and traffic volume; and (2) technology. Measures that can be employed to reduce emissions across England, or across a particular urban area have been considered in this study. There are additional, highly localised infrastructure changes that can be put in place to address the highest $PM_{2.5}$ concentrations when the targets have been established. This include things like intelligent signalling and traffic lights to smooth traffic flow, road layout and junction changes and bus gates to restrict access to other vehicles at certain times. The benefits and feasibility of such measures are location specific and they are not considered further in this study.

Mobility and Traffic volume

Introduction

Measures that encourage model shift away from private car use, or make freight movements more efficient will affect $PM_{2.5}$ concentrations by reducing the vehicle km (vkm) travelled and associated exhaust emissions and NEE from motorised road vehicles.

The effect of a variety of measures has been considered individually based on the literature reviewed and the stakeholder engagement. For modelling purposes, and to avoid double counting of measures (for example increased home working, and reduced car commuting trips due to workplace travel planning), the effect of the measures on vkm has been aggregated within each scenario (medium, high and speculative).

Localised Active Travel Plans

Measure Description

The government published its vision for cycling and walking in England in 2020 in *Gear Change A bold vision for cycling and walking*[47]. The overarching aim is for half of all journeys in towns and cities being cycled or walked by 2030. Active travel is supported by introducing new infrastructure such as safe routes for walking and cycling as well as secure and weather-proof spaces for parking bikes, scooters, etc. The increasing proliferation of E-bikes (potentially for longer journeys than those that can be walked or cycled) will help the transition away from private car use.

Evidence Base and assessment of evidence

There are many policy papers considering the effect of active travel plans on vkm travelled. Some of these focus on reductions in carbon emissions in relation to the decarbonisation agenda. Whilst there are numerous factors that can affect modal shifts achieved, such as the purpose and length of journeys in a particular area, and the demographic makeup of the population, the results from case studies and modelling of the impacts of modal shift to walking and cycling on vkm are fairly consistent.

Summary of evidence

The evidence suggests that local cycling and walking strategies can deliver significant modal shifts at the local scale. This is reflected in the England target in *Gear Change A bold vision for cycling and walking* of 50% of all journeys in towns and cities being cycled or walked by 2030[47]. The literature reviewed and interviews carried out suggested that the effect on vkm is inherently lower as only the shortest car journeys can be replaced by walking and cycling. Transport for Quality of Life report 2.3% reduction in per capita traffic volumes as a result of Sustainable Transport Fund measures[48]. In a study from New Zealand, Chapman *et al* reported that active travel measures resulted in a 1.2% reduction of total motorised vkm[49]. Other studies have considered the theoretical reductions in traffic that could be achieved, on the basis of trip length and purpose (and therefore the potential for changing to cycling and walking). The TRL report *Healthy mobility and road safety* suggests that total vkm could be reduced by 0.94% through the mode change of the 0-8km trips that could be walked/cycled[50].

Other studies consider carbon emissions, which can be considered to be broadly proportional to vkm. The Royal Town Planning Institute (RTPI) 2021 report on *Net Zero Carbon Transport: The role of spatial planning and place-based solutions*[51] suggests that around 1-4% of road transport carbon emissions could be saved through active travel measures. The 2020 Institute of Health Equity (2020) report on Sustainable Health Equity: Achieving A Net-Zero UK[52] reports that if the proportion of the English population who cycle regularly for short journeys increased from 4.8% (the rate before the COVID-19 lockdown) to 25%, there would be a 2.2% reduction in passenger-related CO_2 emissions. In summary, the evidence suggests that car vkm could be reduced by around 1-5% through active travel plans. Attendees at the workshop showed general agreement with these numbers but felt that the lower end of this scale was unambitious.

The evidence suggests that investment in walking and cycling infrastructure represents very high value for money in terms of the benefits that can be achieved in terms of public health, both through increased activity and reduced emissions[48]. Local authorities are required to develop Local Cycling and Walking Infrastructure Plans (LCWIPs) in order for them to receive infrastructure funding.

The government in 2020 announced £2 billion of new investment in walking and cycling over the period 2021-2025 in addition to existing funding alongside significantly improved capacity and assistance for local authorities. Stakeholders at the workshop also pointed out that investment is required in local facilities/destinations and mixed-use planning to achieve '15 minute' neighbourhoods which will encourage active travel. The workshop also highlighted that policies that discourage car use (such as a reduced number of parking spaces) are also required to maximise the benefits that this measure could deliver.

The measures can be implemented locally over relatively short timescales, as demonstrated by the emergency infrastructure changes implemented in relation to the COVID-19 lockdown[53]. Strategic planning will take longer, as reflected in the Department for Transport (DfT) goal of 50% of trips in towns and cities being by active travel by 2030. Discussions during the workshop suggested that generational changes in travel choices will also determine the effects (e.g., the number of young people taking driving tests is reducing).

Summary – Localised Active Travel

Factor	Summary		
Benefits	1-5% reduction in private car vkm on urban roads On the basis of short trips by car that could be carried out by walking/cycling Co-benefits include reduced carbon emissions and better places and improved public realm		
Barriers	Entrenched behaviours. Apprehension of individuals about walking and cycling Infrastructure to enable people to feel safe Cycling specific barriers (affordability of bikes and equipment, lack of feasibility for a portion of the population, weather conditions and perceptions on safety) Drivers (private and commercial) do not like to see road space reduced Lack of trip chaining and mixed-use planning to enable active travel		
Investment Requirements	Infrastructure (cycle lanes etc.) Engagement Local facilities/destinations and mixed-use planning to achieve '15 minute' neighbourhoods		
Policy Requirements	Policy support for modal shift Policies to discourage car use		
Factors Affecting Timescales	Can be introduced rapidly (see COVID-19 lockdown) Wide scale roll-out could be achieved in urban areas in ~5-10 years		
Ambition Scenario	**Medium**	**High**	**Speculative**
Initial input for emissions modelling (See aggregated effect on traffic volumes below)	5% reduction in car vkm on urban roads by 2030	N/A	N/A
Justification	Typical value that can be achieved by active travel strategy alone	Regional transport strategies represent higher ambition in terms of car vkm reductions	Planning policies to reduce traffic represent highest ambition in terms of car vkm reductions

Regional Transport Strategies

Measure Description

Transport strategies implemented across an urban area or region typically include active travel measures alongside the public transport network. Implementing cohesive plans therefore have the potential to achieve greater reduction in vkm than active travel plans alone. Shorter private car trips can be replaced by walking and cycling, whilst longer journeys can be undertaken by public transport.

Evidence Base and assessment of evidence

Reductions in traffic flow have been quantified using monitoring of transport plans that have been implemented, and through modelling of the likely impact of these plans. Whilst the reductions in vkm that can be achieved through such plans are dependent on factors such as the land use of the area, the degree of public transport provision that is included, and the road space reallocated to walking, cycling and public transport, there is a degree of consistency in the results.

Summary of evidence

The Oxford Integrated Transport Strategy has reportedly achieved an average reduction at monitoring points of 17% between the year before and the year after (2000) implementation[54]. The Greater Manchester Transport Strategy 2040, part of the Greater Manchester Spatial Framework (GMSF) has an aim that 50% of all journeys in Greater Manchester to be made by public transport, walking and cycling by 2040, resulting in 18.5% fewer car trips than would be the case under the current mode shares[55]. A modelling study in France suggests that modal shift to walking, cycling and public transport could achieve a reduction in car vkm of around 10% (without significantly altering activity patterns and travel time)[56]. The RTPI 2021 report cited earlier[51] suggests that around 5-17% of transport carbon emissions could be saved through combined active travel and public transport measures, with the variation due to the land use and type of area. Several stakeholders in the workshop highlighted how benefits can be enhanced by integrated services and modes as part of a wider Mobility as a Service (MaaS) offering.

The challenges associated with changing behaviours were highlighted in the workshop as a key factor determining the effect of this measure. The need for measures that discourage private car use (e.g. parking restrictions) as well as provision of new transport options is required to deliver significant reductions in vkm.

Wide ranging transport strategies require significant investment. The Greater Manchester Transport Strategy Delivery Strategy forecasts total costs of £493m cycling and walking investment programme alone[57]. The Birmingham Financial Plan[58] forecasts over £217,000,000 of spending on transport and highways over four years in relation to the Birmingham Transport Plan.

The targets for the Greater Manchester Transport Strategy are for 2040, providing an indication of the timescales for delivery of such strategies. There was consensus during the workshop that it will take a long time to change travel patterns, particularly in places where car usage dominates.

Summary – Regional Transport Strategies

Factor	Summary
Benefits	10-25% reduction in private car vkm on urban roads On the basis of short trips that could be carried out by walking/cycling and longer trips that can be undertaken on public transport Co-benefits include reduced carbon emissions and better places and improved public realm
Barriers	Apprehension of individuals about walking and cycling Infrastructure to enable people to feel safe Drivers (private and commercial) do not like to see road space reduced Need for significant investment in public transport COVID-19 concerns about public transport
Investment Requirements	Infrastructure (cycle lanes, etc.) Engagement Public transport
Policy Requirements	Policy support for modal shift Policy support for reductions in private car use, and reduced congestion Public transport subsidy
Factors Affecting Timescales	Integrated planning required Public transport procurement process Delivery of comprehensive strategies can take 10-20 years

Factor	Summary		
Ambition Scenario	**Medium**	**High**	**Speculative**
Initial input for emissions modelling (See aggregated effect on traffic volumes below)	N/A	15% reduction in car vkm by 2040 on roads in urban areas	N/A
Justification	See active travel summary	Typical value that can be achieved by regional transport strategies	Planning policies to reduce traffic represent highest ambition in terms of car vkm reductions

Land Use Planning

Measure Description

Urban form is a key factor in determining the number of trips taken by private car (as opposed to walking and cycling or public transport) and the distance of those trips. Both factors combine to determine the vkm travelled by car in a particular area. Density of development, land use mix, connectivity, and accessibility are interrelated and interdependent factors that need to be considered together in order to reduce vkm and therefore emissions. Co-locating residential areas with employment opportunities and encouraging higher densities and land-use mixes all enable more trips to be undertaken by walking and cycling and reduce car use. This can be supported by measures to reduce car ownership, such as provision of fewer parking spaces. This is the essence of the 15-minute city concept that is being implemented around the world[59]. The National Planning Policy Framework[60] states that planning policies and decisions should support development that makes efficient use of land, including the promotion sustainable travel modes that limit future car use.

Evidence Base and Assessment of Evidence

Several studies are available considering how the built environment can be used to reduce vkm. Several of these focus on reductions in carbon emissions but are relevant for this study where they relate to reductions in distance travelled. The Intergovernmental Panel on Climate Change (IPCC) study Human Settlements, Infrastructure, and Spatial Planning[61] reviewed the interrelationship between urban form and vehicle distance travelled and concluded that there was a medium level of evidence and a high level of agreement between sources. Comprehensive reviews of these interactions are also available from the Royal Town Planning Institute (RTPI)[62], Canadian Victoria Transport Policy Institute (VTPI)[63] and the US National Research Council[64].

Summary of Evidence

There is consistent evidence that co-locating residential areas with employment and other land uses, and increasing the density of development supports active travel and reduces private car use. The IPCC study cites several sources showing that vkm can be reduced by around 25% with increased density and mix of land uses. The VTPI report that mixed-use areas typically have 5-15% less vehicle travel. The US National Research Council study reports reductions in vkm of 5-25% as a result of a variety of built environment features. The University of Leeds Institute of Transport Studies Distillate project reported that neighbourhood design factors (density, mix and design) can reduce per capita vehicle travel on the order of 10-20%, while regional accessibility factors (i.e., where a neighbourhood is located with respect to the urban centre) can reduce car travel by 20-40%[65]. A specific study for the North East of England reports that respondents from traditional mixed land-use neighbourhoods drove 36% less miles than those in suburban neighbourhoods[66].

Relatively minimal investment is required to develop new planning policies to enable development that encourages reduced car use. The need for national and local policies to reduce car used (e.g., reductions in parking provision) was raised by several stakeholders at the workshop. During the workshop, the role of Active Travel England was discussed. Funding will be required for this body, which will act as a statutory consultee for some developments and be able to encourage active travel.

The timescales over which benefits are likely to be realised are significant, however. The RTPI[51] reports that average trip lengths have recently stabilised, and the modal shift towards private vehicles has also started to decline, in part due to a more integrated approach transport and land use planning policy in the early 2000s. This provides an indication of the timescales over which planning changes can have effects. Stakeholders at the workshop agreed that planning policy changes will not deliver immediate benefits and it will take a long time to change current travel patterns.

When considering costs, relevant information is available from details of government spending. The Ministry of Housing, Communities and Local Government (MHCLG) has been allocated £12 million to take forward the radical planning reform agenda[67].

Summary – Land Use Planning

Factor	Summary		
Benefits	7-50% reduction in private car/ LGV vkm on urban roads On the basis of shortening trip length to make walking/cycling and use of public transport a viable option Co-benefits for other emissions (NO_X and carbon) plus public health, equality, reduced congestion, retail and better places		
Barriers	Resistance to change of the current "speculative housing model" Resistance to changes aimed at reducing car use Local authority resources to develop new planning policies Poor policy integration (local/national, net zero etc.) Generally speaking, only applies to new development, and difficult to make similar changes to existing areas		
Investment Requirements	Investment in the development of new planning policies Relatively minimal government investment required		
Policy Requirements	Reduced car ownership and car travel as national policy goals Local planning policies		
Factors Affecting Timescales	Benefits likely in 10-20 years (informed by local plan timescales) Planning policy in the early 2000s took 10-20 years to stabilise trip lengths and reduce modal shift towards private cars		
Ambition Scenario	**Medium**	**High**	**Speculative**
Initial input for emissions modelling (See aggregated effect on traffic volumes below)	N/A	N/A	25% reduction in car vkm by 2040 on urban roads
Justification	See active travel summary	See regional transport plans summary	Typical value that can be achieved through planning policies (mix and diversity)

School and Workplace Travel Planning

Measure Description

Modeshift STARS defines a travel plan as "*a package of measures that aims to reduce car use to and from any given site*"[68]. Travel plans can be applied in educational and workplace settings. Travel plans typically include measures such as encouraging ride sharing and supporting active travel by measures such as new walking and cycling routes, Cycle to Work vouchers, provision of facilities for cycle parking and showering.

Evidence Base and assessment of evidence

There are case studies available documenting the reductions in single occupancy car trips that have been achieved through the development of travel plans. The reductions in traffic that can be achieved depend on the specific site situation, funding and measures available, but there is a degree of consistency in the traffic reductions that can be achieved.

Summary of Evidence

The DfT National Travel Survey: England 2019[69] show that around 25% of car and van driver miles per year are for commuting (Table NTS0409), with 11% for business travel and 3% for education / escort education.

Several reviews of travel planning are available. In a review of the effectiveness of workplace travel plans, Transport for Quality of Life reports that travel plans with parking management will typically achieve reductions in the order of 20-25%[70]. The European Commission report *Quantifying the Effects of Sustainable Urban Mobility Plans*[71] provides many examples of travel plans. Examples include a 10% reduction in car use by employees at a site in Toulouse and a shift of individual car use from employees at Heathrow Airport from 72% to 17%. Further examples have been obtained for Plymouth (15% decrease in the number of people using the car and driving as a sole occupant to get to work[72]) and the Isle of Wight (7.5% reduction in car mode share[73]). With regards to education specific travel plans, Modeshift STARS reports an average reduction in car traffic for silver and gold accredited schools (those which have established a working group and delivered 20 Sustainable Travel Initiatives, ten Supporting Initiatives, and seven Consultation Initiatives) of 22%. As highlighted in the workshop, the level of benefit that this measure can achieve will depend on the level of public transport provision in any particular area.

The case studies reviewed showed that travel plans can be introduced and deliver significant results within a couple of years. Travel plans typically cost in the range of £5,000-£50,000 per business, depending on the measures included and the size of the business and the number of employees. Travel planning can be supported by grant funding and implementation support from local authorities. Stakeholders emphasised this support as a key factor to determine the success of such measures. The need to integrate travel planning into the wider transport planning for new developments was also highlighted in the workshop.

Summary – Travel Plans

Factor	Summary
Benefits	7.5-22% reduction in private car school escort/work vkm Dependent on the site and availability of public transport options Can also reduce peak time congestion and idling outside schools
Barriers	Apprehension of individuals about walking and cycling Infrastructure to enable people to feel safe Lack of public transport options COVID-19 concerns about public transport
Investment Requirements	Engagement Facilities to support active travel Public transport options Local authority support/coordination Subsidies to support public transport
Policy Requirements	Policy support for modal shift and reduced congestion

Factor	Summary		
Factors Affecting Timescales	Can be introduced rapidly Benefits can be demonstrated within one or two years		
Ambition Scenario	**Medium**	**High**	**Speculative**
Initial input for emissions modelling (See aggregated effect on traffic volumes below)	7.5% reduction in school/work vkm by 2025. 2% reduction in total car km	15% reduction in school/work vkm by 2025. 4% reduction in total car km	20% reduction in school/work vkm by 2025. 6% reduction in total car km
Justification	Based on ~20% of car distance being commuting/school escort, and the range of improvements travel planning can deliver		

Changes to Work Patterns

Measure description

The mode per purpose statistical dataset produced by the DfT[74] shows that, in England in 2019, 25% of miles travelled in cars/vans were for commuting, with a further 11% on business travel. Although these values vary in different parts of England, and even in different areas of towns and cities, improvements in connectivity and changes in the ways that people work have significant potential to reduce overall vkm. People now have the possibility of working from home and business meetings can be carried out over video calls rather than face to face. Both of these trends increased dramatically as a result of the COVID-19 pandemic. Continued support for these practices could reduce vkm in the long term. The DfT report that there is already a downward trend in the number of commuting trips from 7.1 journeys per worker per week in 1988/92 to 5.7 in 2013/14[75].

Evidence Base and Assessment of Evidence

No studies quantifying the reductions in vkm that could be achieved through such changes to work practices have been found. Reducing the need to travel by car is a specific policy recommendation of several organisations. Several organisations have provided evidence of the public desire to continue working from home, at least several days of the week, particularly in relation to capitalising on the behavioural changes and reduced air pollution in the initial COVID-19 lockdown. Studies into preferred working patterns can be used in conjunction with travel statistics to consider how vkm could change under long term changes in work patterns.

Summary of Evidence

Organisations recommending changes to work patterns to reduce car traffic include the Institute of Health Equity and the Local Government Association. In *Sustainable Health Equity: Achieving A Net-Zero UK*, the Institute of Health Equity recommends encouraging continued remote working and virtual conferencing to reduce the need to travel by car[76]. In *Decarbonising transport, travelling less and the role of online opportunities*[77], the Local Government Association states that as social distancing restrictions persist for office work, there is currently great scope to reduce commuting and business travel for an extended period, and for much of this to remain in the long-term. This report also states that business travel has great potential for substitution by online communication, and refers to case studies showing that shifting towards the use of shared fleet vehicles, for work-based journeys reduces the business miles driven and encourages staff to evaluate the need for a journey to be made at all. Global Action Plan reports that almost one in five commuting journeys by car could be avoided if employees continue to work remotely following lockdown[78]. One study obtained indicates that teleworking in Switzerland could have reduced traffic by 2-3%, reducing PM_{10} concentrations by around 3%, and concluded that teleworking has important beneficial effects for society[79]. Several stakeholders at the workshop pointed out that it will be challenging to quantify benefits as increased home working may lower commuting travel demand but may increase demand for deliveries, leisure trips and building emissions. Another confounding factor is that commuting traffic may increase following lockdown if there is reduced confidence in the safety of the public transport system.

The COVID-19 pandemic has shown that work patterns can be changed very quickly. The cost of these changes is minimal as most people that are able to work from home already have the facilities and connectivity to do so.

Summary – Changes to Work Patterns

Factor	Summary		
Benefits	20% reduction in commuting car vkm 50% reduction in business travel car vkm Potentially reduced benefits if coupled with greater home delivery		
Barriers	Resistance to changing ways of working Desire for social interaction with colleagues Connectivity issues in some areas		
Investment Requirements	Connectivity investment		
Policy Requirements	Companies and government policies to support flexible working		
Factors Affecting Timescales	Can be achieved immediately (as demonstrated by COVID-19 lockdown)		
Ambition Scenario	**Medium**	**High**	**Speculative**
Initial input for emissions modelling (See aggregated effect on traffic volumes below)	5% / 15% reduction in commuting / business travel distance by 2022. 3% reduction in car vkm	10% / 25% reduction by 2022. 5% reduction in car vkm	20% / 50% reduction by 2022. 10% reduction in car vkm
Justification	Based on ~20% of car distance being commuting, and a range of reductions in commuting and business travel that have been forecast		

Shared Mobility

Measure Description

In recent years technology has developed with smartphones now sufficiently prevalent across the population for the shared mobility market to become viable. More intensive use of fewer vehicles offers cost-effective options to reduce overall vehicle distance travelled and emissions. Options include carpooling (space sharing among a group of friends), carsharing (time sharing), ride sharing and on-demand minibus services[80]. This can be offered as part of a wider MaaS offering.

Evidence Base and Assessment of Evidence

There is only limited evidence of the reductions in car distance travelled that has been achieved through shared mobility options. This is to a certain extent because of the novelty and relatively low market uptake of the services. A review of the evidence by Imperial College London[81] reports that car sharing schemes are becoming increasingly popular and have been shown to reduce overall distance travelled by car but concludes that evidence for the impact of ride sourcing and ride sharing on travel behaviour is very limited. Another review has been published by the Commission on Travel Demand[82]. The effect of shared mobility schemes is also considered through modelling of future traffic scenarios.

Summary of Evidence

The review by Imperial College London reports that car sharing schemes have reduced overall distance travelled by car (reduction of 6–16%). As discussed in the workshop, this is partly due to reduced car ownership (studies show that when people use a car club instead of having their own vehicle they tend to reduce the overall distance they drive). Modelling for the DfT Road Traffic Forecasts 2018[83] predicts traffic flow being 22% lower in 2050 under a "Ride Sharing" scenario, where ridesharing becomes a common form of travel and thus car occupancy rates increase, than the reference scenario. The International Transport Forum[80] reports a reduction in vkm of 17-23% under shared mobility scenarios.

The barriers to a shared mobility future largely relate to personal preferences. Many people struggle with the idea of giving up their cars or sharing vehicles[82]. There are also significant concerns around the safety of ride sharing[84]. Another factor that may reduce the potential for shared mobility is the lower motoring costs due to electrification[82]. These issues, and the added complexity of travel, were discussed in the workshop. The timescales for benefits to be seen therefore relate to a change in the way that people expect to move around. This is therefore considered to occur over 10-20 years. Conversely, several case studies for particular sites and areas were discussed in the workshop. Where operators have control over roads and transport patterns, localised shared mobility schemes can be planned and implemented within a few years.

Summary – Shared Mobility

Factor	Summary		
Benefits	Car vkm reductions of 15-25%		
Barriers	Resistance to changing ways of car use COVID-19 related apprehension about sharing rides Desire for car ownership		
Investment Requirements	Engagement and awareness raising Car club infrastructure Potentially investment into systems to integrate shared mobility into a wider MaaS offering		
Policy Requirements	Needs to work alongside planning policies that reduce car ownership		
Factors Affecting Timescales	Likely to occur over 10-20 years due to cultural change required		
Ambition Scenario	**Medium**	**High**	**Speculative**
Initial input for emissions modelling (See aggregated effect on traffic volumes below)	N/A	N/A	20% reduction in car vkm by 2050
Justification	Considered to be a speculative scenario considering the significant change in culture required. % based on DfT Road Traffic Forecasts		

Financial Mechanisms

Measure Description

Measures to encourage modal shift towards walking, cycling and public transport can be supported by measures that levy a fee to discourage car use (as opposed to other schemes that aim to improve the emission standards of vehicles entering a particular area). The fees can be in the form of charges to enter a particular area, or an approach using the available smartphone technology could be used to implement a distance-based variable charge scheme so that drivers that visit a designated area of poor air quality, or a congested area at rush hour would pay more than travelling at other times of day. The scheme could be implemented as part of a wider MaaS offering.

Evidence Base and Assessment of Evidence

There are relatively few examples of charging schemes in the UK to consider the effect of charging on vkm, however the schemes in London provide good examples. Other schemes around the world also add to the evidence base. Traffic modelling considering the sensitivity to economic scenarios also provides information on the effect of costs on driving behaviour. Clearly, the reductions in car use as a result of charging depend on the mechanism employed, but the evidence is relatively consistent in terms of the reductions in vkm that can be achieved.

Summary of Evidence

Examples of the effect of charging on traffic volumes are available from the schemes implemented in London. The GLA reports that the Central London Congestion Charging zone western extension reduced traffic within the zone by around 14% (with an increase of up to 4% on the boundary route)[85] and that charges in relation to the Ultra Low Emission Zone (ULEZ) reduced vkm by 5%[86]. Modelling carried out for the Mayor's Transport Strategy[87] for *Package F: Longer term changes to the way road use is paid for*, including an indicative distance-based charge, predicted that this measures would reduce London morning peak hour vkm by 6% by 2041. The Centre for London[88] carried out a review of schemes around the world and showed that they have reduced traffic volumes by 22-24%. Modelling carried out for the scheme recommended by the Centre for London indicates that it could reduce overall demand by around 10-15%.

The effect of travel costs on traffic volumes is routinely considered for traffic growth forecasts and taxation strategies. This provides information on how traffic volumes could be expected to respond to increased costs. The DfT Road Traffic Forecasts[83] show a difference of 7% in overall traffic in 2050 between the reference and Low GDP, High Fuel scenario, demonstrating how higher costs could potentially affect traffic volumes. Similarly, Transport & Environment[89] suggest that an increase on petrol, diesel and natural gas fuel taxes to increase the final price of the fuel by 10%, would decrease demand (passenger activity) by 3-5%. Stakeholders at the workshop agreed that measures such as the London ULEZ/ Congestion charge have led to significant improvements in air quality by encouraging fleet upgrades. Schemes provide local authorities/transport authorities with revenue which can then be ring-fenced and reinvested in active travel and public transport.

As an indicator of investment required, costs of around £162 million were incurred in implementing congestion charging in London[90]. Annual revenue was £210 million after the increase of the charge to £8.

Stakeholders at the workshop considered that road user charging can only work if well-coordinated. There could be confusion if multiple schemes in different locations are not managed in a coordinated manner. The timing for benefits will depend on the policy decisions that are taken. Several stakeholders consider that some form of road pricing will be required in future as fuel duty incomes decrease when electric cars become more prevalent in the national fleet. As noted in Parliament, if the Government meets the CCC recommendation of near-zero emissions from transport by 2050, then fuel duty receipts (£27.5 billion (1.4 per cent of GDP) in 2017-18) would tend towards zero on current policy settings[91].

Summary - Financial Mechanisms

Factor	Summary
Benefits	5-24% reduction in all vkm in urban areas where these is no current charging Can be used to renew the fleet on the road Mechanism that could replace lost revenue from fuel duty resulting from move to EVs
Barriers	Resistance to new charges Resistance to charges that add costs to use of electric vehicles Lack of alternative modes of transport in some places Potential displacement of traffic to boundary locations Need to consider social equality
Investment Requirements	Infrastructure requirements (Apps, control systems etc.) MaaS

Factor	Summary		
Policy Requirements	National (or local) policy support Measures to reduce car usage (e.g., end freeze on fuel duty)		
Factors Affecting Timescales	Although the technology does exist, this is likely to be a longer-term measure Could take 5-10 years to get approval and establish system		
Ambition Scenario	**Medium**	**High**	**Speculative**
Initial input for emissions modelling (See aggregated effect on traffic volumes below)	N/A	5% reduction in all vkm in urban areas by 2030	15% reduction in all vkm in urban areas by 2030
Justification	Considered to be a high/speculative scenario	Lower end of the range of vkm reduction that could be achieved through charging mechanisms	More optimistic reduction that could be achieved through charging mechanisms

Aggregated Measures Affecting Car VKM

As the measures detailed above affect the same journey choices and options (e.g. travelling to workplaces), they have been considered in combination to develop assumptions to be applied in the medium, high and speculative scenarios. The assumptions per measure are brought together in the table below and the final assumptions in reduction in distance travelled relative to the future baseline are provided.

Summary - Aggregated Measures Affecting Car VKM

Measure	Medium	High	Speculative
Localised Active Travel	5% reduction in car vkm on urban roads by 2030	N/A	N/A
Regional Transport Planning	N/A	15% reduction in car vkm by 2040 on roads in urban areas	N/A
Land Use Planning	N/A	N/A	25% reduction in car vkm by 2040 on urban roads
Travel Planning	7.5% reduction in school/work vkm by 2025. 2% reduction in total car km (based on annual average as changes in peak hour traffic flows cannot be discretely accounted for in modelling)	15% reduction in school/work vkm by 2025. 4% reduction in total car km	20% reduction in school/work vkm by 2025. 6% reduction in total car km
Changes to Work Patterns	5% / 15% reduction in commuting / business travel distance by 2022. 3% reduction in car vkm	10% / 25% reduction by 2022. 5% reduction in car vkm	20% / 50% reduction by 2022. 10% reduction in car vkm
Shared Mobility	N/A	N/A	20% reduction in car vkm by 2050
Financial Mechanisms	N/A	5% reduction in all vkm in urban areas by 2030	15% reduction in all vkm in urban areas by 2030

Measure	Medium	High	Speculative
Combined Total Reduction in Urban Car vkm	10%	29%	76%
Total Reduction in Urban Car vkm - Input for Emissions Modelling	5% by 2025 10% by 2030, 2040 and 2050	10% by 2025 15% by 2030 30% by 2040 and 2050	15% by 2025 25% by 2030 50% by 2040 60% by 2050

Freight Consolidation and Urban HGV Restrictions

Measure Description

The consolidation of freight in consolidation centres enables vehicle load factors to be increased, reducing vkm, and management of freight vehicles in towns and cities. Consolidation centres can be operated by single landlords (e.g., shopping centres, hospitals, airports), and can also be multi-operator (e.g., serving all or part of an urban area or a particular major construction project).

Consolidation centres vary in size depending on the area and number of facilities or businesses served but are typically warehouse/outside spaces with thousands of square metres of space and good links to the Strategic Road Network (SRN). Consolidation of freight offers the opportunity of making final deliveries by zero emission modes. These measures can be coupled with measures to reduce HGV trips in congested areas with high air pollution.

Evidence Base and Assessment of Evidence

There are several documented examples of freight consolidation centres reducing vkm in urban areas. The evidence is fairly consistent in terms of the extent to which trips can be reduced.

Summary of Evidence

The London Environment Strategy[92] reports a 77% reduction in vehicle movements in the area of a consolidation centre. The TfL Freight and Servicing Action Plan[93] provides case studies of consolidation centres cutting total vehicle movements by 30-40%. A report into a Central London trial reports a reduction in kilometres per parcel (km/parcel) of 52%. A Review of Urban Consolidation Centres[94] shows that they can reduce freight vkm in urban areas by 60-80%. A study into freight consolidation at Southampton University Hospital[95] showed that the redirecting of goods vehicles from the hospital to the warehouse would result in a slight decrease in overall traffic flows around the Hospital vicinity in the morning hours, and an increase at the warehouse vicinity. The National Infrastructure Commission reports that multi-operator freight consolidation centres have been proven to help reduce total distance travelled, improve vehicle utilisation, and allow for loads to be transported by cleaner vehicles for the last mile[96]. Stakeholders in the workshop agreed that benefits of such schemes are well established, but some stakeholders highlighted the need to ensure that any increases in HGV volumes, particularly in urban areas, are well managed

Benefits could be increased through better use of data. *Decarbonising Road Freight*[97] states that improvements in backhaul and loading factors could be achieved if data and journey information were pooled across multiple organisational boundaries.

Freight consolidation centres require significant investment as land is required for their creation and they need to be planned and built. Benefits are also maximised through collaboration between operators, which can be a challenge. For the schemes to be successful, agreement is required from all parties. End customers need to agree to route deliveries to a consolidation centre and shippers need to accept that deliveries will not be made to the final destination. As freight consolidation adds an additional leg to the journey, how this is managed will play an important role in determining the overall impacts. Further barriers identified in the Transport Systems Catapult report[95] include the potential need for public sector subsidies to cover the added leg of the journey, a lack of adequate transport infrastructure and insufficient volumes to make consolidation centres successful.

Consolidation can potentially work alongside restrictions for HGVs. A scheme in Barcelona restricted HGVs on particular roads by 97%[98]. Conversely, one issue discussed in the workshop was that HGVs may have lower emissions per kg of freight transported than LGVs. There is also a need to avoid proliferation of movements of LGVs with ICEs, so it is important that measures are put in place to control this, and that electric and zero emission LGVs are prioritised.

Summary - Freight Consolidation and urban HGV restrictions

Factor	Summary		
Benefits	40-96% Reduction in HGV vkm in urban areas Co-benefits of reduced emissions (NO_X, carbon) and more attractive urban spaces		
Barriers	Resistance to changing ways patterns of work Lack of facilities to consolidate freight Transport network infrastructure deficiencies in some locations Insufficient volumes to make consolidation viable Lack of cooperation between businesses Continued increases in LGVs		
Investment Requirements	Freight consolidation centres Awareness raising/cooperation between businesses Potentially subsidies for last leg		
Policy Requirements	National policy support for freight consolidation Local policies required to restrict HGV access		
Factors Affecting Timescales	HGV restrictions can be brought in relatively quickly ~two years Freight consolidation needs 5-10 years due to infrastructure requirements		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	25% reduction in HGV vkm in urban areas by 2030.	50% reduction in HGV vkm in urban areas by 2030.
Justification	Considered to be a high/speculative scenario	Based on studies into freight consolidation - Moderate level of HGV reduction	Based on studies into freight consolidation - High level of HGV reduction

Zero Emissions Last Mile Deliveries

Measure Description

When loads are better planned and organised through consolidation (as discussed above), further reductions in emissions can be achieved by making deliveries through zero emission modes. This could be using electric vans, or other vehicle types such as cargo bikes. Delivery emissions can also be avoided using local collect and drop points that people are able to walk to from home.

Evidence Base and Assessment of Evidence

There are numerous examples of the benefits of zero emission last mile schemes. Whilst benefits will depend on factors such as the degree of consolidation and the journeys required, the evidence is fairly consistent regarding the reductions in the distance travelled by vehicles with ICEs that can be achieved.

Summary of Evidence

The TfL Freight and Servicing Action Plan[93] reports on studies that show reduction in conventional LGV movements of 14-20%. A report for the Local Government Association[99] suggests that Cargo bikes can replace up to 10% of conventional vans in areas where the last mile delivery is no more than 2 km (without changing network efficiency). The same report suggests that drop and collect points could reduce emissions by 26-40%. The European Commission report *Quantifying the Effects of Sustainable Urban Mobility Plans*[71] provides further examples of emission-free delivery service. Several stakeholders in the workshop mentioned improvements in the urban environment due to reduced ICE delivery vehicles.

Some of the barriers to the use of zero emission vehicles for last mile deliveries are similar to those for freight consolidation. For the schemes to be successful, agreement is required from all parties. Users of such services may need to be prepared to pay a premium for such delivery services. Another issue with such schemes is the volumes and loads that can be transported. As with freight consolidation, some stakeholders highlighted the need to ensure that any increases in HGV volumes for journeys to a consolidation centre, particularly in urban areas, are well managed. Numerous small vehicles could create congestion, which could increase overall emissions. The need to consider LGV movements in view of increased home working and associated deliveries was also discussed in the workshop. Another barrier highlighted with regards to the widescale use of electric vehicles is that that there may be significant investment requirements for electric charging infrastructure.

Zero-emission last mile delivery services already exist on a successful commercial basis. Schemes can therefore be implemented in the short term. However, the infrastructure requirements (e.g. charging and consolidation/distribution centres) were also highlighted in the workshop as something that would govern the timescales for widescale implementation.

Summary - Zero Emission Last Mile Deliveries

Factor	Summary		
Benefits	10-30% reduction in LGV vkm in urban areas		
Barriers	Resistance to changing ways patterns of work Resistance to moving away from home delivery (collect and drop points) Lack of charging infrastructure		
Investment Requirements	Awareness raising/cooperation between businesses Potentially charging facilities for electric vehicles Consolidation/distribution centres		
Policy Requirements	National policies to reduce LGV movements Local policies required to reduce LGV movements Policies to restrict the proliferation of ICE delivery vehicles		
Factors Affecting Timescales	Can be implemented quickly ~2 years		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	5% reduction in LGV vkm in urban areas by 2035	10% reduction in LGV vkm in urban areas by 2030	15% reduction in LGV vkm in urban areas by 2025
Justification	Slow uptake and low benefit	Medium uptake and benefit	Fast uptake and high benefit

Rail Freight

Measure Description

Using the rail network to transport freight offers the potential to reduce HDV vkm on the road network, and particularly on the Strategic Road Network. The Rail Delivery Group reports[100] that one freight train can remove up to 76 HGVs from the road.

Evidence Base and Assessment of Evidence

The benefits of this measure in reducing vkm are discussed in the MDS Transmodal report in *Rail freight forecasts: Scenarios for 2033/34 & 2043/44*[101] produced for Network Rail.

Summary of Evidence

Comparison of rail freight tonne kms and the rail share tonne kms under the scenarios with "Factors which favour rail relative to road" and the scenarios with "Factors which disfavour rail relative to road" enables quantification to tonne kms (assumed to be proportional to vkms) that could be removed from the road. The report shows that the proportion of freight transported by rail could be increased from 11% in 2016/17 to 14-15% in 2023/24, 17% in 2033/34 and 20-21% in 2043/44 under favourable conditions. In all assessment years the reduction in road tonne kms is around 5-10%.

Investment in infrastructure will be required to facilitate shifts to rail transport. However, the modelling by MDS Transmodal does not account for planned infrastructure upgrades that could potentially reduce operational costs along certain routes. The forecasts (and selection of routes) reflect the network of early 2017 and do not reflect any upgrades implemented since then or any planned upgrades.

The scale of investment required can be considered in relation to investments that have been made previously. Government investment in infrastructure through the Strategic Freight Network Fund has funded new enhancements on the rail network to support the growth of rail freight, with £235 million allocated in the funding period covering 2014-2019[102]. The Rail Delivery Group[100] reports that Network Rail has invested approximately £700m into improving the capacity and capability of the rail network for freight operations. Ports invested over £250m between 2007 and 2014 to connect their infrastructure to the rail network.

Summary - Rail Freight

Factor	Summary		
Benefits	5-10% reduction in HGV vkm on motorways/SRN		
Barriers	Lower costs of road transport Lack of door-to-door journeys		
Investment Requirements	Strategic Rail Freight Interchanges (SRFI) Investment in rail infrastructure		
Policy Requirements	Aligned cross-modal national policy National/local/project specific policies to discourage road haulage and incentivise use of rail		
Factors Affecting Timescales	Can be implemented quickly ~3/4 years with share of tonne km increasing into the future		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	5% reduction in HGV vkm on motorways/SRN by 2030	10% reduction in HGV vkm on motorways/SRN by 2030
Justification	Considered to be a high/speculative scenario	Moderate level of HGV reduction	Approximate maximum level of HGV reduction in the rail freight forecasts

Technology

Introduction

Progressive tightening of emission standards has been used to reduce emissions from road vehicles since the Euro standards were introduced in 1992. Introduction of new emission standards offers the potential to continue this process. Developments in the understanding of brake and tyre wear offers the potential to apply similar approaches to non-exhaust emissions.

Clean Air Zones

Measure Description

Clean Air Zones (CAZs) are areas where older vehicles with higher emissions are restricted (through the use of vehicle emission standards). The most polluting vehicles are required to pay a charge on entry to a specific area to encourage a movement away from the most polluting vehicles and uptake of cleaner alternatives. There are four potential classes of access restriction within a Clean Air Zone:

- Class A: Buses, coaches and taxis.
- Class B: Buses, coaches, taxis and heavy goods vehicles (HGVs).
- Class C: Buses, coaches, taxis, HGVs and light goods vehicles (LGVs).
- Class D: Buses, coaches, taxis, HGVs, LGVs and cars.

The London ULEZ provides an example of the implementation of a system similar to a Class D CAZ. The central London ULEZ was launched in April 2019 and will be extended in 2021.

Evidence Base and Assessment of Evidence

Evidence is available from the example of the London ULEZ, and the feasibility studies produced for CAZs around the country (although not all of them evaluate total emission savings in tonnes per year).

Summary of Evidence

TfL estimated[103] that the early introduction of the ULEZ would reduce $PM_{2.5}$ emissions by 6% and NO_X emissions by 20% in Central London in 2019. Following introduction of the ULEZ, the GLA reported[104] that $PM_{2.5}$ and NO_X concentrations had reduced by 15% and 35% in 2019 in comparison to a "no ULEZ" scenario. An example of a C Class CAZ from Cambridge[105] indicated that $PM_{2.5}$ emissions would reduce by 8% in 2021 with a CAZ and 38% in 2031. $PM_{2.5}$ emissions were predicted to decrease by 15% in 2021 and 6% in 2031. The greater reduction in 2031 in NO_X emissions was a result of a move to zero emission buses. Generally speaking, emission reductions as a result of a CAZ would be expected to decrease with each year, as shown in the Committed Clean Air Zone Impact Assessment[106]. The Emissions Factors Toolkit[107] indicates that a CAZ based on Euro 6/VI emission standards would reduce NO_X emissions by 16% and $PM_{2.5}$ emissions by 2% in 2025, with reductions being close to zero by 2030.

CAZs can be planned and implemented in around 3-5 years. Defra suggested that implementation costs are around £4 million, with running costs of around £16 million (based on total costs for five CAZs of £101 million)[106]. The total upfront cost estimated for of the proposed Cambridge CAZ in 2021 was £1.7 million of with £162,000 operational costs recurring on an annual basis[105]. CAZs may be associated with additional costs such as scrappage schemes (see below) to enable residents and businesses to upgrade their vehicles. The variation in costs and benefits in terms of emission savings reflect the variety of ways in which CAZs can be implemented. The costs of CAZs on businesses has been identified as an important barrier, particularly in relation to the effects associated with the COVID-19 pandemic. Several CAZs were delayed in 2020[108].

Summary - Clean Air Zones (CAZ)

Factor	Summary		
Benefits	2-15% reduction in $PM_{2.5}$ emissions in urban areas in 2025 16-40% reduction in NO_X emissions in urban areas in 2025 Benefits reducing each year and close to zero by 2030		
Barriers	Administrative requirements Cost of infrastructure Effect on businesses Considering of inequalities Only likely to deliver significant benefits in the short-term Wide geographic area required to deliver benefits relative to any displacement of impacts		
Investment Requirements	Upfront costs for infrastructure Administration		
Policy Requirements	Targeted localised policies Continued support for CAZ framework		
Factors Affecting Timescales	Planning of CAZs Consultation requirements		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Not modelled for $PM_{2.5}$ specific scenarios. Benefits on $PM_{2.5}$ concentrations (~2%) within uncertainty of the modelling. Effect of the London ULEZ extension included in modelling (all scenarios).		

Scrappage of older vehicles

Measure Description

Similar benefits to those of CAZs could also potentially be achieved through scrappage schemes for older vehicles (e.g. pre-Euro 4 petrol Light Duty Vehicles (LDVs) and Pre-Euro 6/VI diesel LDVs and Heavy Duty Vehicles (HDVs)). Other financial mechanisms, including grants the reduce the costs of low and zero emission vehicles, could have a similar effect by encouraging replacement of older vehicles.

Examples of schemes already exist. People living in London who are claiming benefits are eligible for grant to scrap vehicles that do not meet the ULEZ emissions standards. The grant is £2,000 per car, which can be used to purchase a new car that meets the ULEZ standards[109].

A trial has recently been announced for specific areas of Coventry with air quality concerns[110]. Residents with an older car can exchange their vehicle for mobility credits which can be spent on public transport, car clubs, or bikeshare schemes. Anticipated credit values are between £1,500 - £3,000.

Schemes could be localised, such as the Coventry examples, or there could be a nationwide scheme created whereby car owners in specifically designated areas (perhaps Air Quality Management Areas) are eligible for credits.

Evidence Base and Assessment of Evidence

Details of the implementation of such a scheme can be taken from the recently announced example in Coventry. The benefits of removing older vehicles from the road can be quantified using the Emissions Factors Toolkit.

Summary of Evidence

The Emissions Factors Toolkit[107] indicates that removing all pre-Euro 4 petrol LDVs and Pre-Euro 6/VI diesel LDVs and HDVs would reduce NO_X emissions by 16% and $PM_{2.5}$ emissions by 2% in 2025, with reductions being close to zero by 2030.

The Mobility Credits scrappage scheme in Coventry is part of the £22m West Midlands Future Transport Zone programme. Anticipated credit values are between £1,500 - £3,000. The advantages of a scrappage scheme over CAZs are the reduced requirements for infrastructure and enforcement. Costs would therefore be lower and would also reduce into the future, as fewer vehicles would need to be scrapped with each passing year.

Summary – Scrappage of older vehicles

Factor	Summary		
Benefits	2% reduction in $PM_{2.5}$ emissions in urban areas in 2025 16% reduction in NO_X emissions in urban areas in 2025 Benefits reducing each year and close to zero by 2030		
Barriers	Administrative requirements Costs of grants/credits Availability of alternative modes (in the case of credits for public transport) Potential inequalities in access to the scheme Difficulty of targeting a national scheme		
Investment Requirements	Upfront costs for scheme creation Scheme administration		
Policy Requirements	Potentially a national policy Targeted localised policies		
Factors Affecting Timescales	Can be employed rapidly, subject to availability of funding for grants/credits		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Not modelled for $PM_{2.5}$ specific scenarios. Benefits on $PM_{2.5}$ concentrations (~2%) within uncertainty of the modelling. Effect of the London ULEZ extension included in modelling (all scenarios).		

Exhaust Emission Regulations

Measure Description

This measure involves using current Best Available Technology (BAT) for exhaust emissions to impose tighter emission standards for road vehicles powered by ICEs. This could be included in forthcoming proposed Euro 7 standards for cars/LDVs.

Evidence Base and Assessment of Evidence

There is limited detail on what Euro 7 standards could entail but preliminary findings have been discussed and presented at meetings. Evidence on tighter emission standards is also available from regimes in other countries/regions such as China and California.

Summary of Evidence

Preliminary findings on Euro 7 emission limits[111] suggest that Solid Particle Number (SPN) emission limits could be up to 90% lower than those for Euro 6 (6×10^{10} (SPN_{10}) against 6×10^{11} (SPN_{23})). SPN_{10} means SPN emissions with a size cut-off at 10 nm.

China 6b emission standards to be applied from July 2023[112] show that 0.003 g/km is achievable compared to the 0.0045 g/km for Euro 6 (33% reduction). In California[113] a 1 mg/mi PM standard will be introduced from 2025 and applicable for all new model year 2028 light-duty vehicles (86% reduction compared to Euro 6).

The timing of this measure will depend on the implementation of Euro 7 (expected after 2025), whether Euro 7 emission standards are employed in the UK, and the purchase rates of Euro 7 ICE cars. At the workshop it was agreed that as sales of standard new ICE cars and vans is ending (for the most part) in 2030, and Euro 7 standards are only likely in 2026-2028, there is a limited window for benefits. However, it is likely that between 2030 and 2035, new cars and vans can be sold if they have the capability to drive a significant distance with zero emissions (for example, plug-in hybrids or full hybrids)[114], so new emission standards will affect emissions from these vehicles.

Summary - Exhaust Emission Regulations

Factor	Summary		
Benefits	33-90% Reduction in tailpipe particulate emissions all ICE cars sold from advent of Euro 7 standard (2026-2028) Effect on overall emissions may be minimal because of prevalence of electric cars by 2028		
Barriers	Technical barriers to be overcome in ensuring low emissions under certain operating conditions There is a need for continued development of Real Driving Emissions testing to ensure that future emissions standards deliver the outcomes that they are designed for		
Investment Requirements	Agreement of testing protocol Manufacturer investment		
Policy Requirements	Inclusion of tightened emissions standards in Euro 7 UK decision on alignment with Euro standards post-Brexit		
Factors Affecting Timescales	Finalisation of Euro 7 standards (or UK equivalent) Euro 7 adoption date Purchase rates of ICE cars and vans after Euro 7 adoption		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	50% reduction in tailpipe $PM_{2.5}$ emissions from petrol LDVs sold after 2026	90% reduction in tailpipe $PM_{2.5}$ emissions from petrol LDVs sold after 2026
Justification	No new emissions regulations	Assumes that emission standards are less tight	Assumes that tight emission standards are applied

Checks for Defective Diesel Particulate Filter (DPF)

Measure Description

Emissions from diesel vehicles where the DPF is either defective or has been removed are 20 to 50 times higher than those from vehicles with a correctly functioning DPF. The current MOT regime does not test whether the DPF is working correctly[115]. Use of a Particle Number check in the MOT process could establish whether the DPF is functioning correctly and therefore lead to replacement of the DPF and reduced emissions. Remote sensing at the roadside is an alternative option.

Evidence Base and Assessment of Evidence

There is a strong evidence base for this measure in the Netherlands, where Particle Number checks will be added to the Periodic Technical Inspection (similar to the annual MOT in the UK)[116]. A similar system will also be introduced in Germany[117]. One study on DPF failures has been obtained from the UK[118].

Summary of Evidence

The evidence suggests that between 5%[119] and 10%[118] of cars originally fitted with DPFs have removed or defective DPFs. Studies have shown that vehicles with defective DPFs have around 95% higher emissions than those will correctly operating DPFs[120].

The implementation of this measure in the Netherlands and Germany demonstrates that it can be implemented over a relatively short timescale. However, there was consensus in the workshop that the MOT system in the UK would make it highly challenging to implement this measure at MOT test centres. There are around 20,000 to 30,000 of these in the UK, which would all need new testing equipment and staff training. Remote sensing at the roadside offers an alternative approach that may be more feasible for England. This was discussed at the workshop. Investment in research into this type of approach would be required. This means that the timescales for implementation would be extended.

Summary - Checks for Defective DPF

Factor	Summary		
Benefits	95% reduction in tailpipe particulate emissions from diesel LDVs with removed or failed DPFs May apply to 5-10% of Diesel LDVs (Dutch/Imperial figures)		
Barriers	MOT system in the UK (20,000 to 30,000 MOT centres) Current last of an agreed remote sensing method		
Investment Requirements	Investment in test equipment at MOT centres, or investment in remote sensing method and protocol Replacement of defective DPFs (~£1k-4k)		
Policy Requirements	Inclusion of low idle speed Particle Number check in MOT Remote sensing protocol/policy		
Factors Affecting Timescales	Development of remote sensing approach Development and instigation of testing (~5-10 years)		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	No LDV DPF failure from 2030	No LDV DPF failure from 2025
Justification	No new regulations	Development and implementation of measure by 2030 (Adjustment made to NAEI DPF failure rate assumption)	Faster development and implementation of measure (Adjustment made to NAEI DPF failure rate assumption)

Regenerative Braking

Measure Description

Standard ICE cars use friction braking systems, where the excess kinetic energy is converted to heat by friction in the brakes. This friction wears the brake pads and discs, and particulate matter is emitted. A proportion of these particles goes into the air. The increase in the number of electric cars on the road offers the potential for reduced emissions as they use regenerative braking systems where the electric motor uses the momentum of the vehicle to recover energy that would be otherwise lost to the brake discs as heat. When the regenerative braking system is used there is no component wear and therefore no emissions. Electric cars have friction brakes for emergency stops and ICE vehicles can be fitted with regenerative braking to charge the battery that powers ancillary systems.

Evidence Base and Assessment of Evidence

A number of studies have been carried out on the reductions in brake wear emissions that are achieved through the use of regenerative braking systems as opposed to friction braking systems. Ten studies are summarised in the OECD report *Non -exhaust Particulate Emissions from Road Transport an Ignored Environmental Policy Challenge*[121]. There is a degree of consistency in the studies and the authors of the report considered that there was sufficient evidence to make an assumption around the reduction in $PM_{2.5}$ emissions for modelling purposes.

Summary of Evidence

The OECD[121] report $PM_{2.5}$ emissions from friction braking systems being reduced by 25% to 100% when replaced with regenerative braking systems. The majority of the studies suggest that reductions are likely to be greater than 66%. The authors assume a 75% reduction in brake wear from regenerative braking systems.

The timescales for the benefits of regenerative braking systems to be realised depend on the uptake rates of electric cars. The DfT Road Traffic Forecasts[83] provide a number of scenarios on uptake rates and proportions of cars which are electric (or hybrid) on the road. It was highlighted in the workshop that the sale of petrol/diesel-only cars from 2030 (and other policies in favour of battery electric vehicle (BEV) uptake) will lead to increased uptake of BEVs. Regenerative braking can also be employed in hybrid cars, which are likely to remain on sale until 2035.

Summary - Regenerative Braking

Factor	**Summary**		
Benefits	25-95% BEV Brake wear emissions relative to ICE vehicle Overall benefits dependent on uptake of BEVs		
Barriers	Purchase price of BEVs Range anxiety of BEVs Charging infrastructure/capacity Reduced fuel duty income		
Investment Requirements	Development in BEV performance Infrastructure to support widescale BEV use		
Policy Requirements	Policies to support BEV uptake Policies to restrict ICE sale		
Factors Affecting Timescales	BEV uptake rates Performance development of BEVs		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	75% reduction in brake wear emissions from hybrid/BEVs relative to ICE vehicles	As for Medium	As for Medium
Justification	Applied in all scenarios to account for the benefit of regenerative braking in reducing emissions		

Deweighting of BEVs to reduce tyre/road wear

Measure Description

The heavier a vehicle is, the greater the amount of energy is required for acceleration and deceleration, which results in higher friction between tyres and the road, leading to increased tyre wear. Vehicle weight also increases road abrasion and resuspension of particles deposited on the road surface into the air. Heavier vehicles therefore result in greater $PM_{2.5}$ emissions from tyre wear and road abrasion. Studies have shown that, at present, electric cars are heavier than similar models of ICE cars, meaning that tyre wear, road abrasion and resuspension emissions may be higher. Improvements in battery technology (maintaining range while reducing size) and use of different materials, may make it possible to reduce the weight of electric cars in future, reducing the tyre and road wear and emissions.

Evidence Base and Assessment of Evidence

A number of studies have been carried out comparing the weight of electric cars to comparable ICE models and the conclusions are fairly consistent. There is however much more debate about the effect of weight on emissions, particularly as electric cars are fitted with tyres developed specifically for that use[122 123].

Summary of Evidence

Timmers and Achten[124] found the average difference in weight between ICE cars and electric cars to be 24%. Other studies reporting similar values are reported in the OECD report[121]. There is a wide range in reported emissions. The OECD report provides a range of emission factors for different battery sizes with emissions from car tyre wear being 4% to 53% higher than for comparable ICE models. Beddows and Harrison[125] report that tyre wear and road abrasion emissions could be 9% and 15% respectively higher than comparable ICEs. A report for the Nordic Council of Ministers[126] considers that the increasing use of electrical cars can worsen tyre wear because electric cars are generally heavier and have higher torque than similar sized ICE cars. In the workshop, stakeholders agreed that reducing vehicle weight would likely reduce tyre wear emissions and also reduce resuspension. However, it was also emphasised that BEVs are supplied with specific tyres that are designed for the forces applied and these have lower wear rates.

The timescales depend on the uptake rates of electric cars, the development of battery technology and the performance benefits of tyres developed for electric cars. Several stakeholders in the workshop suggested that policies to encourage certain vehicle types in urban areas may be more appropriate. For example, incentivising smaller, lighter, low speed, low acceleration vehicles and deterring larger, heavier SUVs. It was also suggested that this could be achieved through policies related to vehicle range, where city runabouts would be subject to different tax rates than vehicles designed for high mileage.

Summary - Deweighting of BEVs to Reduce Tyre/Road Wear

Factor	Summary
Benefits	9-65% Avoided increase in tyre wear emissions relative to ICE vehicles 15-24% Avoided increase in road abrasion emissions relative to ICE vehicles BEVs currently ~25% heavier than equivalent ICE models Reduced weight would also lower carbon emissions and increase range
Barriers	No incentive for manufacturers to reduce weight at present Battery weight needed to bring BEVs closer to ICE range at present Costs of advanced lightweight materials
Investment Requirements	R&D into lightweight materials R&D into battery technology
Policy Requirements	Policies related to vehicle weight

Factor	Summary		
Factors Affecting Timescales	Battery technology development (i.e., what data BEVs achieve range parity, then weight parity with ICE vehicles)		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	The effect of the heavier weight of electric vehicles in increasing NEE is understood to be unaccounted for in the NAEI. Therefore, there is no additional source in the model that can be reduced to account for any strategic move to reduce electric vehicle weight.		

Brake Wear Emission Regulations

Measure Description

This measure involves using current Best Available Technology (BAT) in relation to friction brake emissions to impose emission standards for the first time. This could be included in forthcoming proposed Euro 7 standards. A number of ways in which brake wear emissions could be reduced have been discussed. These include options regarding component materials such as Non-Asbestos Organic (NAO) brake pad formulations, heat treatment for cast iron brake discs, carbon ceramic discs and titanium discs. There is also the option to impose type standards for brake components rather than whole vehicle emission standards. Measures that focus on emissions of the system as a whole could also be employed, such as enclosed systems (potentially using drum brakes), filtration technologies, and brake emission capturing systems.

Evidence Base and Assessment of Evidence

There are a number of secondary sources that gather evidence on emissions from brake wear. Examples have been produced in recent years by the UK Air Quality Expert Group (AQEG)[127], OECD[98] and Ricardo E&E on behalf of Verband der Automobilindustrie (VDA)[128]. Given the wide range of technologies available to reduce emissions from friction brakes, there is a wide reported range in the $PM_{2.5}$ emission reductions that can be achieved. Some information is provided on the emission reductions that can be achieved by collection systems from manufacturers.

Summary of Evidence

The reviews highlighted above indicate that specification of particular components with the aim of reducing emissions can reduce them by something in the range of 32-65%. The AQEG report and manufacturers of filtration/collection systems suggest that these can remove 80-92% of particulate matter emitted[129 130 131]. At the workshop, stakeholders agreed that this measure could be beneficial given the importance of brake wear emissions as a source. However, there is some debate about how important this is as a source. In the *Air quality in Europe – 2019* report, the European Environment Agency estimates that tyre wear contributes 2% of road transport $PM_{2.5}$ emissions[132].

Another key point discussed is that Euro 7 limits and test requirements are subject to negotiation so there is a large amount of uncertainty on the possible benefits likely to be achieved and the dates by which they could be achieved. Some stakeholders consider that initial regulations may be light-touch (focusing on removing of worst materials for example), whilst others think that stringent regulations can be brought in. It is not yet confirmed that the UK will adopt any Euro 7 emission standards that do emerge.

Consensus at the workshop was that, as the sale of standard new ICE cars and vans is ending (for the most part) in 2030, and Euro 7 standards are only likely in 2026-2028, there is a limited window for benefits as most vehicles sold from this point will be hybrid or fully electric and therefore not use friction brakes except in extreme braking situations.

Summary - Brake Wear Emission Regulations

Factor	Summary		
Benefits	10-90% reduction in brake wear emissions from all ICE cars sold from advent of Euro 7 standard (2026-2028 estimated)		
Barriers	Need to finalise appropriate test regime Definition of appropriate technologies		
Investment Requirements	R&D into test regime R&D into technologies (including brake wear collection)		
Policy Requirements	Inclusion of brake wear in Euro 7 standard UK decision on alignment with Euro standards		
Factors Affecting Timescales	Finalisation of Euro 7 standards Euro 7 adoption date Purchase rates of ICE cars after Euro 7 adoption		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	25% reduction in brake wear emissions from all ICE vehicles sold after 2026	90% reduction in brake wear emissions from all ICE vehicles sold after 2026
Justification	No new emissions regulations	Assumes that initial emission standards are less tight (e.g. material specifications)	Assumes that tight emission standards are applied (e.g. additional brake wear collection)

Tyre Composition and Wear

Measure Description

Different compounds are used for tyres for different vehicles because of the differing stresses that they are put under. Examples include the HDV tyres and tyres for electric vehicles. One of the ways in which tyres of different compounds (and manufacturing processes) differ is in wear rates. Intuitively, tyres that wear at a lower rate would have reduced $PM_{2.5}$ emissions. Systems are also under development to collect tyre particles that are emitted.

Evidence Base and Assessment of Evidence

Tyre wear and particulate emissions is an issue that is discussed in the literature, including in the reviews produced by AQEG[127] and the OECD[121], however there is a lack of quantified information on how tyre composition may affect $PM_{2.5}$ emissions. This is in part because tyre manufacturers retain information on tyre composition and manufacturing processes as their Intellectual Property, and in part because there is no agreed testing regime against which tyres can be tested for $PM_{2.5}$ emissions.

Summary of Evidence

The lack of evidence in relation to this measure is highlighted in the AQEG review[127] which states that materials are being explored which "*offer the opportunity to reduce wear and potentially particulate emissions*". The OECD review[121] states that "*it is necessary to conduct research on the benefits and drawbacks of different combinations of road and tyre materials*". Another review, from Sweden[133], draws no conclusions regarding the effect of tyre design and dimensions on wear. The Norwegian Institute for Water Research[134] estimates that around 14% of airborne tyre wear particles (1% of all tyre wear particles) are $PM_{2.5}$.

Some estimates of reductions in emissions that can be achieved have been made. In modelling of emissions from tyre wear, the Pew Charitable Trust[135] makes the assumption that by 2040, new tyres will have 36% lower release rates than today, with the least durable tyres eliminated. The Tyre Collective is a company that is currently developing a device that directs and captures charged tyre particles and undertaking research into the benefits that could be achieved[136]. Systems to collect tyre wear are estimated to collect up to 60% of airborne particles under test conditions.

At the workshop there was consensus that regulating emissions from tyres could have benefits through reductions in both atmospheric $PM_{2.5}$ concentrations and microplastic pollution. However, the workshop agreed that further research is required regarding how much ambient $PM_{2.5}$ is from tyre wear emissions and that a harmonised methodology for the measurement of tyre wear emissions needs to be developed. The report for the Nordic Council of Ministers[126] agrees that a standardised wear test is crucial in adopting tyre wear as a factor in regulations or labels. Development of such a regime will determine when benefits are delivered. Discussions at the workshop also highlighted that tyre composition alone will not govern wear rates. The manufacturing process is also important. These factors are generally protected Intellectual Property for manufacturers.

At the workshop, the British Tyre Manufacturer's Association (BTMA) reported that the industry is developing a robust, reliable and reproducible test method to measure tyre abrasion rate reflective of European usage and anticipated that this will support a regulatory minimum standard for tyre abrasion resistance by the mid-2020s.

The first step in regulation of tyre wear emissions may be in the labelling of tyres to include abrasion rates. In 2018, the European Commission[137] adopted a proposal for a new regulation on the labelling of tyres that would include abrasion (once suitable testing methods become available). The need for educating consumers in this issue was highlighted in the workshop.

Although research is at a preliminary stage, this field of research will advance in the coming years and therefore an emission reduction of up to 30% has been allowed for by 2050 in the speculative scenario.

Summary - Tyre Composition

Factor	Summary		
Benefits	Effect of tyre composition on $PM_{2.5}$ emissions (as opposed to wear generally) seems largely unknown However, there are compounds which wear less (e.g., HDVs and EV specific tyres) and therefore would be expected to have lower $PM_{2.5}$ emissions Reduced tyre wear emissions would reduce contamination of watercourses and potentially plastic concentrations in the oceans		
Barriers	Lack of a tyre wear $PM_{2.5}$ emission testing regime Lack of understanding of how tyre composition and manufacture affects wear Lack of understanding of particle sizes and composition		
Investment Requirements	Development of a testing regime Tyre R&D		
Policy Requirements	Largely depends upon a testing regime		
Factors Affecting Timescales	Development of a testing regime Tyre R&D programmes Seems like any regulation would be at least 5 years + away		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	30% reduction in tyre wear emissions by 2050.

Factor	Summary		
Justification	N/A	N/A	Based on emerging technologies (it has been claimed that emission reductions could be up to 60%) and initial research into this field

Vehicle Condition (wheel alignment and tyre pressure)

Measure Description

Vehicles with misaligned wheels and underinflated tyres are operating inefficiently. Proper maintenance of vehicles to ensure that wheels are aligned and tyres are correctly inflated can have significant effects on fuel use and tyre wear. Systems have been developed to monitor these factors and inform drivers or fleet managers so that corrective action can be taken. Tyre Pressure Monitoring Systems (TPMS) already exist for new vehicles (every new car sold in the EU from 2014) according to the EU Directive 2010/48/EU. Wheel alignment is checked in the MOT[138].

Measures like this that reduce fuel use are likely to be of particular benefit to fleet operators given the high total distance driven and the decision making related to costs.

Evidence Base and Assessment of Evidence

Little evidence was obtained regarding this measure, but it is a generally accepted approach to vehicle management. Some estimates have been made of the benefits of TPMS. The contracts that fleet operators take up with tyre manufacturers typically include monitoring of tyre pressure to ensure maximum fuel efficiency.

A discussion was also held with RL Auto, a company that has developed the Auto-Align system for monitoring wheel alignment for similar reasons. These measures are likely to reduce $PM_{2.5}$ emissions.

Summary of Evidence

The OECD review[121] references several studies showing that correct tyre pressures (rather than deflated tyres) can reduce $PM_{2.5}$ emissions by around 10%. The Pew Charitable Trust[135] assumes that eco-driving, including tyre pressure, reduced tyre wear rates by 6%. These measures are likely to be beneficial to fleet operators and individual drivers as they are associated with reduced fuel consumption.

The workshop highlighted that 50% of commercial fleets are already running on contracts from tyre manufacturers which monitor, and correct, tyre pressure issues. This enables operators to be more fuel efficient. Also reported at the workshop that TPMS only becomes mandatory for new heavy commercial vehicles from 2022. Easy-to-install wireless retrofit TPMS packages are widely available at low cost, offering improved safety and environmental performance when warnings are acted upon.

RL Auto[139], who are undertaking further testing in 2020, suggest that correctly wheel alignment will enable owners and operators to save 10% in fuel use, extend tyre life by 15% and reduce airborne particulate emissions by 7-17%. The VTI review[133] reports that incorrect wheel alignment may increase tyre wear by 10%.

Summary - Vehicle Condition

Factor	Summary		
Benefits	Assume 30% of vehicles have misaligned wheels and/or underinflated tyres and can reduce tyre wear emissions by 10-15%. Result: 3.75% reduction in total HDV emissions		
Barriers	Investment by fleet operators		
Investment Requirements	Awareness raising/cooperation between businesses Potentially charging facilities for electric vehicles		
Policy Requirements	Investment in wheel alignment checking systems by fleet operators (may be paid back quickly in saved fuel use) Tyre condition checks should be included as part of standard vehicle checks		
Factors Affecting Timescales	Tyre pressure already monitored by largest fleets Commercialisation and uptake of wheel alignment monitoring technologies and systems for fleet operators		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	3.75% reduction in tyre wear emissions by 2030	3.75% reduction in tyre wear emissions by 2025
Justification	No new regulations/requirements	Assume 30% of road vehicles have misaligned wheels and/or underinflated tyres and can reduce tyre wear emissions by 10-15%. Result: 3.75% reduction in total tyre wear emissions	Assume 30% of road vehicles have misaligned wheels and/or underinflated tyres and can reduce tyre wear emissions by 10-15%. Result: 3.75% reduction in total tyre wear emissions

Road Composition

Measure Description

A variety of road surface compositions are available for different situations, including traffic volumes and safety requirements. Some road surface compositions are likely to wear better than others, and hence, could be specified to reduce $PM_{2.5}$ emissions. This might be of particular benefit in urban areas where $PM_{2.5}$ concentrations are elevated.

Evidence Base and Assessment of Evidence

Similar to tyre wear, road composition and particulate emissions is an issue that is discussed in the literature, including in the reviews produced by AQEG[127] and the OECD[121] and one produced by Penkala *et al*[140], however there is a lack of quantified information on how road surface composition may affect $PM_{2.5}$ emissions. The OECD review states that "*the influence of pavement type and structure remains largely unknown*". Penkala *et al* state that "*data on this subject is clearly lacking. This scarcity concerns both the availability of data on PM/dust emissions from road-surface abrasion in various places, and studies on PM/dust emission factors and related elements from different types of road surfaces*".

Summary of Evidence

The relationships between road surface materials and densities, wear rates and particulate emissions have yet to be conclusively determined. This makes it challenging to define a particular road surface that would reduce $PM_{2.5}$ emissions. Another factor raised at the workshop is that there are situations where safety reasons mean that road surface friction needs to be enhanced, which could potentially increase tyre and road wear.

The OECD review discusses the effect of various features of the road surface, such as aggregate size, density and road condition. Coarser material is considered to result in reduced wear but evidence is also discussed that the lower the maximum size of coarse aggregate (and the lower the Nordic abrasion value of the aggregate material), the lower the particle formation. The OECD review also references studies on asphalt relating density to particle retention and wear rates. Hollow spaces in asphalt can retain wear particles but it is also mentioned that lower-density asphalt can have a higher wear rate. It is also discussed that asphalt roads have higher wear rates than concrete roads (which have other issues, such as increased noise and reduced comfort). A review by Gustafsson[141] does report studies showing PM_{10} emission rates over twice as high for a given Nordic ball mill value which gives an indication of the range of emissions for different road types (*a ball mill is used for testing resistance to abrasion from tyres*).

The condition of the road is clearly an important factor. The OECD review references a study showing that a damaged road surface can emit ten times more road wear particles than the same pavement in good conditions. Similarly, Penkala *et al* state that current research shows that direct road-surface abrasion is of minor importance when the road is undamaged.

At the workshop it was agreed that there is a need for further research into the interaction of road and tyre materials before policy specific to $PM_{2.5}$ can be developed. The relationship between wear rates and $PM_{2.5}$ emissions needs to be evaluated further. The road maintenance programme (how often roads are relayed) would also mean that the time to relay roads and deliver any benefits could be significant.

Although quantified information is not available at present, it is considered reasonable to assume that this field of research will advance in the coming years, and therefore an emission reduction of up to 25% has been allowed for by 2050 in the speculative scenario.

Summary - Road Surface Composition

Factor	**Summary**		
Benefits	Effect of road composition and particle density on $PM_{2.5}$ emissions (as opposed to wear generally) largely unknown However, there are clearly compounds which wear less (and therefore may be expected to have lower $PM_{2.5}$ emissions)		
Barriers	Lack of a road wear $PM_{2.5}$ emission testing protocol Lack of understanding of the impact of texture and composition		
Investment Requirements	Development of a testing regime Road composition R&D Road maintenance programme		
Policy Requirements	Largely depends upon a testing protocol There is a need for further research into the interaction of road and tyre materials before policy specific to $PM_{2.5}$ can be developed		
Factors Affecting Timescales	Development of a testing protocol Road R&D programmes Seems like any regulation/policy would be at least 5 years + away Road maintenance/replacement would mean that any benefits would take even longer		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	25% reduction in tyre wear emissions by 2050.
Justification	Only included in the Speculative scenario to account for potential future developments in this field of research		Based on the range of particulate emissions (some road types have less than 50% of the emissions of others) and initial research into this field

Road treatment to reduce resuspension

Measure Description

Sweeping and/or washing of roads has long been discussed as a measure to reduce particulate emissions from resuspended material. Treatment of roads with chemical compounds like calcium magnesium acetate (CMA) to retain particulates has also been considered.

Evidence Base and Assessment of Evidence

The treatment of roads to reduce emissions has been considered in the reviews produce by reviews produced by AQEG[127], the OECD[121], Penkala *et al*[140], and Querol *et al*[142]. There is reasonably wide variation in the results produced (largely dependent on the initial dust loading and methodology applied), but there is consensus that he more frequently the road is washed, the greater the benefits and that a combination of washing and sweeping is more effective than washing or sweeping alone.

Summary of Evidence

Most of the studies considered in the reviews assess the impact of washing regimes or use of dust suppressants on local particulate concentrations. The regimes have been shown to reduce concentrations by between 6% and 22%. The benefits typically depend on the frequency of washing. The OECD review reports that some municipalities in Korea have employed self-cleaning road systems that are operated twice a day during the summer. The OECD review references a study which found that street washing can reduce road dust mobility by 60-90% depending on the particle size and methodology applied.

At the workshop, stakeholders agreed that road surface wetness (including through meteorological conditions) plays an important role in determining concentrations of $PM_{2.5}$ from non-exhaust emission sources, but that the labour costs of regular washing could be significant. There was debate about the desire to introduce other substances, for example calcium magnesium acetate, to the road and a general feeling that this might be undesirable, and if used at all, is only practical for restricted areas.

Summary - Road Treatment to Reduce Resuspension

Factor	Summary		
Benefits	90% reduction in particle mobility (assumed equivalent to emissions)		
Barriers	Resources to carry out daily street washing Issues associated with runoff		
Investment Requirements	Local investment in street cleaning R&D into road composition and effect on road abrasion emissions Potential need to treat runoff		
Policy Requirements	Localised measures to reduce concentrations in hotspots		
Factors Affecting Timescales	Street washing can be deployed relatively quickly ~1 year Measures related to road material need much greater research into the effect of composition		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Resuspension is not accounted for in the NAEI baseline, therefore there is no source to adjust in the modelling to account for any benefits of this measure.		

Connected Autonomous Vehicles

Measure Description

The technology for Connected Autonomous Vehicles (CAVs) has been in development for a number of years. How the technology is introduced on a wide scale will determine the effects on air quality. Connected Autonomous Vehicles could potentially help to reduce $PM_{2.5}$ emissions through ways such as regulating traffic flow and reducing congestion and the stop/start driving conditions that lead to a high proportion of emissions (including platooning of freight vehicles) and by supporting the transition to shared mobility. On the other hand, some reports suggest that the widespread use of CAVs could increase the total vkm.

Evidence Base and Assessment of Evidence

There are a variety of studies considering the implementation of CAV technology on a wide scale. Some suggest that there could be benefits for air quality, whilst others have the opposing view. A variety of different implementation models are considered and it is clear that this will determine what effects the technologies have.

Summary of Evidence

There are some studies that consider the effect of CAVs on carbon emissions and predict that these could be reduced by 15-30% as a result of reduced traffic waves (and in relation to the increase in electric vehicles)[143] [144]. The Center for American Progress[145] produced a report citing several studies highlighting the benefits of CAVs in reducing congestion and cited a study suggesting that if all HDVs platooned, a feature that automated technology could facilitate, their energy intensity would drop 10-25%.

The consensus is that for any benefits to be seen, CAVs will need to be electric vehicles and integrated into a system that facilitates walking, cycling, and public transport use[146]. The Center for American Progress report also cites studies predicting that CAVs may reduce many of the costs typically associated with car travel and stimulate growth in vkm. Increases in vkm could potentially be offset by integration of CAVs as part of a shift to shared mobility where transport patterns change. Shared mobility, using CAVs could lead to on-demand ridesharing and car-sharing and reduced car ownership. However, the International Transport Forum[147] presents a scenario where the total number of cars is dramatically reduced but there is an increase in car vkm because "Taxibots" replace buses as well as private cars and traditional taxis meaning that less people are transported per vehicle and there are more empty journeys. This highlights the importance of the implementation of the technology on determining the effects. This was discussed at the workshop. Several stakeholders mentioned that CAVs may increase vkm and congestion by making trips low cost and low effort. Discussions at the workshop also highlighted that even if CAVs reduce congestion, this may increase the popularity of driving and increase vkm, and that the largest benefits may be achievable in closed systems such as airports.

There is also no consensus regarding the timescales for CAVs. The Victoria Transport Policy Institute[148] suggests that because of their high labour costs and predictable routes, long-haul buses and freight trucks are particularly appropriate for autonomous operation, so self-driving buses and lorries may become common in the 2030s and 2040s with cars later. Conversely, the Connected Places Catapult[149] has suggested that up to 72% of car sales in the UK in 2035 could be CAVs and that there is likely to be a 3-year lag for buses, 5-year lag for vans and an 8-year lag for lorries.

Summary - Connected Autonomous Vehicles

Factor	Summary		
Benefits	Dependent on how the technology is implemented Could have AQ benefits through reduced congestion and stop/start driving, allowing platooning of freight vehicles and supporting shared mobility Some studies also suggest that it could increase the appeal of car use and increase total vkm travelled		
Barriers	Safety concerns The need to develop a regulatory regime Personal preference for driving Potential increased road surface wear due to standardised vehicle positions		
Investment Requirements	R&D into technology Infrastructure investment		
Policy Requirements	Development of a regulatory regime Harmonisation of different technical systems		
Factors Affecting Timescales	Autonomous cars could become common in the 2030s Vans/Trucks expected to lag behind this (5-8 years)		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Unquantified as highly dependent on decisions regarding the implementation of the available technology		

Zero Exhaust Emission Buses

Measure Description

The use of zero emission buses has the potential to significantly reduce tailpipe emissions, which could have a significant benefit in reducing $PM_{2.5}$ concentrations in urban areas that have a high level of bus traffic.

Schemes to retrofit emission abatement technology such as DPFs to existing buses could also significantly reduce exhaust emissions depending on the age of the vehicles in the fleet. This can be a short-term and expensive solution, particularly for vehicles that are due for replacement in a few years and is not considered separately.

Evidence Base and assessment of evidence

Relatively little evidence has been found on the procurement of zero emission bus fleets. Details of plans in London provide the most information. The government has announced £50m funding for the West Midlands Combined Authority to support Coventry becoming Britain's first All-Electric Bus Town or City, which will see the entire bus fleet of the area changed to electric buses[150].

Summary of evidence[7]

Use of zero emission buses has the potential to remove 100% of tailpipe exhaust emissions.

[7] Note that data in this section is accurate as of February 2021 and does not include information on additional funding made available in the 2021 spending review.

As set out in the National Bus Strategy, government will invest £120 million in zero emission buses in 2021-22. In combination with the first All Electric Bus Town or City in Coventry, government funding could support delivery of up to 800 cleaner and greener zero emission buses[151]. In addition to this funding, as announced in the National Bus Strategy the DfT had launched an initial consultation on ending the sale of new diesel buses in England.

In addition to the Coventry electric bus scheme, proposals in London include details in the levels of investment required for this measure, although it should be noted that the bus market in London is based around a franchising model, which does not exist anywhere else in England. In the London Environment Strategy[152], the Greater London Authority (GLA) has a stated ambition of all Transport for London (TfL) buses being zero emission by 2037 at the latest. This target provides an indication of the timescales for delivery of fleet strategies in terms of vehicle replacement and procurement and manufacturing (in a bus franchising system). The GLA has already invested over £300m on improving the bus fleet[153], including creation of twelve Low Emission Bus Zones[154]. As an indicator of the relative scale of investment required, the DfT Annual bus statistics: England 2019/20[155] show that bus mileage in London (26%) was similar to the mileage in all other metropolitan areas combined (25%).

Several important points around implementation of measures such as this were raised at the workshop. These included the need to ensure that the capacity of the electricity grid can support the level of charging required (alongside wider public uptake of electric vehicles), and the need to ensure that older ICE buses are not displaced to other locations.

Summary - Zero Emission Buses

Factor	Summary		
Benefits	100% reduction in tailpipe emissions Co-benefits for other emissions (NO_X and carbon) Reduction in vehicle maintenance costs		
Barriers	Procurement costs Vehicle availability Grid capacity for charging (and industry confidence in this)		
Investment Requirements	Vehicles Charging and/or refuelling infrastructure Capability development e.g. operators, local authorities		
Policy Requirements	Specific local air quality targets in priority zones Alignment of electric bus policy with electricity grid policies Policies to avoid displacement of older buses to other locations if they could worsen air quality		
Factors Affecting Timescales	Lifetime of existing vehicles Procurement and manufacturing timescales GLA target for all 9,200 buses to be zero emission by 2037 at the latest		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	All urban buses zero exhaust emission by 2045	All urban buses zero exhaust emission by 2037
Justification	No wide-scale rollout of zero emission buses	Based on DfT proposed options for the ending the sales of non-zero emission buses.	Speculative scenario with all buses zero emission by 2037, meeting the timescale proposed for London, which is considered to be highly ambitious for everywhere else in the country

Zero Exhaust Emission HGVs

Measure Description

In addition to reducing road freight movements, emissions from the transport of freight can also be reduced through the use of zero (exhaust) emission HGVs, such as those powered by electric batteries, hydrogen fuel cells and electric road systems.

Similar to buses, schemes to retrofit emission abatement technology to existing HGVs could also significantly reduce exhaust emissions depending on the age of the vehicles in the fleet. The Clean Vehicle Retrofit Accreditation Scheme[156] has been established to support the operation of CAZs by enabling operators of buses, coaches, HGVs, mini-buses, taxis and vans to source accredited equipment that enables their vehicles to meet CAZ standards. This can be a short-term and expensive solution, particularly for vehicles that are due for replacement in a few years and is not considered separately.

Evidence Base and Assessment of Evidence

The potential for alternatively fuelled HGVs is reviewed in the CCC Sixth Carbon Budget report on Surface Transport[157].

Summary of Evidence

The CCC report discusses potential uptake rates and barriers regarding zero exhaust emission HGVs. With regards to battery electric vehicles, packaging sufficient battery range into the vehicle is the major challenge. Based on present battery capacity, this means that a significant charging network would need to be established (potentially at least every 50 km on the Strategic Road Network). Furthermore, such technology may not be suitable for some drive cycles where there is not time to stop and recharge regularly.

The CCC reports considers that hydrogen vehicles offer a similar operational profile to current vehicles and are attractive for operators who require long ranges. Again, the infrastructure requirements are significant. The CCC estimates that 500-600 hydrogen refuelling stations would be required to support the use of hydrogen by larger HGVs only. The CCC cite a study estimating that with suitable infrastructure, 99% of larger HGVs could be hydrogen fuelled by 2040, although the costs of operating hydrogen vehicles may be considerably higher than that of electric alternatives due to energy losses. Electric road systems, enabling HGVs to connect to draw power or recharge, can offer operational benefits to operators. However, the CCC considers that once other zero-emission technologies become widely available, the use of an electric road system may become expensive relative to other options due to high upfront costs.

Summary - Freight Consolidation and urban HGV restrictions

Factor	Summary		
Benefits	Potential for HGVs with zero exhaust emissions Co-benefits of reduced emissions (NO_X, carbon)		
Barriers	Lack of infrastructure to enable fuelling/charging State of technological readiness		
Investment Requirements	Development of technologies (e.g., batteries and fuel cells) Infrastructure (charging/hydrogen)		
Policy Requirements	National strategy around infrastructure		
Factors Affecting Timescales	Technology development Infrastructure deployment		
Ambition Scenario	**Medium**	**High**	**Speculative**

Factor	Summary		
Input for emissions modelling	N/A	Zero exhaust emissions from HGVs by 2050	Zero exhaust emissions from HGVs by 2040
Justification	Considered to be a high/speculative scenario	Based on CCC Surface Transport Report – slower uptake	Based on CCC Surface Transport Report – fast uptake

Shipping

Introduction

As illustrated in Section 2, shipping is estimated in the NAEI to contribute 2% of total $PM_{2.5}$ emissions in England plus 10% of NO_X emissions and a minimal amount (less than 0.01%) of NH_3 emissions. Clearly, shipping activity exerts a greater effect on $PM_{2.5}$ concentrations close to ports as a result of fuel combustion associated with the movement of ships, plus the use of auxiliary engines for other functions and the use of equipment powered by fuel combustion at the port. However, ships do not need to stop at a UK port to contribute to UK $PM_{2.5}$ concentrations. Domestic shipping contributes a small proportion of the shipping emissions around the UK, and the UK only has indirect influence on international shipping e.g. through the International Maritime Organisation (IMO).

It should be noted that a number of the measures presented in this section have been developed with reference to the Department of Transport Clean Maritime Plan (CMP) and the underlying analysis that has informed its development. It is emphasised that scenarios developed in this report have been developed by Wood plc and represent the views of Wood plc, and it does not imply that these have been taken directly from the research that was commissioned to inform the CMP.

Alternative fuels

Measure Description

A variety of different specific alternative low/zero emission fuels have been investigated and assessed in terms of their potential to displace the 'traditional' marine diesel fuels currently used as the primary source of propulsion for the vessel fleet. These include liquified natural gas (LNG), biofuels, ammonia, methanol and hydrogen. For purposes of this discussion, the alternative fuels are considered together, noting that the specific considerations in terms of their potential (e.g., for emission reduction, feasibility, barriers and costs) are highly variable between different fuels.

Evidence Base and assessment of evidence

The use of alternative fuels is included in the Department of Transport Clean Maritime Plan (CMP)[158], and assessed in the analysis[8] that underscored the CMP[159] [160] [161]. This provides a consideration of alternative fuels as a means of providing reductions in air pollutants and greenhouse gases under different scenarios of policy ambition and discusses the relative pros and cons of different fuel options.

In general, some fuel types have been assessed in more detail than others. For example, there are a number of studies that have specifically investigated the feasibility and potential for LNG and biofuels in the shipping sector (e.g., DNV GL, 2016[162] ; Kollamthodi *et al*., 2016[163]), as these are technologies are relatively more mature and being implemented in the sector already. For more emerging technologies (e.g., hydrogen/ammonia) there is relatively little information, as this is seen as a more long-term solution with more associated uncertainty, although some assessments have been carried out (e.g., Hansson *et al*., 2020[164]).

[8] Note this work was independent research and was not undertaken by DfT.

Summary of evidence

The use of 'cleaner' alternatives to marine diesel fuel is highlighted in the CMP as a significant measure to achieve significant reductions in air pollutants and greenhouse gases in the shipping sector, with the industry seeing this as a viable option with many ship and port operators moving towards the use of alternatives. For example, evidence has been noted of the LNG terminal installed at Portsmouth[165], and the use of hydrogen fuel in Orkney[166].

The level of $PM_{2.5}$ reduction achieved is likely to be variable between different fuels (e.g., ~40% for biofuels, >90% for LNG, >95% for hydrogen). In the case of ammonia used as a fuel, this presents the risk of possible NH_3 'slip', which would have air quality implications (including the formation of secondary $PM_{2.5}$). Based on the discussion at the workshop, A widespread switch to hydrogen/ammonia is envisaged from around 2035 to 2050.

Operators have indicated that in the shorter term, biofuel and LNG will continue to be pursued and used.

For some alternative fuels (e.g., LNG, biofuels), the industry has already started to use these in relatively large volumes. The future use of biofuel and LNG as a source of power in shipping is a point of some contention in the industry. On the one hand, LNG and biofuels offer the potential for large reductions in $PM_{2.5}$, but may have limited GHG savings when compared to incumbent fuels (heavy fuel oil, marine diesel oil) and considering the full lifecycle of the fuel (e.g., upstream emissions associated with the production of biofuel). The use of biofuel and LNG in the shipping sector may have limited support from Government due to the limited potential to achieve decarbonisation (e.g., there is no coverage for biofuels in shipping under the Renewable Transport Fuel Obligation).

The long-term outlook, however, is for the sector to transition towards propulsion powered by hydrogen fuel (including that stored as carrier fuel such as ammonia or methanol). In the DfT (2019 a,b,c) scenarios, it is envisaged that in 2050, 60-80% of the fuel mix for UK shipping will be powered by ammonia fuel. This measure could be implemented in different ways, depending on the machinery it is used with (e.g., directly in ICE or using on-board fuel cells). There is currently uncertainty regarding precisely how this technology will be implemented in practice in the long-term and this may have implication for the overall uptake and feasibility and associated emissions saving and costs. It is expected that fuel cells will be more practical and effective in some types of vessel (e.g., ferries) than others (e.g., container ships travelling long distances) but could have significant cost implications.

There are a number of key factors and barriers identified in the development of alternative fuels in shipping. Firstly, many alternative fuels result in the need to change onboard storage and port supply/storage infrastructure. Some fuels (Biofuels, LNG) can be used directly in marine diesel engines or turbines and hence, are likely to be more compatible with existing ships and supply/storage infrastructure. For others, e.g., hydrogen/ammonia, there is a need for compression or liquefaction, resulting in new infrastructure and storage equipment, as well as issues around the safe handling requirements (for fuels with high flash point/toxicity). Industry stakeholders indicated they require clarity on what the direction of travel is for the fuel mix in the sector, in order to adequately plan their approach to supply and storage.

Overall, in the relative short term, it is expected that there will be a higher unit cost for alternative fuel relative to traditional diesel fuel. However, there is limited data currently available, as the use of hydrogen/ammonia is seen a more long-term measure and is currently at trial stage. The development of alternative fuels also has implications for investment in new/modified vessels, as the vessels that are being developed currently will need to be compatible with the fuel supplied for the next 30+ years, leaving the operators with a risk of 'stranded assets'. Another implication for operators, is that alternative fuels may also have lower fuel density than liquid fossil fuels, requiring more storage space and reducing the available cargo space for vessels.

One further aspect is that the international nature of shipping must be considered. Standards and targets are often agreed at international level, giving UK ports and authorities limited direct control over the supply of fuels in other parts of the world.

Enabling this measure to be implemented widely will require significant investment in both the technology and widespread production of alternative fuels, and the necessary infrastructure to enable its safe and efficient supply to ports. There also is a need to committed policy support to encourage the uptake of alternative fuels in this sector, through appropriate incentives, standards and international cooperation.

Summary - Alternative Fuels

Factor	Summary		
Benefits	LNG – PM (>90% reduction); NOx (85% reduction) Biofuels – PM (38% reduction); NOx (0% reduction) Ammonia/Hydrogen – PM (>99% reduction); NOx (0% reduction); issue of potential NH3 'slip' Some fuels (e.g., hydrogen/ammonia) are expected to also have GHG reduction benefits; other fuels (e.g. biofuel, LNG) are considered less beneficial from a GHG perspective.		
Barriers	Implications for fuel density – knock on effects for vessel efficiency and storage/cargo capacity Alternative fuels often come at a higher cost (price premium for alternatives) Engine warranties may not often cover alternative fuels. Possible disconnect between air quality action and climate actions, with some fuels (e.g. hydrogen/ammonia) likely to be more supported by government than others (e.g. LNG, biofuel). Ports are not able/willing to bunker/supply many different fuel types so require clear guidance on likely future trends to enable them to plan for the 'right' fuels in the future. Safety issues around handling of toxic/flammable fuels International nature of shipping / lack of control over what other global operators do in terms of fuel transition		
Investment Requirements	Investment in the innovation and scape up of domestic production of alternative fuels to meet the demand of the shipping sector New/modified infrastructure will be required for supply and storage of some alternative fuels Training of port and seafaring staff		
Policy Requirements	Incentivisation for take-up of cleaner fuels (e.g., lower tax on alternative fuels to encourage its use). Standardisation of systems to encourage industry uptake. Exploration of synergies in alternative fuel development. A tighter NOx standard could bring forward alternative fuels as the costs of alternative fuels become more comparable to (synthetic fuels and exhaust treatment). Further funding and development of 'Clean Maritime Clusters' to support transition to cleaner fuels. Support of global partnerships and collaboration.		
Factors Affecting Timescales	Both fleet and infrastructure have ~30 year life so what is built now needs to be compatible with operation in 2030s – risk of stranded asset and tech lock. This is why it has been indicated that LNG is not an option. CMP envisages widescale uptake of ammonia/hydrogen from 2035-2040 onwards. Likely that LNG/biofuels will be used in the shorter term.		
Ambition Scenario	**Medium**	**High**	**Speculative**

Factor	Summary		
Input for emissions modelling	**For LNG:** 10% uptake from 2030 (no additional uptake beyond this expected) **For biofuels:** 5% uptake in 2030 10% uptake in 2040 5% uptake in 2050 **For Ammonia/Hydrogen:** 5% uptake by 2030 10% uptake by 2040 50% uptake by 2050	**For LNG:** 15% uptake from 2030 (no additional uptake beyond this expected) **For biofuels:** 10% uptake in 2030 20% uptake in 2040 10% uptake in 2050 **For Ammonia/Hydrogen:** 5% uptake by 2030 15% uptake by 2040 60% uptake by 2050	**For LNG:** Same as high **For biofuels:** Same as high **For Ammonia/Hydrogen:** 10% uptake by 2030 20% uptake by 2040 70% uptake by 2050
Justification	For ammonia/hydrogen - based on scenarios presented in the DfT CMP and stakeholder feedback. For LNG and biofuels - aligns with the medium scenario of the MPMD.	For ammonia/hydrogen - based on scenarios presented in the DfT CMP and stakeholder feedback. For LNG and biofuels - aligns with the high scenario of the MPMD.	For ammonia/hydrogen - based on scenarios presented in the DfT CMP and stakeholder feedback. For LNG and biofuels - aligns with the high scenario of the MPMD.

Electrification of vessel propulsion

Measure Description

Electrification of vessel propulsion refers to the storage of electrical power in batteries (primarily of the lithium-ion type) which can be used to power all operations (full electric), some operations or to manage variations in power demand on ships (hybrid systems). No emissions are produced through the operation of batteries, but upstream emissions can be high depending on how the electricity used for charging the batteries is produced.

Hybrid systems use battery technology commonly in combination with a diesel engine (or other engine types including fuel cells and gas turbine engines) power to power some of the ship's propulsion usually to ensure that the diesel engine is operating most efficiently[167].

Evidence Base and assessment of evidence

The electrification of vessels is considered to be a measure/technology suitable for a zero-emission shipping industry by the DfT as evidenced in the CMP. This has also been supported by a series of reports (the *Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution* series), commissioned by the Department of Transport[9]. In particular, within this series, the reports on *Maritime Emission Reduction Options* and *Economic Opportunities from Low and Zero Emission Shipping*[159]. *Technical Annexes* indicated the current status of this technology. Several academic papers[168], and a report by the EU Commission[169] were used in order to extract quantitative values for implementing this measure. The *Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs* [161] report, commissioned by the DfT, provides an indication of the emission abatement potential and uptake of the measure in the UK. Further anecdotal evidence for this measure was available from port and shipping operators during the consultation (interviews and workshop).

Summary of evidence

[9] Note this work was independent research and was not undertaken by DfT.

When used as a full electric setup, is has been indicated that electrification is most applicable for ships that spend a lot of time at berth or those that have variable energy requirements as part of their role (offshore ships, ferries and some fishing vessels) (DfT, 2019). Hybrid systems are suitable for use in both new-build and retrofitted ships and are most suitable to ships with a variable power requirement (occurring from manoeuvring and changes in speed) and smaller to mid-sized ships[170]. Indeed, hybrid systems are commercially available and used currently in tugs, offshore vessels and cruise ships.

Given the relatively limited number of vessel types suitable for full electrification, the electrification of vessels using full electric systems has the potential for a moderate $PM_{2.5}$ abatement (30+%). However, this level of abatement is what could be achieved locally. The abatement for emissions at sea using a full electric system is variable and has been modelled by the DfT at 0-30%[171]. For hybrid systems utilising a diesel combustion engine, a moderate fuel reduction efficiency of up to 20% has been seen[170]. Upstream emissions from the use of electrification technologies can occur when electricity is generated and is variable dependent on the method of electricity generation. Furthermore, the production of batteries and their disposal can both have environmental impacts with respect to the metals used for their construction[172].

Information on costs was most widely available for hybrid engines as they have been more widely implemented than full electric systems. A report for the EU Commission on the GHG emission reduction potential of EU-related maritime transport and on its impacts estimated the investment costs for diesel electric hybrid systems to be between EUR 1-2m and more for very large vessels[169]. For example, the investment cost for the hybridisation abatement measure is EUR 1,112,500 in general cargo ships and EUR 4,180,000 in container 4,000 TEU ships[169].

Others modelling attempts from academia have estimated the capital costs of diesel electric hybrid systems at EUR 912,086 for a small passenger ferry compared to EUR 632,660 for a conventional diesel engine. These same authors have modelled the first year operational costs for a diesel electric hybrid small passenger ferry at EUR 2,217,934[173]. The cost of electricity was taken from Department for Business, Energy & Industrial Strategy's quarterly energy costings and was indicated as £0.11/kWh[174]. The cost of training seafarers in the use of this technology would also need to be factored in to total costs. Infrastructure would also be required to supply electricity to charge onboard battery units and this comes at a substantial cost (see the shore power measure).

Clearly, the cost of both new build/retrofitted electrified systems is high, as well as the cost of supplying the infrastructure needed to support this measure. As a result, the costs associated with this measure form a barrier to implementation and, as identified in the workshop, public funding would be needed to allow payback of this measure to occur. Further barriers to implementation of electrification of vessels include the fact that this measure is not readily competitive with liquid fuels (e.g., volume and cost of storage). Furthermore, the size and weight of batteries for ships limits their range and they are unsuitable for use in larger ships[158]. As a result, the use of a full electric system is currently only used in ships where a short (1 to 2 hour) journey time is needed. There are also current limits on where electrified vessels can charge, as well as limits on being able to easily retrofit existing ships with this measure as there are often incompatibilities with engine types[158].

Summary - Electrification of Vessel Propulsion

Factor	Summary
Benefits	Full electric systems have the potential for moderate $PM_{2.5}$ abatement (30+%) (DfT, 2019). Hybrid systems have the potential for moderate fuel reduction efficiencies (<20%)[170]. The maximum emissions saving potential has been estimated to be <5%[169]. Battery/hybrid solutions are more appropriate for ships with varied operational profiles. There are other efficiencies associated with shaft line orientation and mass balance in vessel.

Factor	Summary		
Barriers	There is a resistance to moving away from today's technologies; marine diesel engines and turbines are inherently reliable. There is a high cost of the machinery to overcome – key barrier for operators. Electrification of vessels is not competitive with liquid fuels (e.g., volume and cost of storage). Size and weight of batteries for ships limits their range and they are unsuitable for use in larger ships. Currently only short (1 to 2 hour) journey times are possible using full electric systems. The current shoreside network capacity is limiting for charging batteries (in some ports more than others). Electrification is more suited to new build ships than retrofitting due to different engine type.		
Investment Requirements	There is a massive initial capital investment needed with no reasonable business plan showing pay back without public financial input. High Infrastructure costs associated with the supply of electricity to ports and in large enough quantities. The use of containerised battery banks that could be swapped out (short trips) (a more modular approach) could disperse investment costs.		
Policy Requirements	Wider policy aspect concerning the sources of electricity provided for vessel electrification from the grid – need to support clean and renewable sources of electricity to ensure the emissions are not simply transferred to another sector. Incentives are needed for investment - e.g., capital allowances, exemptions from some of the per unit taxes. It was suggested in workshops that mandating that ships switch to renewable sources of energy when at anchor could be beneficial e.g., batteries, fuel cells etc.		
Factors Affecting Timescales	The timescale of electrification of vessels will be determined by battery development timescales. The supply of trained/qualified crew will also influence the timescales of implementation. To reduce these timescales, it could be mandated that ships are berthed without using fossil fuels.		
Ambition scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	**For hybrid vessels:** 5% uptake by 2030 10% uptake by 2040 20% uptake by 2050 **For full electric vessels:** 20% uptake by 2030 40% uptake by 2040 60% uptake by 2050	**For hybrid vessels:** 10% uptake by 2030 20% uptake by 2040 10% uptake by 2050 **For full electric vessels:** 30% uptake by 2030 50% uptake by 2040 70% uptake by 2050	**For hybrid vessels:** 10% uptake by 2030 30% uptake by 2040 20% uptake by 2050 **For full electric vessels:** 40% uptake by 2030 60% uptake by 2040 80% uptake by 2050

Factor	Summary		
Justification	Based on scenarios presented in the DfT CMP and stakeholder feedback. These values apply only to applicable vessel types (e.g., ferries, tug boats).	Based on scenarios presented in the DfT CMP and stakeholder feedback. These values apply only to applicable vessel types (e.g., ferries, tug boats).	Based on scenarios presented in the DfT CMP and stakeholder feedback. These values apply only to applicable vessel types (e.g., ferries, tug boats).

Fuel efficiency measures

Measure Description

A variety of technical measures can be applied to vessels (e.g., propulsion devices, changes in the shape of the hull, hull coatings), machinery and engine modifications (e.g., design improvements to the diesel engine, energy recovery from waste heat, air cavity lubrication) to improve the energy efficiency of the vessel movement, and achieve a proportionate saving in fuel usage and associated primary emissions ($PM_{2.5}$, NO_x, SO_2). Similarly, behavioural changes and modifications to operations can also improve energy of vessels (e.g., speed/voyage optimisation, just in time arrival/turnaround at ports) and reduce the fuel usage and associated emissions from vessels.

Evidence Base and assessment of evidence

The use of technical and operational measures to improve vessel energy efficiency are highlighted as potential measures to achieve reductions in air pollutants and greenhouse gases in the shipping sector in the Department of Transport Clean Maritime Plan[175]. An overview of a number of technical efficiency measures for shipping vessels has been produced by the Royal Academy of Engineering (2013)[170]. Assessment of the potential fuel efficiency saving and costs associated with implementing a number of these measures has been undertaken, both in the analysis underlying the DfT CMP[10] and in the IMO's Global maritime energy efficiency partnerships (GLOMEEP) programme and Energy Efficiency Appraisal Tool[176].

Summary of evidence The available assessments and industry feedback indicate that the level of energy/fuel efficiency achieved will vary considerably between specific technical measures and level of feasibility and effectiveness of measures will vary with vessel type. A specific technical measure can be expected to have a 1-10% efficiency improvement for a vessel. Operators indicated they expect an improvement in fuel efficiency to have corresponding improvements in air pollutant and greenhouse gas reduction.

The IMO (Energy Efficiency Design Index (EEDI))[177] sets very ambitions targets for improvements in efficiency over time, so there is likely to be a significant BAU improvement in the fuel efficiency of the fleet, largely driven by less efficient stock being taken out of service and replaced with newer efficient vessels. To achieve improvement in addition to this BAU improvement, will require additional retrofit of existing stock and/or encouraging a more rapid replacement of less efficient vessels.

Operators indicate that operational energy efficiency improvements can be applied to the existing fleet and new ships and are generally fast to implement. However, these can be challenging to deliver in practice, and are impacted by factors such as tides, weather conditions etc. While speed reductions have been considered a feasible option, other options have also been adopted in a few instances but are not widespread despite being ready and mature (DFT CMP, 2019). Mandatory speed limits may result in the need for more ships to be built.

[10] Note this work was independent research and was not undertaken by DfT.

Industry have indicated that, despite the potential fuel (and cost) saving from improved efficiency, ship operators are unlikely to be motivated to implement retrofits of additional technical measures, without appropriate financial support/incentives. They are likely to implement the minimum measures to comply with current regulations and standards but not above and beyond this.

The lack of standardisation, coordination and knowledge sharing between port authorities and training of port workers to handle different vessel designs is also viewed as important barriers. Policy drivers and strong incentives are needed to increase the uptake of fuel efficiency measures.

Summary - Fuel Efficiency Measures

Factor	Summary		
Benefits	Variable (<1%-10% saving possible) – corresponding proportional reduction in emissions/GHGs. Fuel (and associated cost) saving for operators.		
Barriers	Lack of incentive for retrofitting measures. Cost savings via fuel efficiency technologies (wind/hull coatings) face significant barriers to uptake through lack of Demonstrators/Innovation Funding. Challenges of a variety of issues affecting arrival times – e.g., tides, weather conditions etc. Lack of standardisation in practices for ports. Lack of practical knowledge/training at ports for handling new/different ship types. Shipyards need to reduce the premium added to non-standard designs (i.e., new designs that are more efficient).		
Investment Requirements	Initial installation costs are large Additional maintenance/training costs		
Policy Requirements	Policy and strong incentives needed to increase the uptake of fuel efficiency measures as companies respond to policy drivers.		
Factors Affecting Timescales	Technology is mature and available, timescale is dependent on supporting and incentivising adoption of improved efficiency measures.		
Ambition scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	20% uptake by 2030 40% uptake by 2040 50% uptake by 2050	30% uptake by 2030 50% uptake by 2040 70% uptake by 2050	40% uptake by 2030 60% uptake by 2040 80% uptake by 2050
Justification	Based on scenarios presented in the DfT CMP and stakeholder feedback. Uptake potential differs considerably between individual measures.	Based on scenarios presented in the DfT CMP and stakeholder feedback. Uptake potential differs considerably between individual measures.	Based on scenarios presented in the DfT CMP and stakeholder feedback. Uptake potential differs considerably between individual measures.

	Assumes relatively low retrofit incentive.	Assumes moderate retrofit incentive.	Assumes relatively high retrofit incentive.

Renewable power for vessels

Measure Description

The use of renewable energy has been considered as one measure here given the equivalent effects on reductions in fuel combustion. This includes both wind and solar power. The use of nuclear power was also discussed in the workshop and could have similar effects on fuel combustion, albeit there are significant security concerns.

For wind power, fixed sails, Flettner rotors and kites could, for example be used to reduce fuel consumption and the emissions produced from combustion. However, these techniques cannot be used as a sole energy source, and they are most effective at sea rather than near ports, but they can reduce the reliance on conventional fossil fuel combustion. Sails are used to directly harness the power of wind and Flettner rotors spin as wind passes across their surface which in turn develops thrust. Kites fly at high and variable altitudes to produce forces in the direction of ship motion in order "tow" vessels[158]. Solar energy can be used to reduce reliance on the combustion of conventional fossil fuels as it can be used to produce electricity (stored in batteries) to power systems onboard vessels but cannot be used as the sole energy source[158].

Evidence Base and assessment of evidence

The use of renewable power in vessels is considered to be a measure/technology suitable for a zero-emission shipping industry by the DfT as evidenced in the CMP. This has also been supported by a series of reports (the "Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution" series), commissioned by DfT[11] A technical annex to the aforementioned report series by the Department of transport (DfT, 2019), academic papers (Rehmatulla, Parker, Smith, & Stulgis, 2015; Chowdhury, Rahman, Chowdhury, & Nuthammachot, 2020)[178 179] and a consultancy report (Maddox Consulting, 2012)[180] were used in order to provide cost estimates for this measure. The *Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs* report[161], commissioned by the DfT, provides an indication of the emission abatement potential and uptake of the measure in the UK. Further anecdotal evidence for this measure was available from port and shipping operators during the consultation (interviews and workshop).

Summary of evidence

This technology is not applicable to certain vessels due to lack of deck space (including offshore vessels) or the need for cranes/equipment to facilitate loading/unloading (such as some dry bulk carriers)[158]. For example, technologies such as Flettner rotors that require a lot of deck space are often not applicable to container ships or cruise ships (DfT, 2019). Some measures are suitable for new build (NB), retrofitted (RF) or both. According to the Royal Academy of Engineering[170], the ship types most applicable for renewable technology such as solar includes tanker/bulk carriers (NB/RF), Ro and Ferries (NB/RF), cruise ships (NB/RF), general cargo ships (NB/RF) and fishing vessels (NB).

The underlying analysis by Frontier *et al.* (2019)[181] for the DfT CMP showed that some vessel types will implement renewable technologies as BAU. For example, ferries are envisaged to implement solar technology at 100% uptake by 2031. Other vessel types (e.g., container, oil tankers) are expected to have much lower uptake of renewable technologies (0-40%).

$PM_{2.5}$ abatement levels vary depending on whether the measurements are taken locally to ports or at sea. Use of wind power is associated with a local $PM_{2.5}$ abatement of 0-10% and at sea $PM_{2.5}$ abatement of 10-30%. Solar power is associated with general $PM_{2.5}$ abatement of 0-10% (DfT, 2019). Both technologies have associated carbon savings as well as offering $PM_{2.5}$ reductions although both naturally produce end-of-life

[11] In particular, within this series, the reports on *Maritime Emission Reduction Options* and *Economic Opportunities from Low and Zero Emission Shipping. Technical Annexes* indicated the current status of this technology. Note this work was independent research and was not undertaken by DfT.

waste. Solar panels/PV cells have been associated with the leaching of chemicals and heavy metals such as cadmium and lead after their disposal[179].

There are substantial costs association with the installation of renewable technologies to both new-build and existing ships. Indeed, for all renewable technologies, ship system and design changes (e.g., battery and electric systems, hull designs etc) would be required for existing ships to be compatible with these technologies, which comes at a high cost. Participants in workshops identified that the conversion of ships is prohibited if solar, electric powered systems are proposed and identified the need in this instance for new ship designs. Other participants highlighted that development of a wind powered ship prototype could cost at least £20m.

With respect to wind power, a Flettner rotor installation on the largest category of bulker costs $2.7m and kite installation on largest category of container ship costs $3.4m (DfT, 2019). On the other hand, the fuel savings for an oil tanker using wind power to supplement its combustion engines could be $1,128,000 per annum (Rehmatulla, Parker, Smith, & Stulgis, 2015). For solar power, it has previously been identified that a car carrier, with 40kW solar cells, would require an investment of $1.67m[180].

Currently, there are few drivers to encourage shipping to move towards renewable technologies such as these and there are variable returns on investment both of which present a significant barrier to uptake. The costs associated with refitting ships for use with this measure can also present a barrier. Furthermore, the measure is not applicable to certain vessels due to lack of deck space or the need for cranes/equipment to facilitate loading/unloading and cannot be used as a sole energy source[158 180]. There is also a general uncertainty surrounding the commercial competitiveness of renewable technologies compared to other fuels/energy sources. How these barriers are address and the timescales over which these barriers are lifted will both have an influence over the timescale of the uptake of renewable technologies.

Summary - Renewable Power for Vessels

Factor	Summary
Benefits	For wind: Local $PM_{2.5}$ abatement of 0-10% (DfT, 2019). At sea $PM_{2.5}$ abatement 10-30% (DfT, 2019). For solar: $PM_{2.5}$ abatement of 0-10% (DfT, 2019). Some ports have seen improved air quality under this measure. Lower OPEX for vessels can occur through reduced fuel usage. 1-10+% fuel savings could be seen with ships utilising wind power. Technologies for this measure ca be applied to tanker/bulk carriers (but are of less benefit around coasts).
Barriers	There is a lack of a driver at the moment and a variable return on investment. The high capital cost of new hulls needed for this measure can be high. There is a need to get the technologies accepted as standard. Cannot be used as a sole energy source (DfT, 2019). Not applicable to certain vessels due to lack of deck space or the need for cranes/equipment to facilitate loading/unloading (DfT, 2019; Maddox Consulting, 2012). General uncertainty surrounding commercial competitiveness vs other fuels/energy sources (DfT, 2019).

Factor	Summary		
Investment Requirements	A large investment required for renewably-powered vessel e.g., a Wind Ship anecdotal example was given as around £20m to get a prototype during workshops. Conversion of vessels is prohibitive if electric (solar) propulsion is proposed so would need new designs. For several of the measures falling under the category of renewably-powered vessels, the need for ship system and design changes is apparent e.g. battery and electric systems, new hulls, which come at a cost. Need both turnover and retrofit – penalty for retrofit to some extent (harder for vessels where they have higher cap ex). For wind: Flettner rotor installation on largest category of bulker costs $2.7m (DfT, 2019). Kite installation on largest category of container ship costs $3.4m (DfT, 2019). Fuel savings – for an Oil tanker potential savings could be $1,128,000 per annum (Rehmatulla, Parker, Smith, & Stulgis, 2015) For solar: Car carrier, 40kW solar cells, investment of $1.67m (Maddox Consulting, 2012).		
Policy Requirements	It was identified through workshops that international standards via the IMO are required. Others agreed that these more stringent air quality standards and more expensive fuels would create a driver for renewables. Tax incentives for alternative fuels were also seen as a possible policy measure that could support the uptake of this measure. The need for a verification platform for measuring and reporting carbon emissions was raised. One of the biggest challenges for emissions is ships at anchor. It was suggested that mandating that ships switch to renewable sources of energy when at anchor could be beneficial e.g., batteries, fuel cells etc. Link to carbon pricing - fiscal requirement to take up renewables.		
Factors Affecting Timescales	The barriers to implementation should be addressed which will in turn affect timescales.		
Ambition scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	5% uptake by 2030 10% uptake by 2040 20% uptake by 2050	7.5% uptake by 2030 15% uptake by 2040 30% uptake by 2050	10% uptake by 2030 20% uptake by 2040 50% uptake by 2050

Factor	Summary		
Justification	Based on scenarios presented in the DfT CMP and stakeholder feedback.	Based on scenarios presented in the DfT CMP and stakeholder feedback.	Based on scenarios presented in the DfT CMP and stakeholder feedback.

Shoreside power for vessels

Measure Description

Shoreside power (also commonly referred to as onshore power, alternative maritime power or cold ironing), enables ships at dock or in dry dock to use shoreside electricity to power onboard electrical systems, such as lighting, ventilation, communication, cargo pumps, and other critical equipment, while turning off their auxiliary engines, thus eliminating diesel emissions resulting from the auxiliary engines. The electricity comes from the local power grid through a substation at the port and is plugged into special power connectors in the shore power system on the ship[182].

Evidence Base and assessment of evidence

Shoreside power is considered as an emission control measure (greenhouse gas and air pollutants) in the DfT CMP and the underlying analysis. This provides some indication of the potential emission abatement potential and uptake of the measure in the UK. There have been a number of feasibility and cost-benefit analysis studies for major port electrification projects across the world (in Europe, North America and Asia), providing quantitative estimates for the emission abatement for air quality pollutants, and the associated costs of implementation and operation. The potential for shoreside power in the UK has been investigated by the British Ports Authority (BPA, 2019). Further anecdotal evidence for this measure was available from port and shipping operators during the consultation (interviews and workshop).

Summary of evidence

Shoreside power for ocean vessels has been implemented in a number of ports in different areas of the world (Europe, North America and Asia) and its feasibility, effectiveness for reducing air pollutant emission, and associated costs have been estimated (see for example studies presented for Port of Shenzhen, China[182], and the Ports of Los Angeles and Long Beach, USA[183]. The method is generally applicable to all ship sizes and variations although it is most applicable for ships that spend a lot of time at berth (e.g., offshore ships, ferries and some fishing vessels).

From the sources above, it is estimated that the provision of shoreside power for vessels at berth can reduce the primary $PM_{2.5}$ emissions from the use of auxiliary engines by ~90-95%. The use of auxiliary engines only constitutes a relatively small (15-20%) of total vessel emissions, so the potential emission saving for the sector as a whole is likely to be in the range ~10-15%. However, as these emission reductions would be at the port, there is potential for reductions in $PM_{2.5}$ concentrations where people are exposed. The implementation of shoreside power will also have several cross-media effects, including reduction in carbon emissions. This will also enable noise reduction, especially in ports that are close to city centres, as well as helping to enable electrification of vessels (e.g., battery charging).

The implementation of shoreside power requires substantial investment of capital from both port and vessel operators, to install, upgrade or retrofit the required offboard technologies (e.g., substations, switchgear and power connections).

The estimated overall costs of port electrification projects are highly uncertain and variable with location and port size (range of €2-80m EUR quoted in the BPA, 2019 study). The overall cost of installation per berth will vary depending on the type of vessel (see CARB, 2019[183]). The estimated capital costs for installation at ports in the UK has been provided by BPA (2019), noting that the main costs are created by: network capacity upgrades or reinforcement (£2m - £25m); off-grid generation (up to £6m); and infrastructure improvements inside port or terminal, including groundwork, etc (£0.3m to £10m).

Clearly, there is a wide range of total cost per port for the installation of shore power, and an overall total value for CapEx costs from this measure is difficult to estimate as the total number of port locations, and the scale of costs at each location have not been assessed.

For capital costs for vessels, there is a need to install the required equipment (e.g., cable reel, connection boxes, switchgear, transformer and control panel). Installation costs will vary with vessel type and size (e.g. ($50k to $3m USD per vessel, as provided by the GLOMEEP Project). There are also operational costs relating to labour (estimated at ~$2500 USD per vessel visit); and maintenance (estimated at ~$10,000 USD per vessel; $25,000 per berth – CARB, 2019). Further upstream there may also be costs related to power network reinforcement or local generation if the port is in a poorly connected location.

These capital costs are viewed as the main barrier for shoreside power implementation, as the costs are incurred by the port and vessel operators without a direct return on investment from its use, so means there is a lack of initial demand in the absence of incentives. Furthermore, with the costs of electricity in the UK being relatively high (~11p per kWh vs <8 p per kWh in other countries) (BPA, 2019), it is often cheaper to run auxiliary engines than pay for electricity.

Another key barrier is the potential issues with the electricity network capacity in the area around ports, and the requirement for varying voltage levels. The UK's electricity network operates at a frequency of 50Hz, and since there is no frequency standard for vessels, a significant proportion the global fleet is operating 60Hz systems (e.g., 30% of ferry/RoRo and 20% of Oil Tankers in the global fleet are estimated to be compatible with 50 Hz).

Ultimately, the outlook for the implementation of this measure, is that the technology is proven and has the potential to be widely implemented in ports in the UK by 2040, provided there is sufficient policy support to address the barriers (e.g., capital and funding support, mandating use of shore power or zero emissions standards at ports, tax incentives etc).

Summary - Shoreside Power for Vessels

Factor	Summary		
Benefits	Reduction of primary $PM_{2.5}$ emissions from vessel aux engines of >90% (assuming grid energy is derived from a clean source). Aux engines at berth represent a relatively small (e.g., 10-15%) proportion of total vessel emissions; therefore in terms of total emission reduction, a 10% saving is assumed. Cross-media - decarbonisation, noise reduction, electrification of vessels (e.g., battery charging).		
Barriers	Capital costs - seen as the primary barrier, and currently results in a lack of overall demand Capital costs for required infrastructure installation/upgrade at ports (+ lack of direct benefit to port operator) and capital cost of onboard equipment for vessels (+ benefits do not accrue to the ship owner or operator) Lack of capacity in the local energy network, which is related to the capital costs barrier; Price of electricity in the UK is much higher than in other counties Lack of international frequency standard for vessels, leading to potential compatibility issues.		
Investment Requirements	Port infrastructure requirement (estimated made by BPA) e.g.: o Network capacity upgrades, reinforcement (£2m - £25m) o Off-grid generation (up to £6m) o Infrastructure inside port or terminal, including groundwork etc (£0.3m to £10m) Vessel retrofit costs (estimated by the GLOMEEP Project ($50k to $3m USD per vessel) Wider investment in energy grid - extra and variable power demands on the grid so need further infrastructure development.		
Policy Requirements	Funding support for shore power projects (e.g., green maritime fund, or co-investment models) Potential for mandating shore power in ports (aligning with EU requirements) Potential for a zero emission berth standard to incentivise/mandate use of shore power Potential need for a tax exemption for electricity when it is being used to power vessels at berth to bring it into line with marine fuel (which is exempt from tax).		
Factors Affecting Timescales	Shore power technology is available and used already in other ports across the world. Ambition is for some ports to be 'fully' electric by 2030 and for the technology to be relatively widespread by 2040. The potential timescale of rolling out to all ports depends on the level of policy support and incentivisation. Timescales and trajectory of uptake likely to be variable for different sizes of port, and different vessel types (e.g., faster uptake (10-15 yr) for ferries/cruise, moderate (15-20 yr) for container ships, slower (20-30 yr) for larger ships/tankers).		
Ambition scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	5% uptake by 2030 20% uptake by 2040	7.5% uptake by 2030 35% uptake by 2040	10% uptake by 2030 50% uptake by 2040

Factor	Summary		
	60% uptake by 2050	75% uptake by 2050	90% uptake by 2050
Justification	Based on scenarios presented in the DfT CMP and stakeholder feedback. Ambition was for at least one port to be fully electrified by 2030.	Based on scenarios presented in the DfT CMP and stakeholder feedback. Stakeholder feedback indicated that a higher level of ambition was feasible than under the medium scenario.	Based on scenarios presented in the DfT CMP and stakeholder feedback. This scenario assumes uptake is at the upper range to what stakeholder feedback indicated is feasible.

Exhaust treatment

Measure Description

Several of the measures considered have focussed on reducing primary $PM_{2.5}$ emissions, however, secondary PM formation is an important factor, so measures to reduce the emissions of NO_x from shipping need to be considered. This was highlighted in the workshop, noting that, in the short-medium term, it is likely that the industry will likely switch to using low sulphur diesel fuel, that will enable and necessitate the use of exhaust treatment techniques.

Technologies to treat exhaust gases to capture, treat or remove air pollutants are available (e.g. diesel particulate filters, DPF, and selective catalytic reduction, SCR), which can be expected to reduce the emissions of $PM_{2.5}$ and NO_x from vessel exhaust gases.

Evidence base

Exhaust gas treatment options are considered as an emission control measure (greenhouse gas and air pollutants) in the DfT CMP and the underlying analysis. Information on expected uptake, emission reduction and associated costs of exhaust gas treatment measures such as DPF and SCR are also available from the MPMD.

Summary of evidence

DPFs are expected to achieve a reduction in primary $PM_{2.5}$ of >95%, while SCR is expected to reduce NOx by 80%. Some literature sources consider the technology of reducing PM from marine diesel engines is not mature enough[184], however, in the longer term, both DPFs and SCR are expected to be broadly feasible in all vessel types, but may not possible in some specific vessels (e.g. due to engine configuration or space constraints), so maximum uptake is expected to be 90% for both measures.

Information on the unit CapEx and Opex costs for DPF has not been found specifically for shipping. For SCR, the CapEx and OpEx costs have been estimated in the MPMD and vary depending on vessel size (categorised small, medium, large) – CapEx ranging from £130-300 k per vessel, OpEx ranging from £65-450k per vessel).

Summary - Exhaust Treatment

Factor	Summary		
Benefits	DPF – 95% reduction in PM SCR – 80% reduction in NOx		
Barriers	Capital costs of installation + operational costs May not be feasible in all vessels		
Investment Requirements	Costs to the ship operators – new vessels or retrofit		
Policy Requirements	Appropriate incentives/support to encourage uptake Support for innovation and scale up of technologies		
Factors Affecting Timescales	Techniques are mature and available, the timescale of implementation is dependent on the level of incentive/support from Government.		
Ambition scenario	**Medium**	**High**	**Speculative**

Factor	Summary		
Input for emissions modelling	For both DPF and SCR/EGR (NOx only): 45% uptake in 2030 (no uptake beyond this expected due to shift towards alternative fuels.	For both DPF and SCR/EGR (NOx only): 90% uptake in 2030 (no uptake beyond this expected due to shift towards alternative fuels.	Same as high.
Justification	Measure only required in the short term and not beyond due to shift towards alternative fuels. Lower uptake	Measure only required in the short term and not beyond due to shift towards alternative fuels. Higher uptake	Measure only required in the short term and not beyond due to shift towards alternative fuels. Higher uptake

Electrification of port machinery

Measure Description

Ports utilise a range of vehicles and equipment for a variety of purposes, essential to the functioning of the port. This measure would replace existing power sources using conventional, fossil fuel-based engines and generators, to either direct grid connections or to battery power and storage[158]. The move to electrified port machinery will in part be the result of a port's own shift toward reducing emissions in line with their own Air Quality Plan. With reference to NAEI nomenclature, this measure applies to Non-Road Mobile Machinery (NRMM) (shipping) emissions, rather than the shipping sector.

Evidence Base and assessment of evidence

The use of electrification of port machinery is considered to be a measure or technology suitable for a zero-emission shipping industry by the DfT as evidenced in the CMP. Compared to some of the other measures mentioned in this report, the electrification of port machinery was not as widely assessed in the literature as a potential measure for reducing $PM_{2.5}$ emissions than measures related to ship emissions. Information for this section was largely obtained from industry reports, academic papers and expert workshops and interviews. Data on the cost of electrifying port cranes was obtained from Cederqvist and Holmgren[185]. and information on industry electricity prices were taken from BEIS quarterly reports.

Summary of evidence

During workshops with industry stakeholders, it was indicated that $PM_{2.5}$ emission reductions from port machinery could be >99% with other studies highlighted to have shown the small percentage contribution of port machinery to total $PM_{2.5}$ emission.[186]. As a result, although investments are already being made with regards to the electrification of port machinery in some ports, the overall benefits to this measure are likely to be relatively modest. Furthermore, the imminent restriction on the use of Red Diesel in shipping NRMM may shift operators towards the use of electric or other low emission equipment, which can be considered as part of the baseline scenario.

At the workshop, there was considerable debate regarding the barriers of using electric equipment. Some workshop participants believed that the required investments to enable the use of electric equipment are large, but not prohibitively more expensive than the diesel equivalent. However, others thought that electrified machinery is often considerably more expensive the diesel equivalent. The costs association with the electrification of port cranes alone can be of the order USD $500,000 to $1,000,000 (2011 prices) for C-ASC and RTG-type cranes[185]. In general, the costs for electrification of port equipment are large although it has been identified that these costs will reduce as uptake increases.

These high investment costs are a significant barrier to the implementation of this measure. Furthermore, the lifetime of a piece of port equipment can be up to 30 years or more which does not create a business case for switching to an electrified alternative. Further barriers related to existing port infrastructure and equipment include insufficiencies in the existing electricity network infrastructure and the large distances ports are from nearby substations which can result in large costs for this measure. Some stakeholders at the workshop suggested that electrified port machinery often has a lower performance compared to conventional diesel counterparts and it is usually more expensive that its diesel counterpart. Other significant barriers include the split incentives to invest and coordination failures between ports and the shipping industry, imperfect information on abatement options and regulatory constraints (DfT, 2019).

For operational costs, the cost of electricity has been identified from BEIS quarterly reports as being of the order £0.11/kWh. Precisely what the additional demand on electricity will be from the implementation of this measure is unclear. There will be additional costs for electricity but savings in costs due to reduced fuel usage. The volume of fuel saved from this measure is also unclear at this point.

Many of the policy requirements for this measure were identified through stakeholder engagement. Overall, it was highlighted that policies should aim at an end point (e.g., reduced emissions), rather than at technology (e.g., electrification). However, it was also identified that there is the potential for support for investment decisions (e.g., green capital allowances, scrappage schemes) and there is the potential for exemptions on some of the tax elements per MWh cost to improve in use economics and investment cases. Realistic timeframes for the introduction of technologies would be beneficial for industry. However, during workshop, not all participants agreed that policy requirements would be necessary.

The timescales over which this measure could be implemented depends partly on the availability of sufficiently capable equipment necessary for port electrification. They also vary for each port depending on the remaining life expectancies of their existing equipment (which can be more than 30 years for new equipment).

Summary - Electrification of Port Machinery

Factor	Summary
Benefits	Replacement of diesel could reduce direct PM emissions by >99%. Known technology for some applications and initial investment already happening (e.g., eRTGs). Benefits are minimal as ports are a relatively small contributor (<2%) to shipping PM emission).
Barriers	Capital costs - Electrified port machinery usually more expensive that diesel counterpart. Technology is not necessarily mature enough for use at ports yet. Split incentives to invest and coordination failures between ports and operators. Existing infrastructure and onboard technologies (existing electricity network infrastructure is often insufficient Ports are often a large distance from a substation which can result in large costs. Electrified port machinery often has a lower performance compared to conventional diesel counterparts. Ports operate 24 hours a day so the need to charge equipment, can reduce productivity.
Investment Requirements	Initial cost to procure, install equipment Costs are likely to reduce as ports make the shift to going all electric.

Factor	Summary		
	There are further investment requirements related to the cost of electricity supply and infrastructure.		
Policy Requirements	Policies could aim at an end point, rather than at technology (e.g., power supply). Potential for support for investment decisions (e.g., green capital allowances, scrappage schemes). Potential for exemptions on some of the tax elements per MWh cost to improve in use economics and investment cases. Realistic timeframe for the introduction of technologies would be beneficial for industry. During workshops, not all participants agreed that policy requirements would be necessary.		
Factors Affecting Timescales	Impacted by the availability of sufficiently capable equipment - especially for more specialised equipment (where the UK is a small part of what manufacturers consider as a viable market). The timescales are also dependent on the lifetime of current diesel-powered port equipment (which could be 30+ years).		
Ambition scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	No specific port machinery source included in the NAEI, so adjustment for modelling not possible. Emissions of mobile machinery sources adjusted in measures for NRMM covered elsewhere		

Rail

Introduction

As illustrated in Section 2, rail is estimated to contribute 0.4% of total $PM_{2.5}$ emissions in England, 2% of NO_X emissions and a minimal amount (less than 0.01%) of NH_3 emissions. However, it is an important source of emissions at locations near to rail lines.

At present, 38% of all railway lines in the UK (over 6,000 route kilometres) are electrified. Emissions from fuel combustion affect air quality around lines that are not electrified. This can be a particular issue around those stations where trains are stationary (either at the platform or waiting to enter the station) with their engines running.

In addition to emissions from fuel combustion, there are NEE from rail movements, including those associated with brake and rail wear. However, there are no requirements for including NEE from railways in national inventories, nor are there any recommended emission factors and methodologies given in the EMEP/EEA Emissions Inventory Guidebook[127], making it challenging to quantify the emissions and any benefits of measures focussed on rail NEE. Alternative braking options (other than friction wheel brakes) are available for some train/track types, although the effect on particulate emissions is not yet well understood. Magnetic Track Brakes (MTBs) use a magnetic force to create friction between the brake and the rail and therefore cause wear and potentially particulate emissions. Eddy-Current Track Brakes (ECTBs) use magnetic forces alone, rather than friction forces between the vehicle and the rail[187] and therefore would be expected to cause reduced wear. Given the lack of quantification of current emissions and the fact that potential application is limited to high-speed routes with slab track and the right ballast profile[188], this is not considered further.

Traction Decarbonisation

Measure Description

In response to the UK government legal commitment to achieve net zero greenhouse gas emissions by 2050 and the DfT aim of removing all diesel-only trains from the network by 2040 the rail industry has collaborated to prepare the Traction Decarbonisation Network Strategy (TDNS)[189]. Under the TDNS, decarbonisation will be achieved through a combination of electrification (an additional 13,000 Single Track Kilometres (STKs)), hydrogen train deployment (1,300 STKs of infrastructure), and battery train deployment (800 STKs of infrastructure) (plus 300 STKs where a technology choice has yet to be made).

The TDNS will offer a longer-term air quality solution for stations, depots and freight and support the rail industry Air Quality Strategic Framework produced by the Rail Safety & Standards Board (RSSB)[190].

Evidence Base and assessment of evidence

The Network Rail documents on the TDNS[189] provide the main evidence for this measure. In addition to the Interim Programme Business Case, the draft TDNS Programme Business Case has also been provided to give more detail on the geographic aspects of the programme (i.e., which lines are likely to be electrified first).

Summary of evidence

Economic modelling has considered five traction decarbonisation pathways[189]. These are:

- Pathway 1 (Low). The do-minimum plus a decarbonisation strategy that achieves an 80% reduction in traction power carbon emissions from 2019 levels.
- Pathway 2 (Low Medium). The do-minimum plus a decarbonisation strategy that achieves an 95% reduction in traction power carbon emissions from 2019 levels.

- Pathway 3 (Medium). The do-minimum plus a decarbonisation strategy that achieves Net-Zero carbon emissions for traction power from 2019 levels by 2050.
- Pathway 4 (High). The do-minimum plus a decarbonisation strategy that achieves Net-Zero carbon emissions for traction power from 2019 levels by 2040.
- Pathway 5 (Medium). The do-minimum plus a decarbonisation strategy that achieves Net-Zero carbon emissions for traction power from 2019 levels by 2061.

Based on the stakeholder engagement, Pathway 4 is not considered to be feasible as the supply chain is not able to deliver the required amount of electrification in that timescale.

The delivery programme has been refined on the basis of this modelling and economic modelling has been carried out for two further pathways[191]. This has been used to develop a network traction decarbonisation programme framework identifying the relative tranches in which to introduce and implement schemes on a national level. The timescales for the tranches will depend upon the decisions regarding the end points and dates, and the development of the supply chain to meet the increased demand for electrification. The tranches of delivery are broadly aligned to the carbon reporting periods:

- 2027/28 End of 4th Carbon Budget.
- 2032/33 End of 5th Carbon Budget.
- 2037/38 End of 6th Carbon Budget.
- 2050/51 Aspirational date to achieve zero carbon.

Capital costs at this stage have been estimated to range from £1m/STK to £2.5m/STK (2020 prices) for a total of ~£10 billion[189]. The Rail Industry Decarbonisation Taskforce considers that rail will need to move well beyond `business as usual' in decarbonising its operations, to deliver a step change in planning, investment and delivery[192].

Summary - Traction Decarbonisation

Factor	Summary		
Benefits	Focus on decarbonisation Co-benefit of reduced $PM_{2.5}$ and NO_X emissions - 97% reduction in traction power exhaust emissions in 2050 assumed under speculative scenario. 80% assumed under high ambition scenario		
Barriers	Significant financial cost Need to redevelop the supply chain Electricity grid capacity		
Investment Requirements	Ramp-up of supply chain Government investment in infrastructure Development of electricity grid		
Policy Requirements	Strong national government support for traction network decarbonisation		
Factors Affecting Timescales	Policy goals (i.e., decarbonisation by 2050 or 2060) Allocation of funding Development of supply chain		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	80% reduction in activity by 2050	97% reduction in activity by 2050 (Net Zero)	97% reduction in activity by 2050 (Net Zero)

Factor	Summary		
Justification	Partial decarbonisation, representing Pathway 1 (low) in the TDNS	Net zero for rail representing Pathway 3 (medium) in the TDNS	Net zero for rail representing Pathway 3 (medium) in the TDNS

Exhaust Treatment (SCR, DOC, DPF) / re-powering

Measure Description

Devices can be fitted to exhausts of trains with ICEs to reduce emissions. DPFs use ceramic filters to trap Particulate Matter. Selective Catalytic Reduction (SCR) uses an aqueous urea solution (e.g., Adblue) over a catalyst to reduce NO_X. A complete aftertreatment system includes a Diesel Oxidation Catalyst (DOC), DPF and SCR. The DOC enhances the nitrogen dioxide (NO_2) content of the exhaust gases increasing the efficiency of the SCR. The benefits of these measures could also be achieved through re-powering where older engines are replaced by newer models that are compliant with tighter emission standards. Older engines can also be replaced with multiple engines with a combined power of the replaced engine. This enables Selective Engine Shutdown (SES).

Evidence Base and assessment of evidence

Evidence for this, and the following rail measures is taken from the Ricardo report *Air Quality Improvement Measures – Cost and Feasibility Study for the Rail Industry*[193] produced for the RSSB in 2019. The Ricardo project involved an extensive literature review and a workshop with industry experts in 2019. The interviews carried out for the present project indicated that this report represents a comprehensive review of the current understanding of the industry with regards to emission reduction measures. Further work on this area is ongoing and is being coordinated by the RSSB.

Summary of evidence

Ricardo report that complete after-treatment systems can reduce NO_X emissions by 50-75% and reduce PM emissions by up to 90-95% without any engine upgrade. If compliance with Stage V (NRE) is achieved, NO_X emissions will be reduced by up to 95% (requiring a larger volume Adblue tank).

There are potential technical challenges with retrofitting of emission abatement systems that mean that they are not feasible for all vehicles. One of the main technical challenges is space on the vehicle (e.g., for the Adblue tank) which takes an additional 5-10% of the volume required for the fuel tank. SCR is also extremely challenging for certain designs (e.g., Voyager and Meridian). Implementation costs per engine are around £30k-£50k plus costs associated with Adblue and slightly higher fuel use. The benefits are external to the operator, such systems are only commercially viable where there are incentives or legal requirements. The potential for government support regarding these costs was discussed in the interviews. There are around 3,300 diesel passenger vehicles that will need to be replaced, re-powered or converted[192, 194].

The Ricardo report considers that re-powering is only viable when the value of the rolling stock remains sufficiently high (given the 15+ year lifetime). Re-power and modification costs may be hard to recover for a limited number of vehicles and may be more viable when split over a larger production volume.

Summary - Rail Exhaust Treatment

Factor	Summary
Benefits	50-75% reduction in $PM_{2.5}$ emissions 90-95% reduction in NO_X emissions
Barriers	Cost of systems Space for treatment systems on vehicles

Factor	Summary		
Investment Requirements	Investment in exhaust treatment systems (~£30-50k per engine)		
Policy Requirements	National policy around rail emissions, or localised policy for specific lines		
Factors Affecting Timescales	Procurement and installation timescales		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	60% reduction in $PM_{2.5}$ 95% reduction in NO_X from 50% of non-electrified lines by 2040	60% reduction in $PM_{2.5}$ 95% reduction in NOX from 20% of remaining non-electrified lines in 2030 and 2040 (noting the complementary measure to increase electrification to 97% by 2050)	60% reduction in $PM_{2.5}$ 95% reduction in NOX from 20% of remaining non-electrified lines in 2030 and 2040 (noting the complementary measure to increase electrification to 97% by 2050)
Justification	Exhaust treatment required where full decarbonisation is not achieved	Required to a reduced level under net zero scenario as there will be increasing electrification up to 2050 and therefore investment in exhaust treatment would be reducing	Required to a reduced level under net zero scenario as there will be increasing electrification up to 2050 and therefore investment in exhaust treatment would be reducing

Hybridisation

Measure Description

On board energy storage systems such as batteries are used to complement the power supplied by diesel engines. Hybrid power trains can either work in series, where the diesel engine is used to charge the storage system, or in parallel, where the diesel and electric engines can both work individually. The energy storage system can be integrated with regenerative braking to collect kinetic energy during braking.

Evidence Base and assessment of evidence

Evidence has been taken from *Air Quality Improvement Measures – Cost and Feasibility Study for the Rail Industry*[193]. Information is also available from other sources such as the RSSB. There is strong agreement around the benefits of hybridisation.

Summary of evidence

Ricardo report that hybridisation (both new vehicle and retrofit) could deliver high reductions in emissions. This is defined as potential compliance with Stage V (NRE) regulations or significant average reduction of emissions. This could be considered to be around 98.5% reduction in PM emissions (emissions of 0.015 g/kwh against 0.2 g/kwh). Ricardo report that hybrid retrofit can reduce NOx emissions by up to 70% and PM emissions by around 90%[193]. The use of regenerative braking would also reduce particulate emissions from friction braking.

Retrofitting a hybrid powertrain is considered challenging because of the space requirements for the energy storage system. Costs are also significant (£400k-£500k) per railcar. Hybridisation may therefore only be viable for short routes where operational cost savings can cover investments, or with incentives or contractual/legal requirements. The Rail Industry Decarbonisation Taskforce also consider that diesel bi-modes should have only a limited role on a transitional basis as part of any route map to contribute to net zero carbon by 2050[192].

Summary - Rail Hybridisation

Factor	Summary		
Benefits	90% reduction in $PM_{2.5}$ emissions 70% reduction in NO_x emissions		
Barriers	Significant costs		
Investment Requirements	Investment in hybrid powertrain		
Policy Requirements	National policy around rail emissions, or localised policy for specific lines		
Factors Affecting Timescales	Procurement and installation timescales		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	90% reduction in $PM_{2.5}$ 70% reduction in NO_x from 50% of non-electrified lines by 2040	90% reduction in $PM_{2.5}$ 70% reduction in NO_x from 20% of non-electrified lines in 2030 and 2040 (noting the complementary measure to increase electrification to 97% by 2050)	90% reduction in $PM_{2.5}$ 70% reduction in NO_x from 20% of non-electrified lines in 2030 and 2040 (noting the complementary measure to increase electrification to 97% by 2050)
Justification	Required where full decarbonisation is not achieved	Required to a reduced level under net zero scenario as there will be increasing electrification up to 2050 and therefore investment in hybridisation would be reducing	Required to a reduced level under net zero scenario as there will be increasing electrification up to 2050 and therefore investment in hybridisation would be reducing

Natural Gas

Measure Description

Compressed Natural Gas (CNG) or Liquified Natural Gas (LNG) can be used as traction fuels. Natural gas has lower particulate emissions than diesel.

Evidence Base and assessment of evidence

Evidence has been taken from *Air Quality Improvement Measures – Cost and Feasibility Study for the Rail Industry*[193].

Summary of evidence

The use of natural gas could deliver a medium emission reduction, defined as "potential compliance with Stage IIIB/Stage V (Rail) standards or moderate emission reduction". Relative to stage IIIA emission standards, it could be expected to reduce PM emissions at stations by 97.5% (emissions of 0.025 g/kwh against 0.2 g/kwh). NO_X and PM_{10} emissions would be significantly reduced relative to diesel.

Barriers in relation to the use of natural gas relate to its flammability and safety concerns. Crashworthy tanks are however available for HDVs, so similar technologies could be employed in the rail industry.

The difference between natural gas and diesel prices is volatile and industry had previously dismissed natural gas as a commercially viable option. However, interest has reportedly grown more recently although investment would be required for additional refuelling infrastructure, for CNG in particular. LNG fuelled trains could potentially be refuelled direct from tankers driven to the vehicle.

Summary - Natural Gas for Rail

Factor	Summary		
Benefits	~90% reduction in $PM_{2.5}$ emissions relative to diesel		
Barriers	Cost of natural gas Lack of infrastructure Safety concerns Lack of proven examples		
Investment Requirements	Development of infrastructure Alterations to engines		
Policy Requirements	Localised policy for specific lines		
Factors Affecting Timescales	Development of infrastructure Price of natural gas		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Speculative technology with lack of decision regarding where and how it may be deployed		

Eco-driving / Optimisation of traffic to minimise stops

Measure Description

More gentle acceleration and reduced braking can be used to reduce emissions. This can be achieved through driver training or through driver aids.

Rail movements can be optimised also to reduce the need for idling and hard accelerations and braking. Smart data solutions can help to achieve this.

Evidence Base and assessment of evidence

Evidence has been taken from *Air Quality Improvement Measures – Cost and Feasibility Study for the Rail Industry*[193]. Other studies on the benefits of eco-driving have also been obtained.

Summary of evidence

Eco-driving has potential for a moderate average reduction in emissions. A study from the Netherlands[195] reports that eco-driving approach has led to yearly energy savings of up to 5%, which can be used to provide an approximation of PM/NO_X emission reductions.

Although not always viable because of time constraints, eco-driving is considered to be feasible and is likely to be supported because of fuel savings.

Optimisation will require handling and analysis of large amounts of data, although these costs could be recouped through fuel savings.

Summary – Rail Eco-Driving / traffic optimisation

Factor	Summary
Benefits	~5% reduction in PM/NO_X emissions
Barriers	None

Factor	Summary		
Investment Requirements	Driver training or driver aids Investment in data solutions Operating costs may be reduced through fuel savings		
Policy Requirements	Education of the industry to encourage such measures and save fuel		
Factors Affecting Timescales	Can be implemented immediately		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	5% reduction in activity by 2025	5% reduction in emissions up to 2040 when decarbonisation is more important for emission reductions	5% reduction in emissions up to 2040 when decarbonisation is more important for emission reductions
Justification	Reduction in activity/emissions (from non-electric lines) that may be achievable based on the literature reviewed	Reduction in activity/emissions (from non-electric lines) that may be achievable based on the literature reviewed	Reduction in activity/emissions (from non-electric lines) that may be achievable based on the literature reviewed

Reduced Emissions at Rail Stations

Measure Description

Shutting down the engine(s) at stations removes the main emission source. This can be achieved in a number of ways. These include:

- Franchise agreements with operators to enforce or incentivise shutdown.
- Stop-Start or Selective Engine Shutdown Technologies. A system to automatically shut engines down at stations to reduce emissions from idling trains. This can be retrofitted to existing engines or incorporated into new designs. Selective engine shutdown can be used alongside stop-start technology to shut down unnecessary engines when power requirements are lower.
- Shore supply where power is supplied through the station (plug-in, 3rd/4th rail, buffer stop, induction charging).
- Use of auxiliary units, separate engines compliant with Stage V emission standards are used while the train is at the station.

Evidence Base and assessment of evidence

Evidence has been taken from *Air Quality Improvement Measures – Cost and Feasibility Study for the Rail Industry*[193].

Summary of evidence

Stop-start and selective engine shutdown technologies, enforcing or incentivising shutdown and shore power will all deliver medium emission reduction. This is defined as "potential compliance with Stage IIIB/Stage V (Rail) standards or moderate emission reduction". Relative to stage IIIA emission standards, this group of measures could be expected to reduce PM emissions at stations by 97.5% (emissions of 0.025 g/kwh against 0.2 g/kwh). SES may also increase the effectiveness of aftertreatment by increasing the load on the engines operating.

Auxiliary units are expected to deliver low average emission reductions.

The main issues with retrofit of stop-start and selective engine shutdown systems relate to risks around non-restart, although these can be addressed using properly engineered systems. Issues with the provision of shore power relate to safety for plug-in, 3rd rail and buffer stop. Providing shore power through induction charging is considered to be technically feasible and safer. Infrastructure costs for shore power are expected to be significant and likely to be most appropriate for terminal stations. For example, one case study showing that costs for update of an existing system were over £600,000[196]. The cost of electricity relative to fuel will be a key driver for decisions.

Summary – Reduced Emissions at Rail Stations

Factor	Summary		
Benefits	Up to 100% reduction in exhaust emissions at stations (likely to be terminals)		
Barriers	Concerns about non-restart Safety issues for certain systems Significant investment required		
Investment Requirements	Investment in infrastructure		
Policy Requirements	Policies around exposure reduction at stations		
Factors Affecting Timescales	Procurement and installation of systems on trains and stations ~ 10-20 years		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	National scale modelling system does not allow for station-specific measures, so not included in modelling		

Aviation

Introduction

As illustrated in Section 2, aviation is estimated in the NAEI to contribute a minimal amount (0.3%) of total $PM_{2.5}$ emissions in England, 4% of NO_X emissions and a negligible amount (under 0.01%) of NH_3 emissions. Emissions from an airport are an important determinant of the pollutant concentrations in the immediate vicinity. Emissions arise from the combustion of fuel in the main aircraft engines used for movements on the ground and in the Landing and Take-Off (LTO) cycle. Emissions also arise from the Auxiliary Power Units (APUs) used to power other systems on the aircraft, and the Ground Support Equipment (GSE) that supports airport operation. In the context of this research, emissions from surface access are addressed separately as Road Transport and Rail.

New aircraft main engine technology

Measure description

Main engines are responsible for approximately half of $PM_{2.5}$ emissions from aircraft on the ground. There is little regulatory pressure to reduce PM emissions, as current engines comfortably meet the existing standards. Tighter standards could be used to encourage manufacturers to update engine designs and reduce $PM_{2.5}$ emission factors.

Evidence base and assessment of evidence

Although details of engine development are commercially very sensitive, the general trends are well known within the industry and regulatory measures are public.

The latest version of the ICAO emissions databank[197] includes measured emissions of non-volatile particulate matter mass and number, which strengthens the evidence base around estimating emissions of this pollutant. Previously more approximate relationships based on smoke number had to be used[198].

Summary of evidence

There are a number of very substantial barriers to this measure for the short or medium term. These were discussed in detail at the workshop. The barriers include:

- The international nature of the industry and its regulation, which limit the influence that the UK is able to exert. Manufacturers need to satisfy regulators around the world for safety and environmental performance. Standards are set by the International Civil Aviation Organization's (ICAO) Committee on Aviation Environmental Protection (CAEP), which represents the international industry and works to long timescales. The small number of highly specialist manufacturers in a field with very high barriers to entry makes it politically difficult and expensive to refuse certification.
- CAEP standards tend to be technology-following, that is they tend to be set to a level which can largely be met by the technology available at the time they come into effect. As such, they have a limited ability to drive improvements in emissions.
- The long timescales to develop and introduce new engines. Typically, there are about 10–15 years between generations of an aircraft model and its associated engines. Once in service an aircraft has a lifetime in the UK of 20–25 years. At the present point in the aircraft development cycle, no significant new aircraft types (or engines) are expected before about 2030. This means that the current generation of aircraft will still be flying until 2050, unless there are active measures to replace them.
- Emissions of $PM_{2.5}$ from aircraft engines are weakly regulated. Standards to prevent the quantity of smoke found in exhaust in 1970s-vintage aircraft are comfortably met by today's engines, leaving little pressure for further improvements. However, at its 2019 meeting, CAEP adopted standards for non-volatile particulate matter mass and particle number, with effect from 2025. Although nearly all existing engines meet these standards, it provides a framework for future tightening of controls.
- Engine design is highly demanding and must meet a number of trade-offs, including cost, fuel efficiency and CO_2 emissions, noise and NO_x emissions as well as $PM_{2.5}$ emissions.

Overall, there is little likelihood of any reduction emissions from this measure before 2030. Step changes in emissions are likely to follow the introduction of new aircraft with new engines between 2030 and 2050, but these are likely to be relatively modest given the demands on other emissions such as CO_2. Historic data suggests that NO_x emissions improve by about 0.5% per year, so a similar level of ambition seems likely for $PM_{2.5}$.

The main focus for engine improvements is likely to be fuel efficiency and CO_2 emissions.

Alternative engine types such as electric or hydrogen are under research and development[199,200,201], but face major obstacles. Commercial hydrogen engines may be introduced for short-haul around 2030 or 2035. Electric engines likely to be limited to very small aircraft / short flights, from around 2030.

Larger aircraft operating longer flights will continue to use liquid fuels (mineral kerosene and/or Sustainable Aviation Fuel (SAF) - fuel produced from sustainable resources such as waste oils, fats and greases) out to 2050. These will continue to emit $PM_{2.5}$, in contrast to alternative power sources such as electric and hydrogen.

Summary – New Aircraft Main Engine Technology

Factor	Summary		
Benefits	Small reduction in $PM_{2.5}$ emissions over a long timescale.		
Barriers	Very substantial barriers to the speedy implementation of this measure.		
Investment Requirements	Part of normal aviation industry lifecycle		
Policy Requirements	Limited UK influence on this measure, but pressure can be applied through CAEP which has UK representation.		
Factors Affecting Timescales	Long timescales. No appreciable reductions in $PM_{2.5}$ emissions likely before 2030, and slow reductions between 2030–2050.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	0% by 2030, 5% by 2050	0% by 2030, 10% by 2050
Justification	Any reductions in $PM_{2.5}$ emissions likely over a long timescale given fleet turnover rates. Relatively minimal potential for $PM_{2.5}$ emission reductions		

Reduced sulphur in aviation fuel

Measure description

A significant proportion of $PM_{2.5}$ emissions from aircraft main engines arises from sulphates due to the presence of sulphur in aviation fuel[202]. Reducing the amount of sulphur in the fuel will results in a proportionate decrease in this contribution to $PM_{2.5}$. For existing (mineral) fuel, this could be done by desulphurisation as is commonly done for other mineral oil fuels. This could also be achieved by blending in SAF, which does not contain sulphur at appreciable levels.

Evidence base and assessment of evidence

Some contradictory information was received through the literature review and stakeholder engagement about aspects such as the regulation of sulphur in aviation fuel and the need for sulphur for lubrication.

The views on the uptake of SAF were broadly consistent in the stakeholder engagement process.

Summary of evidence

A reduction of the amount of sulphur in fuel should achieve a proportionate reduction in the associated emissions from aircraft main engines, estimated to be about half the total.

Although some engines may require a small amount of sulphur and aromatics in the fuel to provide lubrication, some consultees said this was not the case for aircraft jet engines currently in service. Since SAF contains no sulphur, and it is accepted that a blend of up to 50% SAF is acceptable, it is clear that the sulphur content can at least be halved without adverse consequences for lubrication.

SAF uptake is estimated to be in the range 25–32% by 2050[203,204] following a steady ramp-up, with about 10% by 2030. This suggests a reduction of $PM_{2.5}$ emissions of about 5% in 2030 and 15% in 2050 from this measure.

Further reductions could be achieved by reducing the sulphur content of the mineral component of jet fuel. This is technologically feasible — current fuel content is around 600 ppm[205] compared to 10 ppm for ultralow sulphur diesel widely used in other combustion plant. This would increase costs and could have the adverse consequence of increasing tankering if applied unilaterally within England (*tankering is the practice of taking* *on fuel for more than one journey where the price is cheaper, rather than taking on only as much as needed for the next journey*).

However, regulation of fuel specifications is by international agreement, so unilateral action by England may not be possible or desirable.

Summary – Reduce Sulphur in Aviation Fuel

Factor	**Summary**		
Benefits	Reductions in $PM_{2.5}$ emissions of around 5% in 2030 and 15% in 2050.		
Barriers	No regulatory or other drivers. Development of SAF. Cost of desulphurising mineral jet fuel. Possible effects on climate change from reduction of stratospheric aerosols.		
Investment Requirements	Development of SAF infrastructure.		
Policy Requirements	SAF use driven by decarbonisation agenda. Sustainable Aviation have outline policy requirements for promoting SAF[206]] Defra should align with DfT and BEIS on SAF policy.		
Factors Affecting Timescales	Lack of drivers. Development of SAF infrastructure. Long-term driven by decarbonisation agenda.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	5% by 2030, 15% by 2050	5% by 2030, 20% by 2050
Justification	Based on uptake rates for SAF, driven by carbon reductions		

Aircraft operator measures to reduce engine running time on the ground

Measure description

A range of measures are possible to reduce aircraft engine running rimes on the ground. Some of these are broadly within the control of aircraft operators, and those are included in this measure. Examples include:

- Reduce running times of APUs.
- Reduced engine taxiing (RET).
- Use of reduced thrust on take-off.
- Use of reverse thrust on landing.

Evidence base and assessment of evidence

Major UK airports have developed action plans to reduce air quality emissions over the last decade[207,208]. However, limited information is publicly available, and action plans contain a fair degree of uncertainty.

Sustainable Aviation's paper on air quality[209] outlines many of the measures described here and provides further information and examples.

Summary of evidence

APUs are responsible for approximately 10–20% of ground-level aircraft $PM_{2.5}$ emissions. Most airports have worked to reduce APU usage. Further investment in Pre-Conditioned Air (PCA) and Fixed Electrical Ground

Power (FEGP) at stands will enable further reductions in running times. Some further gains are achievable by further uptake of good practice with existing infrastructure, estimated to be of the order of 10% based on past practice. With investment, reductions of around 50% should be achievable. Heathrow[212] has recently invested £20m on infrastructure to supply PCA and FEGP. Heathrow also undertakes compliance monitoring to ensure that aircraft operators comply with strict limits on APU use.

Reduced engine taxiing (RET) is becoming established as good practice at a number of airports. However, emissions savings are partly offset by the need for APUs to be running during RET. Further procedures need to be developed to expand the use of RET on taxi-in and taxi-out. Use of RET on taxi-out is challenging because engines require several minutes to stabilise and warm up before take-off, so good information on when the aircraft will begin its take-off roll is important; in addition, there are concerns about pilot workload during a busy part of the flight, with safety implications. Overall, widespread use of RET could reduce taxiing emissions by an estimated 10–20%. Taxiing is responsible for around a quarter of ground-level $PM_{2.5}$ emissions, so RET could potentially reduce emissions from this source by an estimated 3%.

Reduced thrust is commonly used on take-off. The reason is that engines are designed to overpowered for normal take-off, providing contingency for the loss of an engine, and using reduced thrust substantially reduces wear on the engine and increases its lifetime. Typically, aircraft take off using 70–90% of full thrust. This is already common practice and there seems little opportunity for further rollout or further reductions in thrust.

Reverse thrust on landing provides additional braking power. Often thrust reversers are deployed at idle thrust, but higher thrust settings may be used for additional braking power. Sometimes this is for safety reasons, e.g. when there is only a short length of runway remaining, but may also be to enable the aircraft to clear the runway early. This may be to reduce the taxi-in length. Overall, considering the safety requirements and trade-offs with taxiing, it is considered that there is little opportunity for further reductions in the use of reverse thrust.

Summary – Aircraft operator measures to reduce engine running time on the ground

Factor	Summary		
Benefits	Reduction of 1–5% in aircraft $PM_{2.5}$ emissions from APU usage, depending on infrastructure investment. Reduction of around 3% in aircraft $PM_{2.5}$ emissions from increased use of RET. Fuel savings for operators but payback time may be appreciable.		
Barriers	Some operator resistance. Some best practice procedures to be developed. Infrastructure required for best use of APU measure.		
Investment Requirements	Some best practice procedures to be developed. Infrastructure investment for PCA and FEGP. "Green stands" would require operation procedures for optimum benefits.		
Policy Requirements	Driven primary by cost savings and decarbonisation. Poor economic case for investment in infrastructure, so may need to be made mandatory (perhaps as condition for expansion).		
Factors Affecting Timescales	Need to develop, roll out and incentivise best practice procedures. Infrastructure requirements.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	1% by 2030	3% by 2030	5% by 2030
Justification	Reduction in activity/emissions that may be achievable based on the literature reviewed, depending on industry engagement		

Airport and ATC measures to reduce engine running time on the ground

Measure description

A range of measures are possible to reduce aircraft engine running rimes on the ground. Some of these are broadly within the control of airport operators and ground and air control, and those are included in this measure. Examples include:

- Use of Collaborative Decision Making (CDM) to optimise journeys. This entails planning the whole flight before it starts, to ensure that permission to start engines is not given until there is a clear journey to the destination without unnecessary delays.
- Management of hold queues to reduce waiting times.

Evidence base and assessment of evidence

Measures are being developed and implemented currently, so there is a good understanding of the practicalities, and a reasonable idea within the industry of future trends and requirements. However, there is less available information on the effects on emissions. That further work is needed in this area was acknowledged in the workshop.

Summary of evidence

There are strong incentives to improve the efficiency of ground (and air) operations. Reducing the amount of waiting time for aircraft saves journey time, improves customer experience, saves fuel, reduces emissions, and makes best use of airport capacity. Consequently airports, airlines, controllers and other stakeholders have been working to find ways to streamline the journey each aircraft takes from gate to gate.

A key technique has been improved data management, such as the introduction of Electronic Flight Progress Strips (EFPS) systems. This provides a single point of truth that can be shared between all parties involved in managing a flight. EFPS has been rolled out at major UK airports. Further rollout and refinements are possible. This has been used to enable controllers to manage ground and air movements more efficiently, reducing delays.

As well as improving the movement of aircraft, these actions allow controllers to give pilots better information about when they are expected to be able to begin their take-off roll. This means that aircraft using RET on taxi-out are able start their remaining engines at the optimum time, given the engine-specific time required for it to warm up before starting the take-off.

There is much improved data on aircraft movements on the ground now available, and operator experience suggests that times and delays have been reduced. However, there does not seem to have been a detailed publicly available analysis of the effect on $PM_{2.5}$ emissions. Such an analysis should be reasonably straightforward to do.

From the current baseline, further incremental improvements are likely in future, as systems roll out more widely, become used more effectively, and new procedures are developed to make nest use of them. No firm evidence on the benefits has been identified. Based on the views of the stakeholders consulted, overall ground-level emissions of $PM_{2.5}$ from aircraft could be reduced by between 2–5% by 2030, although with considerable uncertainty. An ambitious estimate would be up to 20% by 2050.

Further documentation is expected to be published in 2021, including a European Roadmap and Air Transport Action Group (ATAG) work.

Summary – Airport and ATC measures to reduce engine running time on the ground

Factor	Summary		
Benefits	Overall ground-level emissions of $PM_{2.5}$ from aircraft could be reduced by between 2–5% by 2030, although with considerable uncertainty. Substantial co-benefits for operational efficiency, resulting in benefits for CO_2, NO_x, noise.		
Barriers	Technological requirement. Development and implementation of procedures to make best use of available techniques. Data sharing between many parties.		
Investment Requirements			
Policy Requirements	Collaborative Decision Making is a regulatory requirement at some airports. Quite expensive (CAPEX but savings on OPEX?). Implies scope for regulatory enforcement at other airports, but benefits may be lower.		
Factors Affecting Timescales			
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	2% by 2030	3% by 2030
Justification	Reduction in activity/emissions that may be achievable based on the literature reviewed, depending on the level of industry engagement		

Alternatively powered APUs

Measure description

APUs provide power for the aircraft when the main engines are not running and the aircraft is not connected to ground power. Although most usage is while the aircraft is stationary on the ground, the APU also provides a safety-critical function to restart the main engines during flight. APUs are currently fuelled by the same kerosene fuel as the main engines. In future, it is anticipated that as the availability of ground power increases, APU usage will be restricted to when aircraft are taxiing or stationary away from the stand. This measure proposes replacing kerosene-fuelled APUs with either electric batteries or hydrogen-powered fuel cells.

Evidence base and assessment of evidence

No evidence was identified of work towards replacement of kerosene APUs in aircraft in the literature review and stakeholder engagement process. However modern aircraft such as the Boing 787 are known to have greater electrical systems supported by battery power. The driver for change is likely to be decarbonisation but the availability of SAF means the use of liquid fuels is likely to continue for most aircraft types out to 2050.

Summary of evidence

Although aircraft APUs are safety-critical equipment and are regulated as such, there is no regulation of their emissions. In general, APU emissions are not seen within the industry as a major issue and so seem to have been subject to little interest, except through airport-driven measures to reduce operating times. Although they have particular requirements for service, such as being able to operate at high altitude, there are no obvious technological reasons why alternative power systems could not be used.

There is a preference for single fuel, i.e., all systems powered by kerosene. This means that hydrogen is unlikely to be viable for APUs unless the main engines are also hydrogen powered. This may be the case for some short-haul aircraft from about 2030. However, there should not be an obstacle to electric battery replacements for APUs as it is normal to connect aircraft to ground electrical supplies while they are on the ground.

Charging times for electric APUs would be a potential barrier. Fast charging is possible but would create heat dispersal issues.

Infrastructure requirements are significant as all airports served by an aircraft, including diversion airports, would need to be fitted out.

Current aircraft types are unlikely to be retrofitted. Rather, new aircraft types would need to be designed in future with alternative APU systems in mind.

Exhaust treatment of APU emissions (e.g., DPFs) may be more viable, but the extra weight would increase fuel costs and CO_2 emissions, so would need to be evaluated carefully. This is unlikely to happen without a regulatory requirement, probably with international agreement.

Summary – Alternatively powered APUs

Factor	Summary		
Benefits	Potential elimination of $PM_{2.5}$ emissions from APUs. APUs represent around 4-5% of total LTO emissions.		
Barriers	Industry conservatism Safety requirements Investment in development and certification.		
Investment Requirements	Development and certification of alternative power sources. May require new aircraft designs (e.g. electric usage within Boeing 787). Infrastructure investment on international basis.		
Policy Requirements	Regulation is by international consensus – limited UK control. Safety is paramount.		
Factors Affecting Timescales	Very long. Unlikely to begin entering the fleet before 2030 at the earliest. May be some uptake over timescales to 2050.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	0% in 2030 Reaching 50% uptake by 2050
Justification	Stakeholder engagement suggests a lack of innovation in current pipeline		Potential innovation driven by decarbonisation agenda

Improved brake pad materials

Measure description

Brake wear is responsible for about a quarter of $PM_{2.5}$ ground-level emissions from aircraft[210], although there is considerable uncertainty about this estimate and older data suggests[211] that this could be as high as 63%. There is limited scope for reducing braking requirements, particularly in relation to aircraft arrival, but alternative materials might be devised that shed fewer fine particles into the air.

Evidence base and assessment of evidence

No evidence from the literature or stakeholder engagement process has been identified that alternative brake pad materials for aircraft are being investigated by the industry.

Summary of evidence

Brakes are safety-critical, and maintenance of brake pads is afforded high priority. There has been some historical innovation in brake pad material, with steel brakes being largely replaced by carbon fibre brakes over the last 20 or so years. As discussed at the workshop, given the expense of these brake systems, manufacturers and airlines both try to protect them so that they wear as little as possible. There may be small opportunities to limit low power operation but braking on landing is a safety requirement so there is limited potential. Also highlighted at the workshop was that weight is an important characteristic, and heavier materials would increase CO_2 emissions. Any widespread changes in materials would likely be a result of international cooperation/regulation, and this is not seen as a priority in the short to medium term.

Summary – Improved brake pad materials

Factor	Summary		
Benefits	Potential reductions in emissions but nothing expected on foreseeable timescales.		
Barriers	Safety-critical. Currently brake pads are highly managed. Lack of interest or motivation to reduce emissions.		
Investment Requirements	R&D. Safety and certification.		
Policy Requirements	Regulation is by international consensus – limited UK control.		
Factors Affecting Timescales	Unlikely on foreseeable timescales.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Not accounted for in modelling due to lack of data on emission rates (and source in the NAEI) plus safety as the primary driver for technology in this area		

Improved tyre materials

Measure description

Tyre wear is responsible for about a quarter of $PM_{2.5}$ ground-level emissions from aircraft[210], although there is considerable uncertainty about this estimate. Alternative materials might be devised that shed fewer fine particles into the air.

Evidence base and assessment of evidence

Tyre manufacturers will evolve their designs over time but no evidence was identified through stakeholder engagement or the literature review that alternative materials for optimising emissions of $PM_{2.5}$ are being investigated by the industry at present.

Summary of evidence

Tyres are safety-critical, and maintenance of tyres is afforded high priority. No evidence has been found that the industry is focussed on reducing emissions from this source.

Weight is an important characteristic, and heavier materials would increase CO_2 emissions.

Summary – Improved tyre materials

Factor	Summary		
Benefits	Potential reductions in emissions but nothing expected on foreseeable timescales.		
Barriers	Safety-critical. Lack of interest or motivation to reduce emissions.		
Investment Requirements	R&D. Safety and certification.		
Policy Requirements	Regulation is by international consensus – limited UK control.		
Factors Affecting Timescales	Research into emission rates and overall magnitude of emissions plus research and development into approaches to reduce these.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Not accounted for in modelling due to lack of data on emission rates (and source in the NAEI) plus safety as the primary driver for technology in this area		

Low-emission ground support equipment (GSE)

Measure description

GSE comprises the mix of vehicles and plant that operate airside at an airport. Some GSE comprises road vehicles (although these may not necessarily travel landside) and NRMM. Emissions are currently regulated under the road vehicle "Euro" standards and the NRMM "Stage" standards. There is therefore considerable overlap with the road traffic and construction/NRMM topics. This measure involves the replacement of diesel-fuelled GSE with GSE fuelled by alternatives such as electricity and/or hydrogen.

Evidence base and assessment of evidence

Progress has been made in recent years with a view to developing and introducing electric and hydrogen GSE, and rollout has begun. Issues are reasonably well understood within the industry, but details are often commercially sensitive.

Summary of evidence

Uptake of the newest diesel-engine GSE will reduce emissions by ensuring compliance with the latest emission factors. Heathrow Airport[212] has a target for 100% of GSE to meet latest and most stringent, relevant emission standards (Euro 6/VI for road vehicles, Stage V for NRMM, in line with the London ULEZ) by 2025. About 20–25% of Menzies Aviation GSE is electric. Figures at some Scandinavian airports are reported to be up to 80%, benefiting from cheap renewable electricity in those countries.

Driven by both decarbonisation and local air quality requirements, major airports have begun investing in alternative fuelled, zero-emission GSE. Frankfurt Airport[213] is an example which invested in electric GSE in order to reduce airport NO_x emissions, to create headroom for / offset other expansion.

From the workshop discussions, electric battery equipment is more viable than hydrogen, although as the wider market develops this may change, and hydrogen may be more suitable for larger and more powerful plant. Having fixed bases, it is practical to install charging infrastructure to serve the mobile plant.

Heathrow Airport[212] has invested £5m in charging infrastructure for electric GSE. Of Heathrow Airport's own fleet of vehicles (which is a fairly small fraction of the whole GSE fleet), it set a target for 100% of Heathrow's cars and small vans electric or plug-in hybrid by end of 2020, 100% its vehicles less than 3.5 tonnes to be electric or plug-in hybrid by 2030, and 50% of its vehicles greater than 3.5 tonnes to be electric or plug-in hybrid by 2030 (excluding snow kit).

Issues are similar to NRMM generally (see below). As highlighted in the workshop, plant is generally available but infrastructure needs to be developed, both to bring electricity onto the airport site and then to distribute it to charging points. Purchase costs are currently higher than for diesel plant. However, the removal of the red diesel tax break will shift the balance of operating costs towards electric plant.

Duty cycles may need to be adapted to allow for sufficient recharging time. Major airports operate for over 18 hours a day, providing little time for recharging. This is a problem if plant are used intensively, e.g. through sharing between operators. However, duty cycles typically include stationary time (e.g., while loading baggage trucks, waiting instructions to pushback etc.) so loads may average out to be quite low.

Summary – Low-emission ground support equipment (GSE)

Factor	Summary		
Benefits	Potential elimination of $PM_{2.5}$. Potential uptake of around 30% by 2030, up to 100% by 2050. Co-benefits for CO_2, NO_x, noise, workforce exposure. Reduced OPEX, maintenance costs.		
Barriers	Availability of specialist plant. CAPEX investment. Fleet sharing could reduce costs but requires development. Safety concerns, e.g., hydrogen; use of electric plant around fuel vapours. Liability and insurance concerns.		
Investment Requirements	Infrastructure for bringing power onto airport and distributing it to charging points. Fleet turnover.		
Policy Requirements	Driven by carbon and air quality. Removal of red diesel tax break incentivises uptake of alternatives. Low emission zones. Strong policy signals required to encourage shift.		
Factors Affecting Timescales	Fleet turnover 12-15 years lifetime. Most plant available now but supporting infrastructure required.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	10% uptake by 2030, 50% by 2050	20% uptake by 2030, 100% by 2050	30% uptake by 2030, 100% by 2050
Justification	Reduction in activity/emissions that may be achievable based on the literature reviewed, driven by decarbonisation agenda		

More efficient use of ground support equipment (GSE)

Measure description

This measure concerns the more efficient use of GSE (either existing or new) in order to reduce running times. This will reduce engine emissions especially, but will also reduce brake, tyre, surface and resuspension emissions to the existing that there is a reduction in miles travelled. This measure includes reductions in idling (e.g., through use of start-stop systems) and more efficient logistics (e.g., keeping each plant item close to its working area, minimising, travel between working areas).

Evidence base and assessment of evidence

No particular sources of evidence have been identified other than discussion with consultees. Operators are developing procedures for improving management, but little is published.

Summary of evidence

Airports are complex organisations and the management and dispatch of GSE is a key part of this complexity. Delivery is critical to prevent expensive delays to flights. Operators are investing in improved information management systems such as EFPS (see above) which offers the potential to improve the management of GSE and reduce inefficiency.

Operator training and development of best practice could reduce inefficiencies in the use of GSE, for example unnecessary idling. Use of telematics to understand usage patterns and develop improvements will feed into this. However, this requires motivation to spend the time and money on developing and implementing such training. Currently there is little motivation for this. At the workshop, the suggestion was made that these measures could reduce emissions by around 2%.

More on-stand services (fuel, FEGP, PCA, etc), including mobile PCA units, will facilitate more efficient use of GSE.

Zoned stands and sharing of equipment were identified as measures that have been considered to reduce GSE/driving between stands. Smaller, more common GSE could be shared between operators at stands. Larger, less used GSE could be shared between operators. These will allow economies of scale and potentially lead to specialist operators. Barriers to this approach include liability and contractual issues, and operators desire to control their own equipment. Heathrow Airport[212] has worked with stakeholders to contract a supplier to provide a pooled fleet of baggage belt loaders and aircraft stairs to be used collectively by ground handling companies and ensure that all vehicles provided will be low emission and electric where possible.

Summary – More efficient use of ground support equipment (GSE)

Factor	Summary		
Benefits	Potential reductions of around 2%. Co-benefits for CO_2, NOx, noise, workforce exposure, OPEX.		
Barriers	Developing improved data and management systems, Develop and implementing best practice training for operators.		
Investment Requirements	Developing improved data and management systems, Develop and implementing best practice training for operators.		
Policy Requirements	Driven by decarbonisation and air quality. Potential for CSR approach, by analogy with other NRMM (e.g. Considerate Constructors Scheme). Removal of tax break for red diesel will increase fuel costs and provide further motivation.		
Factors Affecting Timescales	Limited current incentives to change procedures beyond cost savings		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	2% reduction by 2030	5% reduction by 2030	10% reduction by 2030
Justification	Reduction in activity/emissions that may be achievable based on the literature reviewed, depending on industry engagement		

Surface access: reduced landside car use

Measure description

Emissions from landside car use are covered elsewhere, but airports are significant generators of road traffic. In general, the highest pollutant concentrations where people are exposed in the vicinity of an airport are adjacent to major roads in the area. This measure concerns ways in which the road traffic generated by airports can be reduced.

Evidence base and assessment of evidence

Airport operators in the UK have tried to encourage sustainable travel to airports for many years, with mixed results. Evidence for successful interventions is therefore mixed.

Summary of evidence

Surface access to airports of all sizes is a major issue for airport operators as provision of suitable parking space is a major undertaking (although car parks also provide a substantially proportion of their revenue). Regulatory pressure is often applied as part of planning conditions, and road traffic is often a major cause of local air quality problems around airports. However, resistance from customers is strong and most airports find it difficult to persuade people out of their cars.

Heathrow's Emissions Strategy and Action Plan212 sets a target for at least 45% of passengers to use public and sustainable transport by 2019 and 50% by 2030.

An essential precondition for reducing car use is good public transport links. Airports vary in their rail access, with Heathrow having good access which is nonetheless close to capacity for example. Developing or expanding rail links is expensive and slow.

Improving bus services is faster and cheaper but may only be effective at smaller airports with major transport hubs close by.

Park and ride schemes may be an option at some airports to reduce exposure from cars travelling to the airport, if suitable sites can be found close to major roads without receptors close by. These schemes will benefit air quality, but co-benefits for CO_2 emissions are reduced if large parts of the journey are undertaken by car with only the last leg by bus. These schemes may be made more attractive to travellers by moving the check-in process to the car park or the bus, compensating for the extra journey time by reducing the time at the airport.

Vehicle access charges are increasingly common. Money raised may be reinvested in public transport. Some respondents suggested that investment in several small schemes may is preferred to a single large scheme.

Low Emissions Zones have been mooted for some airports, particularly Heathrow. These should shift car use to users with newer, cleaner cars, reducing emissions, but will only be effective if users of older cars are persuaded to use public transport.

Summary – Surface access: reduced landside car use

Factor	Summary
Benefits	Potential modal shift will result in proportionate reduction in $PM_{2.5}$ emissions. Experience suggests that modal shifts of up to 10% are achievable but challenging.
Barriers	Public resistance. Infrastructure development.
Investment Requirements	Very substantial investment required to build up public transport share, including installing new infrastructure.

Factor	Summary		
Policy Requirements	Strong policy drivers required.		
Factors Affecting Timescales	Transport infrastructure development is likely to be slow. LEZs may be deliverable in medium term.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Not included in modelling. National scale model does not allow for airport-specific measures. Reduction in car distance travelled accounted for in mobility measures		

4.4 Agriculture

Introduction

As illustrated in Section 2, agriculture is estimated in the NAEI to contribute around 4% of total $PM_{2.5}$ emissions in England and 5% of NO_X emissions. However, agriculture is the major source of NH_3 emissions (around 84%) and NH_3 is an important precursor of $PM_{2.5}$ formation, as discussed in Section 2.2. The measures for agriculture therefore focus on management practices to reduce unnecessary NH_3 emissions including those related to nutrient application.

The first three of the following measures (Storage, Fertiliser change and Low emission spreading) are based on the understanding that NH_3 emissions can be controlled by managing nitrogen use and limiting nitrogen losses. This enables a nitrogen input-output balance to be established at the farm level (integral management of nitrogen) rather than at individual stage management levels.

The UNECE Task Force[219] identifies this approach as a control measure for ammonia emissions as NH_3 emission loss occurs when there is a nitrogen surplus, which happens for 10% to 40% of the N surplus on mixed livestock farms.

HM Government farm practice survey results[214] indicate that 42% of farmers do not implement a nutrient management plan. The uptake of preparing nutrient management plan has the potential to reduce NH_3 emissions as two studies by catchment sensitive farming demonstrate good nutrient management practice on farms result in reduction of NH_3 emission[215,216].

Slurry, manure storage

Measure Description

Storage of slurry and manure is responsible for approximately 9% of NH_3 emissions from agriculture in the UK[217]. Slurry and manure have a high potential to emit NH_3 when left uncovered and untreated. In order to abate NH_3 emissions during the storage stage of manure management the following techniques can be implemented: covering the storage area; reducing the potential for generating NH_3 emissions (such as slurry acidification); and minimizing disturbances.

Evidence Base and Assessment of Evidence

Several studies are available considering the impact of managing slurry and manure storage on reducing NH_3 emissions. The results of the assessment by the Institute of Occupational Medicine (IOM) on behalf of Public Health England[218] identified manure management, storage and spreading to land as one of the major sources of air pollution from farming and one of the main interventions to decrease NH_3 emissions from storage is to cover them. Their assessment extracted data from 162 papers from studies in Europe, North America and China. Another comprehensive reviews of NH_3 mitigation and summary of intervention including slurry and manure storage are also available from the UNECE Task force guidance[219] and Ricardo Energy & Environment[220,221].

Summary of Evidence

There is consistent evidence that leaving slurry and manure storages uncovered and untreated is contributing to a large proportion of NH_3 emissions from the agriculture sector. The *Code of Good Agricultural Practice* (COGAP)[222] provides guidance on how to minimise NH_3 loss from organic manure during storage, including covering manure, keeping solid manure dry, and reducing the surface area exposed to atmosphere to a minimum.

Several techniques are available to cover slurry and manure such as tight fitted rigid covers for tanks and silos, plastic covers or floating covers for small lagoons. The surface can also be left to create a natural crust isolating the slurry from the atmosphere. The level of NH_3 reduction varies depending on the type of cover chosen, a tight fitted rigid cover can reduce NH_3 emissions by up to 80%, while a floating cover will reduce NH_3 emissions by around 40%[219]. Misselbrook and Gilhespy 2019[223] identified 50% reduction in NH_3 emissions from crusting of cattle slurry, up to a reduction of around 80% for tight lid roof or tent covers. These percentages of reduction efficiencies also consider the use of additives to reduce the pH of the material which decreases the potential for NH_3 emissions.

Additives can be used at the storage stage or spreading stage. At the storage stage, this may be beneficial in reducing emissions at the time of spreading to land and after. Aluminium sulphate or sulphuric acid are example of additives that can be used for storage tanks. Evidence of the reduction in NH_3 emissions to air with acidification of slurry is discussed in detail in the Wiltshire and Martineau 2018 report for Defra[221] based on the approach adopted in Denmark. The abatement efficiency by itself is in the order of 27 to 88% depending on the additive and the nature of the slurry.

Good management of manure and slurry considers integrated nutrient planning to ensure NH_3 present in manure and slurry storage in the form of nitrogen will not be released to the atmosphere during manure application to soil. Best practice for manure management involved application of low emission spreading. Different techniques are discussed as part of the low emission spreading measure. During the workshop, stakeholders emphasised the point that slurry store covering will only be effective at reducing NH_3 emission overall if measures are introduced at the spreading stage as well, as is the case for farms located in Nitrate Vulnerable Zones (NVZs), where rules apply for storing organic manures and use of nitrogen fertilisers. Stakeholders also highlighted that this measure will need to comply with Defra Farming Rules for Water[224].

The other benefits for covering slurry and manure store are to maximise nutrient management and to use manure and slurry as fertilisers to reduce manufactured fertiliser costs. Covering slurry tanks also has the advantage of stopping rain adding to the contents and therefore reducing the storage capacity required.

The use of Anaerobic Digestion (AD) has increased in recent years and the digestate residual product can be used as fertilisers on farmland in a similar way as slurry and manure. The Waste and Resources Action Programme (WRAP) estimated that, as of 31st January 2017, there were 266 operational AD facilities in the UK. The composition of the digestate differs from animal manures. However, digestate still requires mitigation measures to reduce NH_3 emissions during storage and spreading. Pig slurry is considered the most appropriate proxy to estimate AD digestate percentage abatement and the costs of abatement measures[221] and, in this study, the level of reduction in NH_3 emissions from digestate is assumed to be similar to pig slurry. The use of digestate should be used with good management of storage and spreading as for animal manure and slurry.

The government published its guidance and regulations on storing silage slurry and agricultural fuel oil (SSAFO)[225] although this has a focus on mitigating water quality impacts. The Clean Air Strategy 2019[226] has more specifics in relation to air quality and includes the ambition to have all digestate stored in covered storage by 2027 at the latest. The timescale for this measure to be put in place is therefore controlled by these regulations and strategy.

When considering the cost of manure storage deployment, IOM[218] estimated costs in the range €1.5 – 4.0 (£1.2 -3.3) per m^3 per year and cost as €0.3 – 5.0 (£0.25 – 4.2) per kg NH_3-N saved assuming it is not emitted from spreading instead A study from catchment sensitive farming estimated a cost of £61,000 for the fixed cover to be installed on a slurry store. Naturally formed crust would not have any cost but the time needed for its formation is difficult to predict and depends on a variety of factors including animal type and whether other materials, such as straw, are added to aid crust formation.

Several estimates of cost for slurry acidification are referenced in Wiltshire and Martineau 2018[220] as £2.5 to 6.0 per kg NH_3-N abated, £2.40 per tonne of slurry or £43 per year for a 500 kg livestock unit. This report also referenced the potential UK uptake of the slurry acidification for larger farms as 94% for dairy cattle, 72% for beef cattle and 95% for pigs and assuming a 25% uptake within 10 years based on the Denmark example.

Summary – Slurry and Manure Storage

Factor	Summary		
Benefits	Cover storage: 50-80 % reduction in NH_3 emissions Slurry acidification reduce NH_3 by 50 -88 % (sulfuric acid) – increase benefit at and after time of spreading to land. Use of AD can reduce GHG emissions Best benefit if measures are also introduced at spreading.		
Barriers	Slurry acidification – new technology requiring technical knowledge Large capital input required for both retrofit and build (Needs to be done in conjunction with Farming Rules for Water) Implementation barriers such as shortage of agricultural building contractors, local planning conditions, challenges around irregular store shapes, cleaning sand bedding. Disposal of effluent. Lowering pH of slurry has cost, practical and safety (storage of additive) and availability Unintended consequences such as other emissions due to changes in storage conditions (i.e., temperature) The need to enforcement to ensure compliance		
Investment Requirements	Engagement / training as part of Catchment Sensitive Farming (CSF) Scheme advice Funding through Countryside Stewardship Investment in storage purchase or retrofit		
Policy Requirements	National policy on emission controls and local planning regulations Need for integrated nitrogen policies Joined-up policy, considering along spreading and in relation to other environmental factors (i.e., water quality) Policy to encourage farmers to invest Extension of the NVZs to a larger area of England (currently only 55%, while 100% in Wales and Northern Ireland)		
Factors Affecting Timescales	Depends on policy development and implementation Investment time scale SSAFO regulations and Clean air strategy 2019 – All store digestate in covered storage by 2027 at latest Acidification of slurry may take multiple years before significant uptake (more likely on new or large facilities with capital to invest)		
Storage cover – Ambition Scenario	**Medium**	**High**	**Speculative**
Individual technical sub-scenarios (reference = No control)			
Floating covered storage – for small lagoon applications	*Reduction in NH_3 emissions by 60% or more and with 50% uptake by 2025 and 60% by 2030*	*Reduction in NH_3 emissions by 60% or more and with 50% uptake by 2025 and 60% by 2030*	*Reduction in NH_3 emissions by 60% or more and with 50% uptake by 2025, 60% by 2030, 80% by 2040 and 100% by 2050,*
Plastic covered storage – for solid manure applications	*Reduction in NH_3 emissions by 60% or more and no uptake*	*Reduction in NH_3 emissions by 60% or more and no uptake*	*Reduction in NH_3 emissions by 60% or more and no uptake*
Tight lid covered storage – for tanks and silos	*Reduction in NH_3 emissions by 80% or more and with 50% uptake by 2025 and 60% by 2030*	*Reduction in NH_3 emissions by 80% or more and with 50% uptake by 2025 and 60% by 2030*	*Reduction in NH_3 emissions by 80% or more and with 50% uptake by 2025, 60% by 2030, 80% by 2040 and 100% by 2050,*
Input for modelling – combined mitigations scenario (reference = No control)			

Factor	Summary		
Input for emissions modelling	Reduction in NH_3 emissions by 60% for plastic cover (lagoons) and by 80% for fixed rigid cover (tanks) UPTAKE: 50% uptake by 2025 and 60% by 2030	Reduction in NH_3 emissions by 60% for plastic cover (lagoons) and by 80% for fixed rigid cover (tanks) UPTAKE: 50% uptake by 2025 and 60% by 2030	Reduction in NH_3 emissions by 60% for plastic cover (lagoons) and by 80% for fixed rigid cover (tanks) UPTAKE: 50% uptake by 2025, 60% by 2030, 80% by 2040 and 100% by 2050
Justification	Emissions reductions taken from UNECE Task force guidance, and uptake from stakeholder engagement and to align with Clean Air Strategy (CAS).	Emissions reductions taken from UNECE Task force guidance and uptake from stakeholder engagement and to align with CAS.	Emissions reductions taken from UNECE Task force guidance and uptake from stakeholder engagement and to align with CAS.
Slurry acidification – Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling (Reference: - no acidification control - to be applied on top of storage NH_3 emission reduction)	N/A	50% NH_3 emission reduction after "Slurry Storage cover" reduction has been applied UPTAKE: 25% uptake from 2025	88% NH_3 emission reduction after "Slurry Storage cover" reduction has been applied UPTAKE:25% uptake from 2025
Justification	Based on stakeholder engagement, considered to be relatively ambitious based on the investment/management changes required and therefore included in High and Speculative scenarios	Taken from Ammonia Futures Study	Taken from Ammonia Futures Study

Fertiliser change

Measure Description

The common mineral fertilisers used on farmland are ammonium nitrate, the urea and ammonium nitrate (UAN) and urea fertilisers. The urea component of these fertilisers generates high level of emissions of NH_3. In this measure, changes to urea fertiliser to reduce their NH_3 emission level are considered, for instance using urease inhibitors or replacing them by other inorganic fertilisers, such as ammonium nitrate as a nitrogen fertiliser.

Evidence Base and Assessment of Evidence

Evidence has been obtained from the review of several studies commissioned recently by Defra[221], the UNECE Task Force Reactive Nitrogen Convention on Long Range Transboundary Air Pollution[219] and studies undertaken under the catchment sensitive farming scheme. The effect on NH_3 emissions of changes in nitrogen fertilisers from urea fertilisers to ammonium nitrate fertilisers or introducing urease inhibitors have been studied and the quantification of reduction is available.

Summary of Evidence

This measure is discussed in the study by Ricardo Energy & Environment[221]. The corresponding mitigation measure used in the model was called "replace urea fertiliser to arable land with another form". This mitigation reduced NH_3 emissions by 7.5% from the 2015 baseline.

In 2016, 21% of total fertiliser nitrogen being applied in the UK were urea-N fertilisers[218]. Although this figure changes from year to year with the market prices. One of the main interventions to decrease NH_3 emissions from fertiliser is to use ammonium nitrate as a nitrogen fertiliser in place of urea fertiliser which can reduce NH_3 emission by 98%[218]. Ammonium nitrate represents 39% of the fertiliser market[221]. Urea based fertilisers are used because they are cheaper, but they have a higher risk of NH_3 losses.

A project (LM0475)[227] commissioned by Defra in 2018 looked at the extent Countryside Stewardship schemes are helping to mitigate NH_3 emissions. Grants under the Countryside Productivity Scheme (CPS) have been implemented on pig farms to change fertilisers to reduced urea fertilisers. However, regulations for different applications of fertilisers were mentioned as a potential barrier.

The workshop discussion suggests that more research and development into use of nitrogen fixing legumes is being undertaken. A recent consultation by Defra on urea fertiliser use will determine the potential uptake to reduce its use. Defra would like to see a drastic reduction in the urea fertiliser use[228].

The practice of improving N use efficiency encourages the reduction of urea fertiliser use and increased use of organic manure instead, with appropriate NH_3 emissions mitigation measure in place, which has the benefit of enabling considerable annual cost savings. As discussed in the workshop, farmers want to reduce fertiliser use for better efficiency which will benefit both the farmers and the environment. The use of organics to soil improve soil biology, chemistry, structure and water retention was also highlighted at the workshop.

Some estimate of NH_3 reduction and cost are provided for the use of urease inhibitors for urea fertilisers as more than 30% reduction in NH_3 emissions and a cost of €-0.5 to 2.0 (£0.42 – 1.7)[220]. A 2012 Defra workshop[229] estimated the reduction of NH_3 emissions and cost associated for replacing urea and UAN fertilisers by ammonium nitrate as 80% and 65% reduction of NH_3 emissions respectively and cost of £0.10 to £0.20 per kg N applied.

Summary –Fertiliser change / Improve Nitrogen Efficiency instead of fertiliser

Factor	Summary		
Benefits	Use of urease inhibitors reduce NH_3 by 40% (18-95% large reduction in experimental conditions) Ammonium nitrate as a N fertiliser to replace urea fertiliser reduce NH_3 emissions by 98% Improve N use efficiency Reduce amount of manufactured fertiliser farmers need Improved yield from use of ammonium nitrate in place of urea		
Barriers	Limited evidence of any agronomic benefit for use of urease inhibitor Knowledge transfer requirement: Use urea fertilizer commonly use as low cost per unit of N but worst for NH_3 emissions and potential yield losses The need for enforcement to ensure compliance		
Investment Requirements	Rural grants and education on best practice Catchment Sensitive Farming (CSF) – pilot program for NH_3 started in 2018 – results being analysed R&D on urease inhibitors usage optimisation		
Policy Requirements	Work with farmers to adopt COGAP voluntary measures Clean air strategy 2019 – Action to reduce emissions from urea-based fertilisers Regulation to provide a level playing field for farm businesses		
Factors Affecting Timescales	Farmers reluctant to apply this measure Choice of N fertiliser available now Availability of market supply for urease and nitrification inhibitors Intention to extend CSF reach across all England for Ammonia from 2022		
Fertiliser – Ambition Scenario	**Medium**	**High**	**Speculative**
Individual technical sub-scenarios (reference = Urea fertilisers - No control)			
Ban of urea fertilisers	*N/A*	*80% NH_3 emission reduction UPTAKE: 100% from 2030*	*80% NH_3 emission reduction UPTAKE: 100% from 2030*
Urease Inhibitors	*70% NH_3 emission reduction UPTAKE: 60% from 2025*	*70% NH_3 emission reduction UPTAKE: 100% from 2025*	*70% NH_3 emission reduction UPTAKE: 100% from 2025*
Improve Nitrogen efficiency = improve fertilisers applications methodologies			
direct incorporation of fertiliser	*N/A*	*N/A*	*80% NH_3 emission reduction UPTAKE: 80% from 2025 and, 100% by 2040*
incorporation after surface application	*N/A*	*N/A*	*50% NH_3 emission reduction UPTAKE: 80% from 2025 and, 100% by 2040*
surface spreading	*N/A*	*N/A*	*40% NH_3 emission reduction UPTAKE: 80% from 2025 and, 100% by 2040*
Input for modelling – combined mitigations scenario			
Input for emissions modelling **Reference: use of Urea fertilisers - No control**	70% NH_3 emission reduction (use of urease inhibitor) UPTAKE: 60% uptake from 2025	70% NH_3 emission reduction (use of urease inhibitor) UPTAKE: 100% from 2025 80% NH_3 emission reduction (urease fertiliser ban) UPTAKE: 100% from 2030	80% NH_3 emission reduction (direct incorporation of fertiliser); 50% NH_3 emission reduction (incorporation after surface application); 40% NH_3 emission reduction (surface spreading);

Factor	Summary		
			UPTAKE: 80% from 2025 and 100% by 2040.
Justification	Based on the use of urease inhibitors Emission reductions based on literature reviewed (UNECE, CAS) and stakeholder engagement	Based on the use of urease inhibitors in 2025 and ban of urea fertilisers from 2030 Emission reductions based on literature reviewed (UNECE, CAS) and stakeholder engagement	Based on the improvement in fertilisers applications which is difficult to apply at all farms Emission reductions based on literature reviewed (UNECE< CAS) and stakeholder engagement

Low Emission spreading

Measure Description

In order to manage nitrogen use and limit nitrogen losses, organic manure, including farmyard manure (FYM), slurry and manure stored on site are used as fertilisers and negate the need for inorganic fertilisers such as urea and UAN fertilisers. Since the urea component of fertilisers from manure generates high emissions of NH_3, reducing NH_3 emissions with the use of FYM is implemented by applying rapid spreading and either mixed within or injected into the soil to reduce the contact with the atmosphere at spreading stage. It is called low emission spreading

Evidence Base and Assessment of Evidence

There is a lot of evidence that reducing the spreading time and applying fertilisers directly into the soil rather than spreading at the surface provides lower emissions of NH_3. The evidence was gathered through studies by IOM[218], UNECE[219], Ricardo Energy & Environment[220] and the inventory of NH_3 emissions from agriculture 2017[223]. There is also evidence that climate and time of year has an impact on NH_3 volatilisation rate, being lower in autumn and winter when the temperature are lower.

Summary of Evidence

Different techniques are used for low-emission spreading. The characteristics of these approaches are to rapidly (within 24 hours) incorporate solid manure or FYM by plough, disk or tine to arable land. For liquid slurry the application will be undertaken with the use of trailing shoe, trailing hose or shallow injection techniques.

A reduction of NH_3 emissions of 30 to 60%[219] is expected assuming the techniques of applications of slurry described above are used. The reduction is higher for injection than for other application techniques. The rapid incorporation (within 4h, although it has generally been revised to 24 hours as more practical) reduce the emissions by 40 to 80% depending on the type of slurry or FYM used[220]. Direct incorporation of solid manure will reduce emissions by 30%. Misselbrook and Gilhespy (2019)[223] report that slurry application by trailing hose and trailing shoe reduce emissions by 30% and 60% respectively and shallow injection by 70%, which is the similar order of magnitude as the UNECE study. Incorporating animal slurry within 4 or 24 hours reduce emissions by approximately 50% and 20% respectively while animal FYM by 40-70% within 4 hours and 19-34% within 24 hours. The reductions noted above take into consideration the different technique of applications but also the best spreading window at the correct time of year and under good weather conditions.

The benefits of low emission spreading are discussed in the Clean Air Strategy 2019 and many farmers and contractors already employ this approach for spreading fertilisers on arable land. The ambition is to have low emission spreading applied by 2025 at the latest. To achieve this goal is likely to depend on the level of funding available. As the machineries are expensive, retrofitting could be cheaper when appropriate and applicable. Both contractors and farmers have now access to advice and training through the CSF. The barriers are related to the size of the farms and the efficiency depends on the weather conditions. Caution should be taken when farms and application areas are near buffer zone of protected areas and where NVZs rules apply.

Limitations of this measure was also discussed at the workshop due to its sensitivity to weather conditions (temperature and humidity) and season. The nature of the soil and type of terrain can also affect the efficiency. If spread in the wrong place, it can have high impact for odour, water and air quality.

The requirement for integrated farming and fertiliser policy across issues (air, water and GHG) and channels (ELM, regulations, CSF and other advice and capital grants) was discussed at the workshop as the requirement for incentivisation for use of organic manures.

Policies and schemes such as Environmental Land Management Scheme (ELMS) introduced from 2022-2023 onwards will determine timescales. Discussions at the workshop highlighted this could be a long-term project and there is a need to start measuring nitrogen use efficiency.

The cost associated with these types of application is in the order of €0.5 – 2.0 (£0.4 -1.7) per kg NH_3-N abated[219]. The cost has also been estimated as between £0.46 to £0.69 per m^3 of slurry spread for the technical application of slurry.

Summary –- Low-emission spreading

Factor	Summary		
Benefits	Improved land spreading methods for manures can reduce NH_3 by 55-80% Better use of nutrient Trailing hose and trailing shoes slurry application can reduce NH_3 by 30-60% respectively Shallow injection – reduce NH_3 by 70% Incorporate of livestock manure to arable land (within 4h or 24h) by plough, disc, or tine – reduce NH_3 by 17 to 82% Some evidence of increase in crop yield Studies show that it is the cheapest and most effective measure		
Barriers	Added cost difficult to justify. Limited perception of benefits		
Investment Requirements	Funding to purchase equipment CSF – pilot program for NH_3 started in 2018 – results being analysed		
Policy Requirements	Requirement to use low-emission spreading equipment by 2025 at the latest Prioritise existing Nitrate Vulnerable Zones		
Factors Affecting Timescales	Availability of equipment Requirement to use low-emission spreading equipment by 2025 at the latest Intention to extend CSF reach across all England for NH_3 from 2022		
Low Emission Spreading – Ambition Scenario	**Medium**	**High**	**Speculative**
Individual technical sub-scenarios (reference = No control)			
Injection, deep injection of slurry	*90% reduction in NH_3 emission UPTAKE: 50% from 2025, and 70% from 2050*	*90% reduction in NH_3 emission UPTAKE: 60% from 2025, 70% from 2030, 80% from 2040 and 70% from 2050*	*90% reduction in NH_3 emission UPTAKE: 100% from 2025*
Injection, shallow injection of slurry	*70% reduction in NH_3 emission UPTAKE: 50% from 2025, and 70% from 2050*	*70% reduction in NH_3 emission UPTAKE: 60% from 2025, 70% from 2030, 80% from 2040 and 100% from 2050*	*70% reduction in NH_3 emission UPTAKE: 100% from 2025*
Trailing shoe, application of slurry	*60% reduction in NH_3 emission UPTAKE: 50% from 2025, and 70% from 2050*	*60% reduction in NH_3 emission UPTAKE: 60% from 2025, 70% from 2030, 80% from 2040 and 100% from 2050*	*60% reduction in NH_3 emission UPTAKE: 100% from 2025*
Direct incorporation (solid manure)	*30% reduction in NH_3 emission UPTAKE: 50% from 2025, and 70% from 2050*	*30% reduction in NH_3 emission UPTAKE: 60% from 2025, 70% from 2030, 80% from 2040 and 100% from 2050*	*30% reduction in NH_3 emission UPTAKE: 100% from 2025*
Input for modelling – combined mitigations scenario (assuming a combination of techniques)			
Input for emissions modelling	*NH_3 emission reduction: 90% (deep injection);* 70% (shallow injection); 60% (trailing shoe); 30% (Direct incorporation UPTAKE: 50% from 2025 and 70% from 2050	*NH_3 emission reduction: 90% (deep injection);* 70% (shallow injection); 60% (trailing shoe); 30% (Direct incorporation UPTAKE: 60% from 2025, 70% from 2030, 80% from 2040 and 100% from 2050	*NH_3 emission reduction: 90% (deep injection);* 70% (shallow injection); 60% (trailing shoe); 30% (Direct incorporation UPTAKE: 100% from 2025

Justification	Accounting for different techniques of Low Emission Spreading. Uptake informed through stakeholder engagement and implementation of CAS.	Accounting for different techniques of Low Emission Spreading. Uptake informed through stakeholder engagement and the implementation of CAS.	Accounting different techniques of Low Emission Spreading. Uptake informed through stakeholder engagement and the implementation of CAS.

Livestock housing

Measure Description

This measure tackles NH_3 emissions from livestock housing. Livestock can be present on site for different timescales. This can be part of the year (e.g., autumn/winter months with livestock grazing during the spring/summer months), or all year long for housed livestock staying indoors and in the yards. In order to reduce NH_3 emission from the housing, changes in the design of the buildings or management of the slurry and manure by applying general good practice are applied.

Evidence Base and Assessment of Evidence

Evidence from several studies considering the impact of changing the design of housing and managing the organic manure and slurry from the buildings on reducing NH_3 emissions was gathered. The results of the assessment by the Institute of Occupational Medicine (IOM) on behalf of Public Health England[218] identified that bringing changes to livestock housing design and management can significantly reduce ammonia emissions. Other comprehensive reviews from the UNECE Task force guidance[219] and Ricardo Energy & Environment[220,221] list mitigation methods and indicate the level of NH_3 emission reduction expected. A study of the CSF scheme at a dairy farm[230] proposes techniques to reduce emissions and demonstrates the benefits of the techniques and cost.

Summary of Evidence

A variety of mitigation methods can be applied for livestock housing. The major methods are:

- Changes to the flooring and slurry pit for effective transfer of slurry to storage, including grooved flooring.
- Install air extraction with air filtration abatement techniques for enclosed buildings. For example, the air is treated by acid scrubber to remove NH_3 present in the atmosphere.
- Increase the frequency of manure removal by washing and scraping housing floors and collecting yards.
- In-house poultry manure drying and increase frequency of litter removal.
- Tree planting around livestock housing.

The IOMP study gathered evidence from several studies and identified that acid air scrubbers reduce NH_3 by 5% to 100% of building emissions, air filtration removes 20 to 95% of PM from exhaust air, in-house fogging reduces $PM_{2.5}$ by 71 to 94%, grooved flooring reduces NH_3 emissions by 35% and tree planting around housing reduces NH_3 by 40 to 80%. Modelling by Ricardo Energy & Environment (2019)[220] predicted that extending the grazing season for cattle would lead to the largest reduction in NH_3 emissions from the 2015 baseline.

Most of these methodologies are Best Available Techniques (BAT) for intensive rearing of poultry or pigs and are already implemented or will be by the end of 2021 for large farms regulated under the Industrial Emissions Directive. This includes animal place thresholds for poultry production and pigs. However, limited regulations are in place for intensive beef and dairy farms and BAT for these farms are being developed as the mitigation measures for pigs and poultry cannot always be transposed directly.

Both the Countryside Productivity Scheme (CPS) and the Farming Ammonia Reduction Grant (FARG)[231] support livestock housing relevant NH_3 reduction measures including air scrubbers and poultry litter drying systems.

The benefits identified beside the reduction of NH_3 emissions is to significantly reduce impacts to the ecosystems for what are typically the primary source of emissions if livestock housing is not regulated (e.g. dairy/cattle or sub-permit threshold farms: <40k birds or <750 pigs). The impact is less if farms are regulated as BAT has already been implemented. Additional benefits to animal health are also reported[230].

From the workshop discussion, some stakeholders considered it better to support management of slurry rather than imposing new regulations for beef and dairy farms. Other barriers identified are the need to ensure measures meet both air and water regulations, ensure availability of suppliers and fitters for low emission flooring and policy/ investment support is required for new infrastructure. Stakeholders were concerned that Beef production might not be able to handle the extra costs.

In terms of policies requirement, stakeholders emphasised the need for joined-up/long-term thinking on policies. Some stakeholders mentioned that they understand that BAT for dairy/cattle is currently being developed. The need for clarification of policies following Brexit was also identified.

The time scale for intensive beef and dairy will depend on BAT proposed, which is complex to identify and depend on the decisions on what size farm will have to be regulated. The ability to implement can also be an issue (e.g., contractor availability, farmer able to fund, feasible for site). Changes to buildings will take a long time due to investment cycles.

The NH_3 emission reduction for livestock housing varies from 20 to 90%, depending on the type of livestock and it does generate an extra cost from €1.0 to 20 (£0.8 to 16.6) per kg NH_3-N reduced[219].

Summary –- Livestock housing

Factor	Summary		
Benefits	Acid air scrubber can reduce NH_3 by 5% to 100% of building emission (from baseline with no control) Air filtration can remove 20-95% of PM from exhaust air (from baseline with no control) In-house fogging reduction of $PM_{2.5}$ by 71-94% Grooved flooring can reduce NH_3 emissions by 35% (from baseline with no control) Tree planting – reduction NH_3 by 40-80% Up to 75% reduction in NH_3 emission for existing dairy housing Up to 30% reduction in NH_3 emission from existing beef cattle housing		
Barriers	Need to ensure measures meet both air and water regulations Ensure availability of suppliers and fitters for low emission flooring Policy/ investment support is required for new infrastructure Beef production might not be able to handle the extra costs. Cost and technical knowledge of filtration techniques for acid scrubbers Strategic tree planting is costly and time requirement to become effective		
Investment Requirements	Funding for installation of air filtrations / upgrade flooring Funding for tree planting / low emission flooring Demonstration		
Policy Requirements	Pig and Poultry – Existing regulation updated, 2017, compliant requirement by February 2021 Extend Regulation to Intensive Beef and Dairy		
Factors Affecting Timescales	Designed flooring started to be implemented on demonstration farms Change in building design can be easily implemented on new large scale dairy units But can take years to implement across substantial numbers of existing farms Define appropriate emission limits and BAT for intensive beef and dairy farms, issue of Regulation expected by 2025 Clean air strategy timelines for regulation will leave a gap for incentives.		
Pig and poultry housing – Ambition Scenario	**Medium**	**High**	**Speculative**
Existing or New housing sub-scenarios (reference = for Pigs: fully slatted houses with a storage pit underneath without techniques for abating NH_3 emissions; for Laying hens – cage housing: conventional cages, non-aerated open manure storage under cages; for Laying-hens – non-caged housing: Deep litter or deep pit with partial litter; for broiler: Deep litter, fan-ventilated house)			
Existing pig and poultry – Pigs: Mitigations: frequent manure removal with vacuum system, flushing gutters, cooling manure surface Poutry: rapid manure removal; more ventilated housing/ manure areas	*20% NH_3 emission reduction* *UPTAKE: 100% from 2030*	*N/A*	*N/A*
New housing pig/ broiler / layer Mitigations: Mitigation of Category 1 from UNECE	*N/A*	*45% NH_3 emission reduction* *UPTAKE: 20% from 2030 and 50% from 2040*	*70% NH_3 emission reduction* *UPTAKE: 20% from 2030 and 50% from 2040*
Input for modelling – combined mitigations scenario (M: Existing housing; H: New housing; S – New housing) – same reference as for sub-scenarios)			

Factor	Summary		
Input for emissions modelling	20% NH_3 emission reduction (existing housing) UPTAKE: 100% from 2030	45% NH_3 emission reduction (new housing) UPTAKE: 20% from 2030 and 50% by 2040.	70% NH_3 emission reduction (new housing) UPTAKE: 20% from 2030 and 50% by 2040.
Justification	Emission reduction taken from UNECE. Uptake based on BREF implementation	Emission reduction taken from UNECE. Uptake rates based on BREF implementation and Nitrogen Future scenario	Emission reduction taken from UNCEC. Uptake rates based on BREF implementation and Nitrogen Future scenario
Cattle Intensive Beed and Dairy - New Housing – Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling **Mitigation measures include:** **-Grooved floor – 25-46% reduction** **-Optimal barn climatization with roof insulation – 20%** **-Grazing 18h/24h – 30%**	N/A	35% NH_3 emissions reduction UPTAKE: 25% new housing uptake by 2040	70% NH_3 emissions reduction UPTAKE: 25% by 2030 and 65% by 2040
Justification	Based on stakeholder engagement, considered to be relatively ambitious based on the investment/management changes required and therefore included in High and Speculative scenarios	Emission reduction and uptake taken from the literature (UNECE and Nitrogen Future: "Mitigated Beef housing")	Emission reduction and uptake taken from the literature (UNECE and Nitrogen Future: "High mitigation" dairy housing").

Changes in Livestock Diet

Measure Description

Excess dietary nitrogen in protein is primarily excreted as urea in urine (mammals) or uric acid (poultry). By changing the feed composition to reduce N intake, manure composition changes accordingly and nitrogen content will be reduced.

Evidence Base and Assessment of Evidence

As for livestock housing measures described above.

Summary of Evidence

25 papers were reviewed by IOM[218] and they found that decreasing crude protein intake for cattle led to decrease NH_3 emissions from manure with a percentage usually larger than 30% and up to 65%, depending on the crude protein reductions. The impact is similar for pigs and poultry, with a decrease from manure emissions up to 65%. In addition, a 10 g/kg reduction in feed crude protein reduces NH_3 emissions from pigs by 8%[232]. However, this measure might already be widely implemented for pigs and poultry as it is part of the environmental permit BAT measures and the reduction in ammonia emissions for future scenarios might not be as significant.

The benefits are likely to be significant for beef and dairy and the uptake will increase if it can be shown that the feed costs will be reduced with the implementation of the measure. This is potentially an easier win and lot cheaper than other livestock housing mitigations such as air scrubbers, as long as profitability is not adversely affected. Harper Adams University is currently undertaking research in this area. A study from Catchment Sensitive Farming[233] scheme discussed how nutritionists seek to improve the diet for pigs with more digestible proteins and additive which contribute to the retention of nitrogen in the gut and good health of the animals. This approach can reduce ammonia by 8 to 13% for each percentage point reduction in dietary protein.

The barriers discussed at the workshop were the possible higher level of management requirement and the uncertainty over how feeds impact growth and health of livestock. The effects on growth could also impact efficiency and other ruminant emissions (i.e., methane).

Assuming an average reduction of 10% of N content in diet for dairy cows, the cost reduction is up to £16 per cow per year[229]. With a total number of cattle and calves in England of 5.2 million in June 2020[234], a reduction in total cost is estimated for cattle and dairy farms as £83 million per year. Although, UNECE Task Force estimated that the costs of diet changes are in the range of ±€10 (±£8.3) per 1,000 kg of feed, depending on the market conditions.

Summary – Change in Livestock Diet

Factor	Summary		
Benefits	Change in cattle diet can reduce NH_3 by 65% (from baseline with no control), usually 30% For change in pig diet, for 10g/kg reduction in feed crude protein, 8% reduction in NH_3 Change in poultry diet reduce NH_3 by up to 65% Decrease in cost for farmer		
Barriers	Uncertainty on how feeds impact growth and health of livestock (training possible with guidance from nutritionists / communications) Higher level of management required Impact on other ruminant emissions		
Investment Requirements	Engagement with farmers (provide communications and knowledge transfer investment / guidance from nutritionists)		
Policy Requirements	Pig and Poultry – Regulation updated, 2017, compliant requirement by February 2021 Extend Regulation to intensive Beef and dairy		
Factors Affecting Timescales	Short time scale – can be implemented anytime Implementation of the Beef and Dairy regulation Intention to extend CSF reach across all England for NH_3 from 2022		
Change in livestock diet – Cattle – Ambition Scenario	**Medium**	**High**	**Speculative**
Input for modelling – (Ref: zero implementation)			
Input for emissions modelling	N/A	20% NH_3 emissions reduction UPTAKE: – 60% from 2030	20% NH_3 emissions reduction UPTAKE: – 60% from 2025
Justification	Based on stakeholder engagement, considered to be relatively ambitious based on the investment/management changes required and therefore included in High and Speculative scenarios	Emission reductions Defra project 2019. Uptake rates based on stakeholder engagement	Emission reductions from Defra project 2019. Uptake rates based on stakeholder engagement

Fuel choice and usage for farm equipment

Measure Description

This measure is discussed in more detail in the construction section across several measures including new Stage V NRMM, retrofit to Stage V NRMM, and electric and/or hydrogen powered NRMM. This measure considers NRMM and off road mobile machineries (ORMM) engines, which are currently almost all powered by diesel combustion, being replaced with a cleaner Stage V NRMM engines or with alternatives such as electric or hydrogen-powered engines.

Evidence Base and Assessment of Evidence

The evidence base with regards to NRMM/ ORMM, fuel choice and usage for equipment and vehicles is discussed in more detail in the construction section. In summary, there is strong evidence that Stage V NRMM engines will deliver significant reductions in $PM_{2.5}$ emissions. There is less evidence that retrofits are available and successfully applied. Alternative fuels are becoming an option in some areas but there is a mix of experience and the practicality for farm use is still to consider.

Summary of Evidence

The evidence base with regards to NRMM/ORMM is discussed in more detail in the construction section. In summary, significant reductions in exhaust $PM_{2.5}$ emissions, of over 95% are to be expected with the use of Stage V diesel engines.

Additional benefits include reduction in NO_X and CO_2. The uptake will be driven by cost case/efficiency study and ease of use.

At the workshop, doubts were expressed about the availability in the short term of non-diesel alternatives for farm machinery. Availability will increase over longer timescales as technologies are improved. Other barriers were discussed including the effect on the convenience of operation for efficient farm operation, continuing the subsidy for red diesel as longer time scale is needed to communicate changes to equipment suppliers, long term infrastructure requirements for electricity/hydrogen and power supply, the cost of investment in new equipment, the impact of a strong second-hand market in farm equipment that needs to be factored in and the role of biomethane for transport fuel.

The replacement cycle was highlighted as one of the key factors affecting timescales. New equipment purchases can be quantified, but the strong second-hand market in farm equipment makes it difficult to determine typical equipment ages. Replacement cycles will depend on the specific piece of equipment, farm size, use of contractors. Most machines cost £100k+ and some pieces of equipment are substantial fixed investments (e.g., grain dryers could last for decades). However, turnover can be quite rapid for others (e.g., a combine harvester is changed after four years). Contractors tend to keep equipment while it is operational and under warranty. Contractors can also focus on new innovations in the industry. Leasing is also an important factor to take into consideration as companies are likely to have a high turnover and more likely to upgrade to new engines.

Summary –- Fuel choice and usage for farm equipment

Factor	**Summary**		
Benefits	Efficient reduction of $PM_{2.5}$ (for Uptake of Stage V engines machineries) Fuel cost savings by switching to hydrogen and electricity (reduction in $PM_{2.5}$ emissions (by 99% reduction) Co-benefits include reduced emissions of NOx and CO_2.		
Barriers	Additional costs to operators from new plant, but expected to be largely cost neutral since this forms part of natural turnover. Pre-Stage V engines can be on the market until December 2021		
Investment Requirements	Purchase of new vehicles / new engines – will be driven by natural plant turnover Retrofitting existing engines		
Policy Requirements	NRMM regulations for larger agricultural and farming machinery Subsidy for red diesel to remain for agriculture equipment Policies to encourage use of new equipment on a regional basis can provide targeted emissions reductions, although use of equipment is in rural areas and exposure is limited		
Factors Affecting Timescales	Biggest challenge within 5-10 years April 2022 removal of tax exemption for red diesel will be a driver for changes in NRMM/ORMM Machineries lifetime varies by equipment from 4 years to decades Biodiesel transition role Production / availability of hydrogen fuel vehicles		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	90% reduction in emissions of $PM_{2.5}$ from new Stage V NRMM. 100% uptake by 2040	90% reduction in emissions of $PM_{2.5}$ from new Stage V NRMM. 100% uptake by 2035	90% reduction in emissions of $PM_{2.5}$ from new Stage V NRMM. 100% uptake by 2030

Factor	Summary		
Justification	Slow uptake of Stage V equipment. Based on stakeholder engagement and equipment lifetime	Medium uptake of Stage V equipment. Based on stakeholder engagement and equipment lifetime	Rapid uptake of Stage V equipment encouraged. Based on stakeholder engagement and equipment lifetime

Change in Land use

Measure Description

This measure proposes change in land use to different crop, unfertilised/ ungrazed land or woodland, and looks at more localised changes such as reduction of livestock densities on land near sensitive sites, targeting mitigation at localised areas (i.e., in NVZs, near sensitive areas or rivers, for example).

This can be considered alongside measures related to increased food sustainability, such as vertical farming that is becoming increasingly common, and can be employed in urban areas[235].

Evidence Base and Assessment of Evidence

There is some evidence that change in land use can impact NH_3 emissions. Newell Price and al (2011)[236] identified several changes that can significantly reduce NH_3 emissions. On the other hand, some other changes have no effects or can increase NH_3 emissions. CEH[231] studied the effect of targeted change in livestock densities and spreading of manures but there is not much evidence of reducing NH_3 emissions at a farm level. Although it has other benefits in reducing nitrogen deposition in specific targeted protected areas.

Summary of Evidence

Newell Price *et al* (2011)[236] list of mitigation methods indicates that significant reduction in NH_3 loss can occur for change of land use from arable cropping to unfertilised grassland (without livestock) and associated manure inputs) and from agricultural land to permanent woodland. Conversion of land to biomass cropping can also have a small reduction in NH_3 loss. However, these methods are usually more suitable to marginal and high erosion risk lands or land close to water and suitable incentives are needed for the farmers to adopt the methods. Grants are available to establish new woodlands. A change to woodland or a change to biomass cropping both represent significant changes to farming business.

IOM[218] did not find any evidence that change in land use can reduce NH_3 emissions. Although one paper focusing on local targeting of mitigations provides evidence for up to 2.2% reduction in total N deposition across UK. These results are in line with the CEH[231] study that NH_3 emissions at farm level is not likely to reduce NH_3 emissions by changing the location of the activities generating NH_3 loss but has an effect in reducing Nitrogen deposition.

Stakeholders mentioned a variety of co-benefits, including agro-forestry and animal health, economic benefit, increase biodiversity and others ecosystem services. This could be one tool for some particularly vulnerable sites with a land management contract in place.

The main barriers discussed at the workshop were a loss of production and loss of incomes but also that the change in land use can also be productive if managed correctly. The need to maintain productive land to produce food was agreed to be essential at the workshop.

The policy requirements need to be linked with locally appropriate solutions (contractually agreed for sensitive sites) supported by advice and evidence and associated with monitoring and incentives.

The workshop noted that regenerative farming and habitat restoration objectives should be linked to land use measures. Several stakeholders also mentioned the use of public money for public goods, such as ELMS payments for environmental management, biodiversity benefits etc. Changing land use will require replacing income streams. As such, the timescales of any uptake of this measure is dependent on policies and incentives.

Summary –- Change in Farming land use

Factor	Summary		
Benefits	Convert arable land to / unfertilized and ungrazed grass or woodland can reduce NH_3 significantly Convert land to biomass cropping can slightly reduce NH_3 emissions Potential reductions in GHG and N deposition		
Barriers	low uptake due to high economic impact on farm businesses change to farming business – financial incentive requirement		
Investment Requirements	Because of reduce crop yield – funding might be required Communication on the benefit of the measure for the farmers and land owners		
Policy Requirements	For sensitive sites and management of SSSIs Regenerative farming and habitat restoration objectives linked to land use measures		
Factors Affecting Timescales	Policy and incentives		
Change in land use to unfertilised land, woodland or biomass cropping – Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Stakeholders considered this measure highly unlikely to be implemented on a wide scale due to the need to maintain productive land for food production, the need for farmers to retain income streams and the limited benefits that could be achieved in relation to NH_3 emissions.		
Localised changes – targeted mitigation – Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	No evidence in NH_3 reduction		

Behaviour change in food consumption

Measure Description

This measure considers whether human dietary change such as reduction in red meat and dairy consumption and replacing it by pork, chicken, human edible crops or novel proteins products and insects can reduce NH_3 emissions.

Evidence Base and Assessment of Evidence

There is limited evidence that this measure is likely to reduce NH_3 emissions. The search by IOM[218] produced no evidence. A CEH[237] study on the impact of future land use scenarios for the CCC evaluated scenarios with potentially significant reduction in red meat and dairy consumption. The results show a significant decrease in GHG emissions but a specific impact on NH_3 emissions is not discussed.

Summary of Evidence

A CCC discussion on climate change and diets[238] highlights the complexity of the scenarios and how difficult it is to estimate both the proportion of food consumption coming from production within England or elsewhere and the ambition of uptake in reducing red meat and dairy consumption. There are significant possible benefits if changes in UK diets and changes in UK agriculture are done at the same pace.

At the workshop there was much debate around whether there are any benefits of this measure in terms of NH_3 emission reduction. For benefits to be realised, this assumes that people consume British meat, so land in the UK would be freed up, resulting in reduced UK carbon emissions. The associated need to reduce food waste throughout the system was also discussed.

One of the barriers discussed at the workshop is the lack of evidence of the benefits to NH_3 emissions of this measure. One comment was that if red meat and dairy consumption is replaced by pork and chicken consumption there are issues associated with intensive farming and associated NH_3 emissions. A full analysis of the nitrogen cycle and carbon footprints associated with the proposed behaviour change was discussed. It was also noted that UK red meat production is and can be low emission and considered that there should be encouragement of more extensive lamb and beef production. However, it is evident that, in the long term, reductions in demand for red meat could result in reduced beef production, and consequent reductions in the associated NH_3 emissions.

The National Food Strategy[239] is required to align nutritional, trade and agriculture policy. But also considering all of the measures as a policy package for NH_3 emission reduction and include carbon emissions, rather than having carbon specific policies separately.

Stakeholders agreed that it may be difficult to implement such a measure and it will take a long time to change the behaviour of shoppers and consumers, price is still a key driver for supermarkets and many consumers.

Summary – - Behaviour change in food consumption

Factor	Summary		
Benefits	Not much evidence in NH_3 emission reduction Difficult to estimate / food combination of what it is grown in England and what is imported Benefit possible if change in UK diets and UK agriculture change hand in hand Can reduce GHG emissions		
Barriers	Public behaviour change Uptake of novel proteins (insects / novel proteins products) Provenance of food consumption		
Investment Requirements	Engagement with public and farmers Introduce new source of proteins Use of local food		
Policy Requirements	National Food strategy to align nutritional, trade and agriculture policy		
Factors Affecting Timescales	Uptake of behaviour change by public National food strategy		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	NH_3 emissions reduction associated with a 20% decrease in number of cattle by 2050	NH_3 emissions reduction associated with a 50% decrease in number of cattle by 2050

Factor	Summary
Justification	Proposed scenario in CEH study[237] for CCC. 50% (Speculative) and 20% (high) reduction in NH_3 emission related to Cattle by 2050. However, the associated reduction in grass land area (reduction in fertiliser), net change in arable land and increase in intensive pig and chicken farming is not quantified.

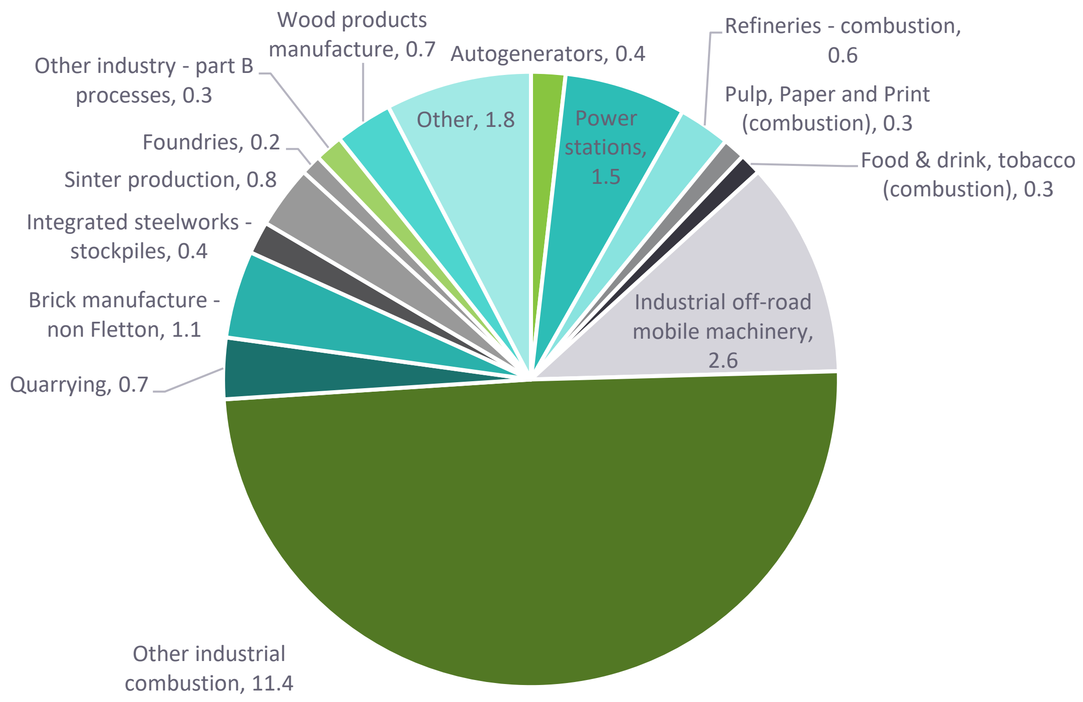
4.5 Industry, Construction and Manufacturing

Industry/Manufacturing

Introduction

The data from the NAEI for primary emissions of $PM_{2.5}$ in England are shown in Figure 4-1. All sources contributing over 1% of the sector total are detailed. This shows that "other industrial combustion" (49%) is the largest source. "Industrial Off-Road Mobile Machinery" (11%) is the next largest source. These represent general sources of emissions across the industrial sector. Measures have been identified for these sources. Emissions from specific industries or activities, such as sinter production (3%) and combustion in the food and drink industry are focused on particular sites and can be tackled through specific site based measures, as identified in the measures detailed below.

Figure 4-1 Primary sources of PM2.5 in England from Industry/Manufacturing (kilotonnes, 2018)[2]



Pie chart showing primary sources of $PM_{2.5}$ from Industry/Manufacturing in England for the year 2018. The pie chart shows that other industrial combustion is the major source followed by industrial off-road mobile machinery. Other industrial combustion 11.4 kT Industrial off-road mobile machinery 2.6 kT, Power stations 1.5 kT, Brick manufacture - non Fletton 1.1 kT, Sinter production 0.8 kT, Quarrying 0.7 kT, Wood products manufacture 0.7 kT, Refineries - combustion 0.6 kT, Autogenerators 0.4 kT, Integrated steelworks - stockpiles

0.4 kT, Other industry - part B processes 0.3 kT, Pulp, Paper and Print (combustion) 0.3 kT, Food & drink, tobacco (combustion) 0.3 kT, Foundries 0.2 kT, Other 1.8 kT.

Decarbonisation of Refineries

Measure Description

There are four refineries operating in England at Stanlow, Fawley, Humber, and Lindsey. The total PM_{10} emissions from these sites in 2018 was 838 tonnes according to the EA Pollution Inventory[240]. Total $PM_{2.5}$ emissions was 351 tonnes, although this is only for Humber and Fawley. The NAEI for 2018 estimates 630 tonnes of $PM_{2.5}$ emitted from combustion at refineries. Based on engagement with the EA, it is understood that there has been a significant reduction in emissions between 2018 and 2019 as a result of meeting the requirements of the Mineral Oil and Gas Refining BAT Reference Document (BREF)[241] and BAT conclusions[242] documents.

The UK Petroleum Industry Association (UKPIA) and EA identify that decarbonisation and progress towards net zero carbon emissions are the measures that are likely to have significant impact on $PM_{2.5}$ emissions. Decarbonisation is likely to be achieved through the use of low carbon liquid fuels (LCLF) in a short term plus the use of hydrogen and biomass as fuels in a long term.

Evidence Base and assessment of evidence

The main evidence is taken from the UKPIA documents *Transition, Transformation and Innovation – Our role in the Net-Zero Challenge*[243] and *The Downstream Oil Sector in a Low-Carbon World*[244]. Information is also taken from the Concawe report *A Clean Planet for all* Impact assessment on the potential implications for our refining system and the link with Refinery 2050[245] and Exploring possible pathways for the EU refining system to contribute to a low-CO_2 economy in the 2030–2050 timeframe[246]. Wood is supporting Concawe to expand the focus of previous research beyond carbon and determine the level of change in air, water and waste parameters for potential 2030/2050 refineries when considering low carbon technologies and feedstocks. Effects on $PM_{2.5}$ emissions will need to be estimated on the basis of the literature on decarbonisation and changes in feedstocks available at this time.

Summary of Evidence

The UKPIA reports that demand for liquid fuels is likely to decrease significantly, due to their substitution by other technologies, for example, electrification of the car and van vehicle fleet, electrification of domestic and commercial heating, and the use of hydrogen for industrial heat and in gas networks. The UKPIA consider that it is feasible that a combination of reduced demand, electrification and CCUS implemented at refineries could reduce the EU-wide total emissions from refining and use of main fuel products by 35%, with a further 85% reduction from using feedstocks other than crude oil. When introducing alternative feedstocks, the main objective would be to reduce the carbon intensity of final products, rather than for reduction of refinery emissions.

Concawe[245] has estimated that under the "1.5 TECH" scenario (achieving 100% net GHG reduction by 2050 compared to 1990 (including sinks) across the whole EU economy) the use of crude/lipid feedstocks would be 121 Mt/a against a baseline of 350 Mt/a. This change in feedstock would be expected to reduce $PM_{2.5}$ emissions significantly. However, it is also noted that this scenario assumes use of biomass feedstock of 55 Mt/a against a baseline of 5 Mt/a. This could lead to increased $PM_{2.5}$ emissions. Use of 100 Mt/a of hydrogen is assumed in the feedstock, which would be expected to have very low $PM_{2.5}$ emissions relative to other feedstocks. The net reduction of the overall crude/lipid/biomass feedstock (~50%) in the 1.5 TECH scenario provides information for considering $PM_{2.5}$ emissions reductions. The Deep-Decarbonisation Pathways for UK Industry[247] report predicts a reduction in direct carbon emissions from the sector of 47% by 2050 relative to the 2018 baseline, which is of a similar scale.

Several barriers to decarbonisation were discussed in the workshop. These include the costs of new technologies, which need to be considered alongside the reductions in demand for current products, and technical challenges around such changes as the use of hydrogen in gas turbines. UKPIA has highlighted that a systems-based approach is required with policies required to support the necessary innovation and investment.

Several barriers specific to the approach to assessing $PM_{2.5}$ emissions were also discussed. These include the limited confidence in the stated $PM_{2.5}$ emissions from refineries, the absence of reference to $PM_{2.5}$ in the Mineral Oil and Gas Refining BREF and the lack of industry focus on $PM_{2.5}$ emissions.

A further relevant measure mentioned in the interview process was the use of Portable CNG or mini-LNG facilities to treat gas on-site and reduce flaring. Up to 89% of flared gas could be eliminated with such technologies[248], although the size of the source in downstream oil and gas and the suitability of the technology at refineries is not clear.

Summary – Decarbonisation of Refineries

Factor	**Summary**		
Benefits	~50% reduction in emissions as a result of changes in feedstock Part of wider industrial decarbonisation		
Barriers	Significant infrastructure costs Significant research and development required		
Investment Requirements	Hydrogen infrastructure Research and development		
Policy Requirements	System-wide integrated decarbonisation policy required Support for investment and maintained		
Factors Affecting Timescales	Hydrogen fuel and electricity availability Low Carbon Liquid Fuels (before 2025) – supporting transition or flexible choice Post 2040 – crude oil be replaced by biomass fuel		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	50% reduction in combustion emissions by 2050	50% reduction in combustion emissions by 2045	50% reduction in combustion emissions by 2040
Justification	Based on reduction in fossil fuel use from Concawe and changes in carbon emissions from CCC. Slow rate of decarbonisation	Based on reduction in fossil fuel use from Concawe and changes in carbon emissions from CCC. Medium rate of decarbonisation	Based on reduction in fossil fuel use from Concawe and changes in carbon emissions from CCC. Rapid rate of decarbonisation

Sinter Plant Bag Filters

Measure Description

The EA Pollution Inventory[255] indicates that around 92% of $PM_{2.5}$ emissions from the metal industry (ferrous and non-ferrous) are from the Scunthorpe Integrated Iron and Steel Works. The potential for reducing fugitive emissions was highlighted in the interviews and is discussed later in this section of the Report.

The proposed installation of a fabric bag filter for the main extraction on the Scunthorpe sinter plant is expected to deliver significant reductions in emissions. The bag filters will be installed downstream of an existing electrostatic precipitator or cyclone. The BAT-associated emission level for dust is <1 – 15 mg/Nm^3.

Evidence Base and assessment of evidence

The evidence for this measure is based on interviews and submissions provided by the EA, supplemented by further research on the benefits of bag filters. Evidence has also been taken from the BREF for Iron and Steel[249] and 2013 BAT assessment for the site[250].

Summary of evidence

$PM_{2.5}$ emissions from the sinter main stack will reduce from 375 tonnes at present to 75 tonnes (80% reduction) as a result of the bag filter installation and the bag filter emission limit of 15 mg/m^3. The earlier BAT assessment predicted a reduction of 196 tonnes (total dust). Other installations of bag filter at sinter plants were expected to reduce emissions of fine particles from the sintering process by at least 75%[251, 252]. The 2018 $PM_{2.5}$ sinter production emission total for England is 0.76kT. A 75% improvement would reduce this to 0.19kT.

Although now superseded by the measure being implemented, the BAT assessment carried out in 2013 identified several constraints to the installation of a bag filter, namely:

- The plant is already fitted with advanced electrostatic precipitators and there are severe space restrictions upon further downstream installations.
- Installation of bag filters would be disproportionately costly compared to the environmental benefit.

The main barrier to introduction of abatement at steel works is still considered to be economic pressures. Excessive requirements for further expensive abatement could potentially lead to the closure of plant was highlighted during the interviews and workshop. Another constraint mentioned was that accurate measurement of $PM_{2.5}$ is not currently possible. Development of continuous monitoring approaches is required.

However, investment in bag filters now seems likely and would be operational in 2023, with an estimated capital cost of over £60m. Annual operating and maintenance costs are estimated to be £3.4m and £2.4m, respectively.

Summary – Sinter Plant Bag Filters

Factor	Summary		
Benefits	~75%-80% reduction in sinter production emissions		
Barriers	Investment required (~£50m)		
Investment Requirements	New bag filters plus OPEX and maintenance costs		
Policy Requirements	None. Already proposed.		
Factors Affecting Timescales	Likely to be operational by 2024		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	75% reduction in $PM_{2.5}$ emissions from sinter production by 2025	75% reduction in $PM_{2.5}$ emissions from sinter production by 2025	75% reduction in $PM_{2.5}$ emissions from sinter production by 2025
Justification	Emissions reduction taken from BAT documentation and other examples. Measure to be employed across all scenarios		

Sugar Industry Fuel Switching

Measure Description

The main sources of dust emissions from the sugar industry are dryers for beet pulp, with emissions from combustion and pulp particles[253]. From the interviews held, gases from the drying process are understood to be abated via cyclones before release to atmosphere.

Application of Food, Drink and Milk (FDM) BAT, including switching from the combustion of a solid fuel (e.g. coal) to the combustion of a gaseous fuel (e.g. natural gas, biogas) and the use of wet scrubbers for the sugar drying process has the potential to significantly reduce $PM_{2.5}$ emissions from the sugar industry.

Evidence Base and assessment of evidence

Several documents are available detailing the emission abatement performances of wet scrubbers relative to cyclones. The installation of wet scrubbers would significantly increase the volume of wastewater requiring treatment, requiring significant capital investment. A new FDM Industries BREF was also published in 2019[254]. Statistics on total emissions from sites are available in the Environment Agency Pollution Inventory (PI)[255]. British Sugar has also provided information through the consultation process.

Summary of Evidence

Particulates emissions from the food and drink sector are mainly associated with grinding, milling and drying activities. There are more than 20 sub-sectors, however the sugar beet processing sector is overwhelmingly the most significant source of reported $PM_{2.5}$ emissions. There are four sites (Bury St Edmunds, Cantley, Newark, Wissington) in this sub-sector in England, all operated by British Sugar. These four sites reported $PM_{2.5}$ emissions of 182 tonnes in 2018, compared to the total emissions for the food and drink sector of 184 tonnes in the same period and the total for "Food & drink, tobacco (combustion)" in the NAEI of 260 tonnes.

Use of gaseous fuels is one of the measures detailed in the BREF to reduce dust emissions to air from beet pulp drying. As previously noted that this can reduce combustion emissions significantly[253]. Of the ten beet dryers at these four sites, four are understood to be coal-fired. Moving away from coal combustion for beet pulp drying could reduce $PM_{2.5}$ emissions by an estimated 79 tonnes (43% reduction for the sugar industry). This would represent a 30% reduction relative to the 2018 "Food & drink, tobacco (combustion)" total in the NAEI of 260 tonnes.

The BAT conclusions document[256] states that the use of gaseous fuels may not be applicable due to the constraints associated with availability. This is an important constraint that needs consideration on a site by site basis. A gas line was installed at a British Sugar site as recently as 2017[257]. It is estimated that changes could be delivered between 2023 and 2026 (subject to derogation requests relating to availability of infrastructure).

The cost of the conversion is also significant and likely to be in the range £5-20m per site for the three sites where fuel switching is under consideration, although there are likely to be savings associated with cheaper fuel and reduced maintenance costs. The 2019 BREF also recommends that future work should include collection of information on $PM_{2.5}$/PM_{10} emissions from FDM sectors.

Indirect drying (steam drying) of beet pulp is also mentioned in the BAT conclusions document and is considered to be a measure that could reduce $PM_{2.5}$ emissions to almost zero but is not considered to be applicable to existing plants due to the need for a complete reconstruction of the energy facilities.

Summary –- Sugar Industry Fuel Switching

Factor	Summary		
Benefits	30% reduction relative to 2018 "Food & drink, tobacco (combustion)" total		
Barriers	Investment required Natural gas availability/network		
Investment Requirements	Connections to gas grid and reconfiguration of sites and operation £5-20m per site for the 3 sites where fuel switching is under consideration		
Policy Requirements	None. Required as part of Food, Drink and Milk BAT, 2019 BAT may need to be updated at some stage to consider particulate matter in more detail		
Factors Affecting Timescales	Likely to be operational in 2023-2026		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	30% reduction in $PM_{2.5}$ emissions from Food & drink, tobacco (combustion) by 2030	30% reduction in $PM_{2.5}$ emissions from Food & drink, tobacco (combustion) by 2030	30% reduction in $PM_{2.5}$ emissions from Food & drink, tobacco (combustion) by 2030
Justification	Applied in all scenarios reflecting the application of BAT		

Medium Combustion Plant Directive (MCPD) - increasing stringency of limits for plants above 1MW

Measure Description

The requirements of the Medium Combustion Plant Directive (MCPD) (Directive 2015/2193/EU) ('MCPD')[258] as set out in Schedule 25A of The Environmental Permitting (England and Wales) Regulations 2016 (as amended)[259] requires that Medium Combustion Plants (MCPs) must meet the appropriate emission limit value (ELV) by the required date. The ELVs are for NO_X, SO_2 and dust. The MCPD requirements are a minimum standard and BAT may require tighter conditions (e.g., for Part A or B processes), but does not necessarily apply[260]. Only 5% of plants in the 1-5 MW class are estimated to be covered by a BAT-based permit[261]. The Clean Air Strategy mentions considering the case for increasing stringency of limits for plants above 1MW [262]. Amendments to the regulations could be used to increase the requirements for BAT-based permits and reduce the allowable emissions. Tighter emission standards for NO_X could be met with the use of SCR.

Evidence Base and assessment of evidence

Evidence has been taken from the Defra Impact Assessment into the implementation of the MCPD[263]. This includes details on the amount of Medium Combustion Plants expected in future years and the expected abatement measures to be employed.

Summary of evidence

The Impact Assessment estimates that up to 10,000 working plants will be required to comply with emissions limits under MCPD with around 90% in the 1-5MW range, running in the main on natural gas, but also solid and liquid fuels, including biomass and biogas. Some 9,430 combustion plants are estimated to be working in 2030. Of these, 70% will be using lean burn / low NOx burners achieving 40-50% NO_X emission reduction. The total NO_X emissions reduction would be 16kT. The NO_X abatement efficiency of SCR is reported to be 70-90%. Regulations leading to widespread use of SCR instead of lean burn / low NO_X burners could increase the NO_X saving by 2 to 6kT. This is equivalent to 5 to 12% of the "other industrial combustion" source of NO_X emissions in England in 2018. The use of SCR has, however, some downside as there is a potential for ammonia slip, which is not quantified yet and therefore not included in the impact. A study funded by the government is looking into further NOx reduction from MCPs with the use of SCR and the level of its potential benefit.

With regards to barriers to this measure, several stakeholders at the workshop stated that retrofit is expensive and that it is necessary to ensure that technologies that are invested in need to be suitable for the long-term and not superseded by any other policies (such as those related to changes in fuels). As an indication of the scale of the costs, the IA estimates that the MCPD policy had total costs of £387m, including Operational/capital cost of technology switch of £148m.

Summary – Medium Combustion Plant Directive (MCPD) - increasing stringency of limits for plants >1MW

Factor	Summary		
Benefits	70-90 % reduction in NOx emissions through SCR (relative to 40-50% for low NO_X/Lean Burn) 5-12% reduction relative to “other industrial combustion”		
Barriers	Knowledge of contribution of NOx to secondary $PM_{2.5}$ formation Cost of retrofit to MCP. Could be particularly burdensome given recent refits. SCR, potential for ammonia slip with retrofitting (to be quantified)		
Investment Requirements	Retrofitting existing plants for NOx abatement Build new plant with abatement system R&D in new abatement system for PM and NOx (SCR / SNCR)		
Policy Requirements	More stringent limits for plants above 1MW Centralised collation of emission information from MCPD testing centrally		
Factors Affecting Timescales	NOx and biomass emissions PM likely to increase from more plants By 2050 combustion emissions of NOx should be much reduced Biomass depends on UK policy		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	10% Reduction in NO_X emissions from “other industrial combustion” by 2050	10% Reduction in NO_X emissions from “other industrial combustion” by 2040	10% Reduction in NO_X emissions from “other industrial combustion” by 2030
Justification	Emission reductions based on MCPD IA. New regulations imposed in the long term	Emission reductions based on MCPD IA. New regulations imposed in the medium term	Emission reductions based on MCPD IA. New regulations imposed in the short term

Regulate Biomass Combustion Plants <1MW

Measure Description

This measure would bring biomass combustion plants below 1MW into regulation under the Environmental Permitting Regulations (EPR) as a Part B activity and set limits on particulate emissions. All these plants would then need an environmental permit requiring abatement of $PM_{2.5}$.

Evidence Base and assessment of evidence

Discussions during the workshop suggested that biomass combustion plants below 1MW could account for a large part of $PM_{2.5}$ emissions in England as they do not need a permit to operate, and their installation and operation is incentivized through the Renewable Heat (RHI) Grant[264]. However, it was acknowledged that the total $PM_{2.5}$ emissions from these plants is not known as they are not regulated.

Summary of evidence

As highlighted in the workshop, the air quality benefits of regulating these plants could be significant as there are more than 11,000 RHI funded small and medium biomass boilers below 1MW in England, with an aggregate capacity of more than 3GW[265]. These plants are typically small boilers with an average size of 250kW in public buildings, offices, and small industrial installations. These installations currently do not require a permit, and it is possible that wet wood no longer sold for domestic use could be transferred to these plants. Waste wood of inappropriate grades is likely being used in these small appliances. The RHI does not apply controls over emissions. Emissions are only controlled if the plant is otherwise regulated.

In 2018, as committed within the Clean Air Strategy, the government consulted on excluding biomass from the RHI if installed in urban areas which are on the gas grid[266]. The consultation document states that *"there is anecdotal evidence that some existing RHI biomass installations emit pollutants to air at far higher levels than those specified by the applicable emission standards. One reason for this is the use of inappropriate fuels such as wood that is wet or contaminated. Another is equipment that is not maintained properly, resulting in its environmental performance reducing over time."*

The response to the consultation was published in April 2020[267,268] with the decision made not to proceed with the removal of eligibility for new biomass installations in on-grid urban areas. Instead, the scheme is to be improved by focusing on the existing accredited biomass installations and any new biomass installations accrediting to the RHI for the remainder of the scheme. The government stated a commitment to ensure that industry standards will play a stronger role in the future of the RHI to minimise air quality impacts and promote a healthy UK biomass supply chain. Air quality from the existing cohort of accredited installations will be improved by:

- Building a fit for purpose fuel quality regime for biomass feedstocks for the remainder of the RHI period.
- Working with industry to introduce a maintenance standard.
- Working closely with Ofgem and other regulators to strengthen enforcement of the existing RHI Regulations in relation to air quality.

Discussions at the workshop confirmed that the RHI requires people to buy fuel that is registered on the Biomass Suppliers List (BSL)[269] to demonstrate sustainability. The BSL is to be adapted to include fuel quality, which will help to ensure that the fuel used is appropriate for the boiler. Non-domestic RHI also requires biomass boilers to carry out mandatory annual maintenance checks.

Summary – Regulate Biomass Combustion Plants <1MW

Factor	Summary
Benefits	Unknown as these sites are currently unregulated. Benefits of regulation could be significant as there is a large number of sites and potential fuel quality issues.
Barriers	Regulation is challenging as it is difficult to prove that poor quality fuel has been used and cost of prosecution would outweigh any benefits. Poor quality installations leading to frequent cycling of the boiler (e.g. over specified or buffer tank too small). Low seasonal efficiency and increased emissions as a result, even with the right fuel.
Investment Requirements	Operator investment in permit application. Investment in enforcement.
Policy Requirements	New permitting requirements Strict requirements in relation to $PM_{2.5}$/NO_X when applying for subsidy for biomass boilers under RHI and planned successor policy (Clean Heat Grant). Change to secondary legislation to include the new processes. Introduction of maintenance and fuel quality standards from 2022 for biomass boilers.

Factor	Summary		
Factors Affecting Timescales	Will depend on policy changes and development of enforcement mechanism.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Impact on emissions unknown as emissions from this source are not quantified		

Monitoring and improved fugitive emissions capture

Measure Description

The NAEI[270] indicates that non-combustion emissions sources of $PM_{2.5}$ make an important contribution to the national total. For example, stockpiles at Steelworks represent 0.5% of the 2018 total for England and emissions from quarrying represent 0.9% of the total.

Fugitive emissions can be controlled in a number of ways. Such as redesign of crushing / sieving equipment (e.g., integration of extraction of filtration into equipment design), use of covered or partially covered work areas), covering stockpiles, wetting and sealing of dusty areas and planting programmes.

Programmes to manage emissions could also be supported by increased monitoring. At present, this is typically done at the site boundary, or in communities near to industrial sites. The potential for stack emissions monitoring of $PM_{2.5}$, to reduce reliance on emission factors has also been discussed.

Evidence Base and assessment of evidence

Advice on the measures that can be employed to reduce fugitive emissions is available from a number of sources, including BREFs and particular sector guidance. The evidence on impact that these measures can make on emissions of $PM_{2.5}$ specifically is less well established. AQEG[271] has previously stated that emissions from fugitive dust sources are particularly difficult to estimate but occur as a result of many industrial and material handling processes. Guidance is available on how emission rates may differ as a result of control measures.

Summary of evidence

Numerous operational guidance documents are available that mention fugitive emissions. The BREF for the Production of Cement, Lime and Magnesium Oxide[272] mentions spraying water to emissions and states that wherever possible, closed storage systems are used. The non-ferrous metals BREF[273] mentions a site where a closed building is used for unloading concentrates, and a truck-washing station to allow particulate emissions to be minimised. The institute of Air Quality Management (IAQM) has *produced Guidance on the Assessment of Mineral Dust Impacts for Planning*[274] including best practice.

Emission factors which vary according to control measures are provided by organisations such as the European Environment Agency (EEA)[275] and US Environmental Protection Agency (EPA)[276]. The EPA highlights that spray systems at transfer points and on material handling operations have been estimated to reduce emissions 70 to 95% and that spray systems can also reduce loading and wind erosion emissions from storage piles of various materials 80 to 90%. Containment of processes will reduce emissions by close to 100%. Consensus was reached at the workshop that measures to reduce total dust and particulate emissions are likely to reduce $PM_{2.5}$ emission, and that monitoring using light-scattering devices has significantly improved the control of emissions at sites where they are used.

The interviews and workshop highlighted the number of sites that could reduce emissions significantly is limited given the age of BREFs and current site practices, however some interviewees did mention this as an area for better control. For example, fugitive releases from the metal sector are understood to have not reduced significantly as these are wind-blown from large legacy industrial areas and planting/greening has stopped for financial reasons.

For modelling purposes, the assumption is made that better monitoring and control processes could be established at around 10-20% of steel stockpile and quarrying sources, reducing $PM_{2.5}$ emissions by 70-90% and hence, an indicative reduction of 7-18% of emissions from these source groups. Since these monitoring and control techniques already exist, as shown at Scunthorpe[277] and other sites[278], techniques are available that can be employed in the short term. The main barriers discussed at the workshop included the cost to operators (Capex and manpower) and reluctance to change ways of working. Capex for monitoring programmes to help site management are estimated at around £50,000 to £150,000 depending on the monitoring equipment employed, and the number of monitors which is related to the size of the site. Light scattering monitors typically cost around £5,000 to £15,000.

Specific barriers that were highlighted in relation to monitoring were that $PM_{2.5}$ monitoring in stacks is not possible using currently available techniques (and not seen to be particularly beneficial if it was) and issues around distinguishing $PM_{2.5}$ from other sources in the area with the commonly used monitoring devices (e.g., road traffic).

Summary – Monitoring and improved fugitive emissions capture

Factor	Summary		
Benefits	~7-18% reduction from steel stockpiles and quarrying sources		
Barriers	Cost Lack of monitoring to understand PM / $PM_{2.5}$ distribution and source of $PM_{2.5}$ ($PM_{2.5}$ monitored on site might not be from site emissions)		
Investment Requirements	Operator Capital investment Manpower Changing behaviour or method of working R&D in design		
Policy Requirements	Local enforcement at existing sites Stricter enforcement of existing legislation (sealing dusty areas, greening)		
Factors Affecting Timescales	Regulatory drivers Can be implemented in the short-term ~2025		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	Up to 15% reduction from steel stockpiles, quarrying and brick manufacture sources by 2025	Up to 15% reduction from steel stockpiles, quarrying and brick manufacture sources by 2025	Up to 15% reduction from steel stockpiles, quarrying and brick manufacture sources by 2025
Justification	Emission reductions based on literature around reductions that can be achieved, such as that produced by the US EPA, and the estimated proportion of sites where there are significant improvements that can be made. Applied across all scenarios		

NRMM Stage V – Diesel Engines

Measure Description

This measure is discussed in more detail in the following section on construction. In summary, equipment that meets the Stage V emission standard meets a Particle Number standard that can only be achieved using a DPF which significantly reduces particulate emissions. Compliance can be achieved by retrofit or replacing the machine or engine. Measures to support rollout of new equipment will therefore significantly reduce emissions.

Evidence Base and assessment of evidence

The evidence base with regards to NRMM is discussed in more detail in the following section on construction. In summary, there is strong evidence available that Stage V will deliver significant reductions in emissions. There was agreement at the workshop that Stage V NRMM regulations would deliver significant reductions in $PM_{2.5}$.

Summary of evidence

The evidence base with regards to NRMM is discussed in more detail in the following section on construction. In summary, significant reductions in exhaust $PM_{2.5}$ emissions, of over 95%, are to be expected. Timescales will be governed by the turnover of machinery. The majority of equipment is likely to be replaced within a ten to 15 year lifetime.

The workshop also highlighted that the removal of tax exemption for red diesel in April 2022[279] is likely be a driver for changes in NRMM.

Other options for reduction of emissions from NRMM, such as use of electricity, were discussed during interviews and the workshop. Several barriers to the use of electricity were mentioned including the cost of electricity, doubts over the increased electricity supply and infrastructure and the feasibility for larger machines with high power demand. So, whilst this does offer further potential emission reductions, it does not need to be considered separately as a measure.

Summary – NRMM Stage V – Diesel Engines

Factor	Summary		
Benefits	Reduction in $PM_{2.5}$ emissions from "Industrial off-road mobile machinery" of 95% or more by 2030–2035 compared with 2018 baseline Co-benefits include reduced emissions of NO_x. Some potential for CO_2 savings based on the reported expectation that Stage V engines are more fuel efficient than lower Stage engines. As well as improvements to local air quality, workplace exposure is reduced substantially.		
Barriers	Additional costs to operators from new plant, but expected to be largely cost neutral since this forms part of natural turnover. Old engines can be on the market until December 2021, after which, new machines will be Stage V compliant		
Investment Requirements	Largely driven by natural plant turnover. Retrofitting existing engines		
Policy Requirements	Not required. Policies to encourage use of new plant on a regional or project basis can provide targeted emissions reductions in particular locations in order to reduce exposure.		
Factors Affecting Timescales	Typical plant lifetime is 10–15 years. April 2022 removal of tax exemption for red diesel will be a driver for changes in NRMM.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	90% reduction in emissions of $PM_{2.5}$ from new Stage V NRMM. 100% uptake by 2040	90% reduction in emissions of $PM_{2.5}$ from new Stage V NRMM. 100% uptake by 2035	90% reduction in emissions of $PM_{2.5}$ from new Stage V NRMM. 100% uptake by 2030
Justification	Slow uptake of Stage V equipment. Based on	Medium uptake of Stage V equipment. Based on	Rapid uptake of Stage V equipment encouraged. Based

	stakeholder engagement and equipment lifetime	stakeholder engagement and equipment lifetime	on stakeholder engagement and equipment lifetime

Industrial Decarbonisation

Measure Description

In 2020, the government produced its Ten Point Plan for a Green Industrial Revolution[280]. This document highlights plans to work with industry in 2021 to devise further sectoral plans and meet carbon budgets and target of net zero by 2050. The government Energy White Paper[281] introduced the Industrial Decarbonisation Strategy[282] which was published in March 2021. This Strategy states that the government expects industrial emissions need to fall by around two thirds by 2035, delivered in a way that capitalises on clean growth opportunities. This is required to keep industry on the journey to net zero and to meet the UK's carbon budgets and nationally determined contribution under the Paris Agreement. The government's expectation is that the following measures will be needed:

- Four of the UK's major industrial regions linked up to the necessary decarbonisation infrastructure by 2030.
- Around 6 $MtCO_2$ of industry emissions captured each year by 2030 (and 9 $MtCO_2$ by 2035) ; the same as planting over 500 million trees.
- Low carbon fuels such as hydrogen, electricity and bioenergy replacing fossil fuels, unless combined with carbon capture. To be on track to deliver net zero, government expects that the minimum, in all future scenarios, is 20 TWh per year of fossil fuel use replaced with low carbon alternatives in 2030.
- Maximum energy, resource and material efficiency within industry, including the adoption of circular economy measures, particularly through the 2020s.
- Development of a thriving market for low carbon materials.
- Established approaches to equip workers and local residents to take advantage of new opportunities of decarbonising industry.
- Cooperation with other leading nations and support to the developing world to ensure that industrial decarbonisation is happening across the world.

Decarbonisation of the industrial sector has significant potential for reducing $PM_{2.5}$ emissions by reducing fossil fuel combustion. This can be achieved through the following measures Element Energy report on *Deep-Decarbonisation Pathways for UK Industry* [283]:

- Resource efficiency, energy efficiency (REEE).
- Electrification – Electric Boilers, Kilns, Furnaces, Ovens, Dryers, and Compressors Electric Arc Furnaces (for Iron and Steel) – All sectors.
- Hydrogen (Green (made from non-fossil sources) and Blue (created from fossil sources, where the carbon emissions are captured and stored) – Hydrogen Boilers, Combined Heat & Power, Kilns, Ovens, Furnaces, Dryers, and Compressors, Hydrogen Direct Reduction (for Iron and Steel) – All sectors.
- Carbon Capture and Storage (CCS) - Internal Fuel Combustion, Large Equipment/Sources, Process Emissions (Refining, Chemicals, Cement, Iron and Steel).

- Bioenergy with Carbon Capture and Storage (BECCS) – Carbon Capture on Existing Biogenic Emissions Fuel Switching to Biomass Combined with CCS – Waste Processing, Cement, Lime, Glass, Paper.

Evidence Base and assessment of evidence

Evidence has been obtained from government sources such as the energy white paper and the CCC Policies for the Sixth Carbon Budget and Net Zero[284]. Decarbonisation measures and their potential effect on $PM_{2.5}$ emissions were discussed in many of the interviews and the workshop. Detailed quantification of the effects of these measures is not yet available. Particularly as many of the strategic documents were published in late 2020. The Element Energy report on *Deep-Decarbonisation Pathways for UK Industry* does provide information on fuel consumption and carbon emissions that provide an indication on changes in fuel consumption, which can be related to combustion emissions. The N-ZIP model developed as part of that study will be published online in 2021.

Summary of evidence

The Element Energy report suggests that REEE measures alone can reduce carbon emissions by 20% by 2030, 27% by 2040 and 33% by 2050. Energy efficiency, reduced resource use, material substitution to reduce fuel use for a level of activity, reduced consumption and effects from economy-wide decarbonisation. Natural gas consumption is predicted to reduce by 32% by 2030, 46% by 2040 and 55% by 2050 in the balanced scenario (includes a balanced mix of technologies in the long term, which enables decision-making to change track depending on developments in the short-to-medium term). One study reviewed[285] indicates that decarbonisation policies across the economy could reduce $PM_{2.5}$ emissions by 38%-50% in 2050.

Some of this natural gas will be used for blue hydrogen production with carbon capture, utilisation and storage (CCUS) of the resulting carbon dioxide emissions rather than as a direct feedstock. On the other hand, hydrogen combustion can be associated with higher NO_X emissions[286], as highlighted by stakeholders during interviews and the workshop.

Each industrial sector will decarbonise at different rates, especially where implementation of low carbon technologies is limited in the near-term, and that there will be variation between smaller sites and industrial clusters[287]. Clusters enable focused investment to develop infrastructure where it is required (the six largest industrial clusters by carbon emissions are Grangemouth, Teesside, Merseyside, Humberside, South Wales, and Southampton).

Decarbonisation will affect usage of different fuels in different ways. Natural gas is the predominant fossil fuel used in all sectors[288] and is expected to decline. Stakeholder engagement suggests that biomass combustion is likely to increase at least up to around 2040. $PM_{2.5}$ emission rates from biomass are expected to be significantly lower than the emission rates used in the NAEI recent years as modern technology and abatement will be employed in new systems. Outputs from the UK TIMES model[289] developed by UCL and BEIS for the "core run" have been used to determine factors to adjust natural gas and biomass combustion emission totals in the Other Industrial Combustion sector.

Significant concerns were raised in the interviews and workshop regarding the challenges of developing the hydrogen transportation and storage network required for decarbonisation. The Energy White Paper states the intention to work with industry to develop 5GW of low-carbon hydrogen production capacity by 2030.

There is a need to invest significantly in UK's energy innovation programme to develop the technologies of the future such as advanced nuclear and clean hydrogen. The CCC[284] considers that funding mechanisms for deep decarbonisation measures (electrification, use of hydrogen and application of CCS) are likely to scale up from 2025 and this will require funding that is not included in the business model of current policies and proposals. Government should establish funding mechanism(s) to enable both electrification and hydrogen-use in manufacturing. The CCC report that estimate that providing subsidy support would cost the exchequer around £2-3bn per year in the early 2030s after which taxpayer support would fall.

Summary – Industrial Decarbonisation

Factor	Summary		
Benefits	Significant reductions in fossil fuel use Reduced emissions of carbon, $PM_{2.5}$ and NO_X Potential for increased biomass combustion, but with low particulate emission rates associated with modern systems Reductions in natural gas combustion (indicator of activity) up to 96% by 2050		
Barriers	Technical barriers/development required Lack of infrastructure Cluster requirement for Hydrogen Increase in use of Hydrogen may lead to more NOx emissions		
Investment Requirements	Significant investment in R&D Significant investment in infrastructure		
Policy Requirements	Policy support for fuel switching Support for innovation Funding mechanisms for new technologies		
Factors Affecting Timescales	Policy decisions Availability of hydrogen and electricity Net zero by 2050 with a pathway over the next 20 years		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	Other industrial combustion. Natural gas: 70% reduction by 2030 88% reduction by 2040 96% reduction by 2050 Biomass: 260% increase by 2030 6% increase by 2040 89% reduction by 2050 New biomass assumed to emit 90% less $PM_{2.5}$ than current biomass emission rates	As for medium	As for medium
Justification	UK TIMES Outputs for core run	UK TIMES Outputs for core run	UK TIMES Outputs for core run

Construction

Introduction

As illustrated in Section 2, construction and demolition is estimated to contribute around 3% of total $PM_{2.5}$. "Industrial Off-Road Mobile Machinery", of which the construction sector is an important user, contributes a further 3%. This also contributes 4% of NO_X emissions.

New Stage V NRMM

Measure description

NRMM emissions are regulated in Stages, with emissions standards depending on end use, type of engine (constant or variable speed, compression or spark ignition), power rating, type approval date and market placement date. This makes summarising the standards difficult. Broadly speaking, most NRMM in current use falls under Stage IIIB/IV, which sets a limit[290] on particulate (all sizes) of 0.025 g kWh^{-1}. Stage V applies to new equipment placed on the market from 2019 or 2020 and imposes tighter controls[291].

particle number (PN) of 1 × 10^{12} kWh^{-1}. Manufacturers were able to meet the Stage IIIB/IV requirement using in-cylinder techniques, but the PN standard can only be achieved using a DPF. The practical effect is that DPFs are rare on pre-Stage V NRMM, but ubiquitous on Stage V plant.

DPFs that meet the PN requirement are able to achieve control of PM mass that is comfortably within the Stage V standard, and substantially lower than was achieved by pre-Stage V plant.

This measure relates to the uptake of Stage V NRMM within the fleet. This may occur through natural plant turnover, as older plant reaches the end of its useful life and new plant is bought to replace it, or through policy incentives to replace older plant with Stage V equipment.

Further tightening of emissions controls is expected in future. This is expected to broadly mirror standards for road vehicles, including a requirement for Portable Emissions Measurement System (PEMS). The exact details are not known at this time and it is unclear whether the UK will implement any future standards derived at a European level, so it has not been considered further here.

The reductions in $PM_{2.5}$ from Stage V are substantial and, given the typical lifetime of a unit of plant, this measure is considered to be the most important factor in the reduction of $PM_{2.5}$ from this sector in the medium term. Emissions reductions are expected to be in the region of 90% over the next 10–15 years even without further policy action. The other measures for this sector, considered below, either make small short-term improvements to $PM_{2.5}$ emissions (typically a few percent) or reduce the residual emissions over a longer timescale (2030 onwards).

There is a huge variety of NRMM, and some NRMM types have only recently come under regulations. For example, compression ignition engines below 18 kW were unregulated until Stage V. Stakeholders considered that the majority of NRMM is now regulated and the overall emissions from old pieces of equipment which were not regulated when originally sold are expected to be small.

Evidence base and assessment of evidence

Emissions limits for NRMM under the various stages are set out in European directives[290,291]. However, the difference between compliance and real-world emissions are largely commercially sensitive and there is little published material other than statements of compliance under laboratory test conditions. This is clearly an area of concern for some pollutants, in light of the variable real-world compliance of on-road diesel vehicles. While most focus on engine compliance has been on road vehicles, there is one study by Desouza *et al*[292] that has measured real-world performance of construction plant.

Although hard quantitative evidence of the effectiveness of this measure is limited, interviews indicated widespread expert opinion that is consistent with this evidence. Overall, therefore, the evidence for this measure is considered to be strong.

Summary of evidence

Desouza *et al*[292] measured tail-pipe NO_x, CO_2, and particle emissions, for 30 of the most commonly used construction machines in London under normal working conditions. However, particle mass was only measured for seven generators of Stage IIIA and Stage IIIB standards under standard test cycle conditions, one of which was retrofitted with a DPF as part of the study. Despite its limitations, this study is the best published evidence of real-world $PM_{2.5}$ emissions from NRMM and the effectiveness of DPFs.

The study found that all generators tested met their respective Stage IIIA emission standards.

Comparing a Stage IIIB generator before and after fitting with a DPF, across a standard ISO 8178 test cycle type D2, Desouza *et al* found that the average particle number emission factor reduced by a factor of 100, from 4.06 × 10^{11} kWh^{-1} without DPF to 0.04 × 10^{11} kWh^{-1} with DPF. This implies that the DPF removes 99%

of particles by number. This is consistent with expert opinion that DPFs reduce $PM_{2.5}$ emissions by upwards of 90%, with 95–97% being one suggested figure.

The same team conducted a follow-up study looking at Stage V equipment. The results of this have not yet been published but interviews with team members indicated that particulate emissions from Stage V equipment were found to be much better compared with the Stage IIIA/IIIB plant and generally met expectations.

Regarding timescales, there was consensus that Stage V plant will enter the fleet due to natural turnover of equipment. Typical lifetimes of an item of plant are in the range 10–15 years, although this varies with plant type, with larger and more specialised items having longer lifetimes. Commonly, major plant hire companies, responsible for around half of plant items, will buy new plant and keep it for around 5–6 years before selling it on. As plant items grow older, they are sold down the value chain and are likely to be used less intensively.

The main driver is natural turnover. Measures to accelerate take-up of Stage V plant can be taken on a national, regional or project basis. Examples are the London NRMM LEZ[293] and HS2's policy to require contractors' plant to meet Stage V in London and at least Stage IV elsewhere from 2021[294]. For private companies, motivations for requiring higher standards include ability to meet regulatory requirements on air quality in order to obtain planning permission and permits, and for reasons of corporate social responsibility and public relations.

The overall benefits of measures to encourage uptake of newer plant are mixed. Where they are regionally focussed in locations of poor air quality, e.g. in London, they reduce exposure. They may also drive the uptake of new plant within the industry, but if they represent only a small fraction of total construction activity, they are likely to simply displace older plant to other locations. A national policy would be required to prevent displacement and could also reduce costs by improving economies of scale as manufacture of compliant equipment is increased.

Costs of this measure are largely borne by the industry, and to the extent that it follows the natural turnover of plant these costs are already embedded in the industry. As such it may be considered cost neutral. Measures to accelerate take-up on a regional or project basis will impose costs on particular operators, but to the extent that older plant is displaced to other projects they are again cost-neutral overall.

Uptake of new plant can also be encouraged through the Annual Investment Allowance scheme, a form of tax relief which allows capital expenditure to be offset against accounts for the year. This entails costs to the Treasury.

Summary – New Stage V NRMM

Factor	Summary
Benefits	Reduction in $PM_{2.5}$ emissions from construction NRMM of 95% or more by 2030–2035 compared with 2018 baseline, with high confidence. Reductions in emissions from other NRMM is more variable depending on the fraction of plant which falls in regulated size categoriesCo-benefits include reduced emissions of NO_x. Some potential for CO_2 savings based on the reported expectation that Stage V engines are more fuel efficient than lower Stage engines. As well as improvements to local air quality, workplace exposure is reduced substantially.
Barriers	Additional costs to operators from new plant, but expected to be largely cost neutral since this forms part of natural turnover.
Investment Requirements	Largely driven by natural plant turnover.
Policy Requirements	Not required. Policies to encourage use of new plant on a regional or project basis can provide targeted emissions reductions in particular locations in order to reduce exposure.
Factors Affecting Timescales	Typical plant lifetime is 10–15 years. London NRMM LEZ expected to require Stage V by 2030.

Factor	Summary		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling (as for industry Work Package)	90% reduction in emissions of $PM_{2.5}$ from new Stage V NRMM. 100% uptake by 2040	90% reduction in emissions of $PM_{2.5}$ from new Stage V NRMM. 100% uptake by 2035	90% reduction in emissions of $PM_{2.5}$ from new Stage V NRMM. 100% uptake by 2030
Justification	Slow uptake of Stage V equipment. Based on stakeholder engagement and equipment lifetime	Medium uptake of Stage V equipment. Based on stakeholder engagement and equipment lifetime	Rapid uptake of Stage V equipment encouraged. Based on stakeholder engagement and equipment lifetime

Retrofit to Stage V NRMM

Measure description

As explained above, 2019 saw a major reduction in particulate mass emissions from new NRMM due to the use of DPFs, which were previously uncommon and are now, in effect, mandatory. DPFs reduce PM mass emissions substantially compared to in-cylinder technologies. As an end-of-pipe technology (albeit one closely integrated with the engine management system), it is possible to retrofit DPFs to older plant items and bring them up to Stage V standard, or close to it.

Evidence base and assessment of evidence

Retrofits for road vehicles are well established, but are much less common for NRMM, because of lower regulatory pressure and the greater diversity of plant types. There is consequently little firm evidence other than the High Speed Rail 2 (HS2) pilot project. Expert opinion is mixed.

Summary of evidence

The key difference between Stage V and earlier stages, as regards $PM_{2.5}$ emissions, is that the former requires the use of DPFs, which reduce particulate emissions by 90–99%. These are essentially end-of-pipe units, albeit integrated with the engine management system, so retrofits are in principal deliverable with a fairly simple hardware and software upgrade.

The HS2 pilot project[295] was the world's first retrofit on large construction equipment, upgrading a large Stage IIIA 224 kW piling rig to meet Stage V standards. The project was overseen by the Energy Saving Trust and is considered by HS2 to have achieved its objective in reducing emissions.

While it is generally accepted that retrofits are technically possible, consultees expressed reservations about the practicality of this measure, especially on cost grounds. The general opinion was that retrofitting might be viable for certain specialist, expensive and long-lived plant items, but less so for smaller, cheaper and more short-lived equipment. For a given plant item, a retrofit allows the operator to meet Stage V standards at lower cost than buying a new item. However, measures such as the London NRMM LEZ are more likely to cause operators to displace older plant outside the LEZ than to retrofit them, since the major companies are likely to have an inventory of plant with a range of ages and therefore meeting a range of standards.

Obstacles to retrofitting NRMM include the wide variety of NRMM, making standardisation of the retrofit difficult and expensive to due poor economies of scale (compared to road vehicles, which are relatively uniform, for example). The short lifetime of some plant types means that the payback period is short, reducing the cost-effectiveness of the capital expense.

Hence the general view is that retrofits are likely to be unusual and largely confined to certain plant types. Given the timescales over which Stage V plant will enter the fleet naturally, the market for retrofits is likely to be small.

Retrofits are likely to be done as a package with SCR for NO_x abatement. They may therefore be driven by requirements for NO_x control as well as $PM_{2.5}$.

In view of the immaturity of the retrofit market, it is unlikely that there will be substantial take-up even for those plant types that are suitable within the next few years. Given the introduction of Stage V plant through natural turnover, this leaves only a short period in which retrofits are likely to be viable for any but the longest-lived plant.

Summary – Retrofit to Stage V NRMM

Factor	**Summary**		
Benefits	Substantial reductions in $PM_{2.5}$ emissions of around 95–97% for those plant items that have retrofits. However, these are likely to be a small fraction of the fleet so overall effect on emissions from the sector is likely to be negligible.		
Barriers	Not yet a mature process. Unclear if there is a mass market or economies of scale, especially given diversity of NRMM. Cost-effectiveness given short payback times.		
Investment Requirements	Less than buying new plant, but a significant cost compared to displacing plant on a project basis.		
Policy Requirements	No explicit policy on retrofits is likely. Driven by existing or future policies to meet Stage IV or Stage V standards.		
Factors Affecting Timescales	Time required for development and scaling-up of retrofit solutions. Natural fleet turnover leading to introduction of Stage V plant naturally. This squeezes timescales on which retrofit is likely to viable from both ends.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	1% by 2025
Justification	Not generally cost-effective on most plant		Potential reduction in emissions from selected plant items given policy requirement to meet Stage V in certain locations or projects

Training for behavioural changes

Measure description

Emissions from NRMM, as with road vehicles, depend strongly on how they are driven and operated. As with road vehicles, it is possible to operate the machine in such a way as to reduce emissions without materially impairing the task in hand. This measure envisages operators being trained to work in a way that is efficient, safe and reduces emissions. This can also be supported by technological solutions such as start-stop systems to reduce idling and monitoring of driver behaviours using on-board diagnostics.

Evidence base and assessment of evidence

A literature review identified some references to case studies and discussions of the role of workers in operating their plant to minimise emissions[296,297], no formal literature or publications were identified specifically relating to this measure. The evidence is therefore based on the expert opinion of consultees.

Training is currently provided by the Fleet Operator Recognition Scheme (FORS)[298], a voluntary industry scheme. Examples of similar training for road vehicles include the Safe and Fuel Efficient Driving (SAFED) scheme, backed by DfT[299].

Summary of evidence

There is potential for improvements to emissions through managing how workers operate plant. This can be done through training, although consultees did not express much enthusiasm for this, suggesting a lack of motivation within the industry. The example of SAFED suggests that there may be commercial benefits to developing a best practice training programme with external certification. The co-benefit with safety could be an important motivator, and this is recognised by the close relationship between FORS and the Construction Logistics and Community Safety (CLOCS) scheme[300].

Technological developments can assist through direct control of the equipment, for example start-stop systems which shut off the engine when the operator's seat is vacant. In addition, the use of telematics to record operating cycles (e.g., location from GPS, engine load) can assist in understanding how to optimise operations. Potentially, telematics could be used to evaluate individual workers' performance, to provide formal or informal incentivisation or gamification; however, this would need to be implemented carefully in view of the wide range of tasks and required skill levels on a construction site to avoid perverse incentives.

One consultee suggested that new technologies to improve efficiency and reduce operating duty cycles could save about 30% of emissions. The potential for fuel savings is likely to be a significant motivator.

Barriers include the absence of established, recognised best practice training in this area. However, there are schemes that could be used to support the development and promulgation of best practice, such as Supply Chain Sustainability School, Considerate Constructors Scheme, Institute of Civil Engineers, and Fleet Operator Recognition Scheme.

Since much plant is hired, there may be less motivation for operators to use them efficiently beyond fuel efficiency.

Summary – Training for behavioural changes

Factor	Summary		
Benefits	Modest scope for $PM_{2.5}$ reductions, perhaps a few percent across the construction sector. Business as usual prospects are low, but a more ambitious roll-out could achieve greater reductions. Benefits for workforce exposure. Co-benefits with safety, NO_x, CO_2, noise.		
Barriers	Lack of industry interest. No formal or certified programme.		
Investment Requirements	Further development of training schemes to increase focus on emissions. Further roll-out of training.		
Policy Requirements	Support various industry accreditation schemes to encourage use of best practice.		
Factors Affecting Timescales	Lack interest at grassroots. Time to develop and roll out additional training.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	1% by 2030	1% by 2030	1% by 2030
Justification	Reduction in activity/emissions that may be achievable based on the literature reviewed. Expect similar level of engagement and delivery in all ambition scenarios.		

Remove tax break for red diesel

Measure description

There are two tax regimes for diesel, depending on the end use. "White" diesel is taxed at a higher rate and may be used for transport. "Red" diesel is taxed at a lower rate but is not permitted for road vehicles. In the March 2020 budget, it was announced that from April 2022, certain sectors will no longer be eligible to use red diesel, including the construction sector.

This measure will not directly affect $PM_{2.5}$ emissions, but will act as a driver, changing the cost-effectiveness calculations for a variety of measures and incentivising reductions in fuel consumption (with concomitant reductions in $PM_{2.5}$ emissions).

Evidence base and assessment of evidence

The government consulted widely on the proposal to change the tax regime for red diesel over the years before it was implemented[301].

Summary of evidence

The summary of responses from the Treasury consultation[302] is largely consistent with the responses received from consultees to the present project. This is to be expected given the significant overlap in consultees and subject matter, but provides reassurance that the present project has not overlooked any major issues.

Summary – Remove tax break for red diesel

Factor	Summary		
Benefits	Indirect — incentivises other measures and makes them more cost-effective. Reduced diesel consumption due to higher cost.		
Barriers	None — in place.		
Investment Requirements	Will increase costs to operators in the short term, but this is already being budgeted for.		
Policy Requirements	None — in place.		
Factors Affecting Timescales	None — in effect from 2022.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Measure already in place and accounted for through adjustment of the baseline.		

Electric and/or hydrogen powered NRMM

Measure description

This measure envisages NRMM engines, which are currently almost all powered by diesel combustion, being replaced with alternatives such as electric or hydrogen-powered engines. Either of these would effectively eliminate tailpipe emissions of $PM_{2.5}$. For the workshops, this measure was divided into three, as there are some significant differences between how they might be implemented, but there are also many common issues. The three workshop measures are:

- Use of electric NRMM at non-construction sites, e.g., warehouses, ports and airports.
- Use of electric NRMM at construction sites.

- Use of hydrogen NRMM.

Particular issues with these three aspects are discussed below.

Evidence base and assessment of evidence

At present, alternatively fuelled NRMM is becoming available in some areas but is some way off being mainstream. The result is that there is a mix of experience and it is currently unclear what solutions will finally emerge.

Summary of evidence

Policy requirements around decarbonisation mean there is a general recognition that sales of diesel fuelled NRMM will need to be phased out over the next few decades, but there is a lack of clarity over what is achievable and on what timescales. Alternatively, fuelled plant are becoming available and are entering the fleet, but mainly for smaller plant sizes (typically below 3 tonne).

The key concern is around the supporting infrastructure requirements. Either electric or hydrogen will require significant infrastructure upgrades before plant become widely useable, and there is the familiar chicken-and-egg scenario that there is little incentive to upgrade infrastructure until there is equipment to use it.

One major concern is uncertainty as to whether electric or hydrogen fuelled equipment will win out in the long term. There was general agreement among consultees that the government should not try to "pick winners", and any policy should be technology neutral and driven by ends rather than means. However, this presents a major risk for operators if they choose a technology which fails to take off. They risk having stranded assets if, for example, they buy hydrogen equipment but the hydrogen infrastructure to fuel it is not built. This can be seen as a hazard for early adopters, being punished for doing the right thing. There is a clear disincentive to invest if equipment becomes redundant before its natural end of life.

If the necessary supporting infrastructure is not widely available nationally and internationally, the resale value of equipment will be lower, increasing the costs to investors.

There was a mix of views among consultees as to whether electric or hydrogen, or a mix, was more likely in the long term. Some expressed the view that electric options would not be available for the largest plant, as electrical units would not be able to deliver the necessary power, and hydrogen was more likely for these plant types. However, electric NRMM is already becoming established on airports, and is long-established for some smaller plant types such as fork-lifts. Progress on electric cars will inevitably feed through into increased options for electric NRMM, both by developing technology/reducing prices and, in the medium term, creating a large supply of second-hand batteries.

A mix of electric and hydrogen NRMM avoids some of these problems, but at the substantial cost of requiring two sets of infrastructure. Some sectors may migrate to electric, for example fixed sites such as airports, and some to hydrogen, for example itinerant sites such as construction sites. This will still require the creation of a hydrogen production and distribution infrastructure. This would be a substantial expense if the construction sector was the only part of the economy using appreciable amounts of hydrogen.

As well as availability of infrastructure, availability of plant and equipment using either alternative fuel is currently limited. However, technology should be available over the next few years if the market demand is there, with the caveat above about possible difficulties developing large electric plant items.

Costs are currently a barrier, with alternatively fuelled plant being substantially more expensive to buy than diesels; some references suggest about three times the price[279, 303]. Running costs could be lower than diesel in future, but one study suggests this is unlikely to pay back the purchase costs. Figures from the Scottish Plant Owners Association[303] suggest that, amongst its members, white diesel would cost approximately £200m per year, and the gross book value of existing plant is about £2.5b; this implies that if alternatively fuelled plant were three times the price of diesel, the payback time from fuel savings (ignoring other costs) would be about 40 years, far longer than the plant lifetime.

In general, it was considered in the interviews and workshop that there was unlikely to be appreciable uptake of alternative fuels before about 2030. However, as with electric cars, if the infrastructure is made available, economies of scale mean the plant can be bought affordably, and other deployment problems can be solved, there is the potential for take-up to increase rapidly. Policy measures which incentivise early adopters can help overcome the initial hurdles and consequently promote wider uptake.

An example policy to promote the uptake of zero carbon plant is the Norwegian KraKK project[304], which is trialling incentives through the use of bonus payments for various types of zero-carbon plant. For example, the project is testing bonus payments for using an emission free excavator > 25 tonnes of 400 NOK./h (400 Norwegian kronor per hour; approximately €40/h) up to a maximum of 2000 h or 800,000 NOK (€80,000) This is a standard Caterpillar excavator, rebuilt in Norway, which can be used for approximately 5 hours work before charging the battery. The first few were delivered in late 2018.

Use of electric NRMM at non-construction sites, e.g., warehouses, ports and airports

Permanent sites have good potential for converting to electric, if the plant are available. Although charging infrastructure would be needed, both bringing sufficient supply onto the site and then distributing it to equipment charging points, once installed little further maintenance would be needed. OPEX is likely to be lower than using (especially white) diesel, so the CAPEX investment might be repaid for some sites.

A concern with electric plant is whether the duty cycle will allow sufficient time for recharging. For example, a baggage tug on an airport may be in demand for more than 18 hours per day, leaving less than 6 hours to recharge overnight. Whether this is viable for a given unit will depend on battery capacity and details of the duty cycle; for example, it will only spend a small portion of those 18 hours actually under load. Given the huge diversity of NRMM, it is impossible to come to an overall answer to this question, or even a generalisation.

As a concrete example, one respondent to the Treasury red diesel consultation[302] said: "due to battery recharging times, two pieces of plant were required to replace one diesel (making this option six times more expensive)."

Use of electric NRMM at construction sites

As well as the usual issues around the use of electric NRMM, construction sites have the particular problem that they are transient, and so the cost of getting the electric supply onto the site may be substantial in proportion to the length of time they are needed for. Several respondents said that there were problems with UK Power Networks installing power to sites.

Use of hydrogen NRMM

Hydrogen has a number of advantages over electric, especially the relative ease of distribution to itinerant construction sites, and the greater practicality for higher-power plant. The main barrier is the requirement for a whole new infrastructure for its generation and distribution. The viability of this will be strongly dependent on whether other sectors, especially heavy road transport, join in with the hydrogen economy or follow cars along the battery-electric route.

Hydrogen may increase NO_x emissions if used in a combustion engine rather than a fuel cell, depending on the engine's design stoichiometry.

Summary – Electric and/or hydrogen powered NRMM

Factor	Summary		
Benefits	Potential elimination of tailpipe $PM_{2.5}$ emissions. Co-benefits for CO_2 (primary driver), NO_x, noise.		
Barriers	General uncertainty about how the alternative fuel economy will develop and whether electric, hydrogen or a mix will emerge as mainstream options. Availability of specialist plant. Infrastructure development. Investment risks from uncertain technological future.		
Investment Requirements	Infrastructure, both electric and hydrogen generation and distribution. This is a substantial requirement for hydrogen, as a whole new infrastructure system will be needed virtually from scratch.		
Policy Requirements	Incentives to encourage early adopters. Measures to reduce risk of stranded assets. Measures to facilitate getting electric power onto sites (remove internal barriers within Distribution Network Operators (DNOs) or UK power network operators). Change to red diesel regime to incentivise change.		
Factors Affecting Timescales	Development of plant and supporting infrastructure and the relative timing of both. Uncertainty about final outcome between electric and hydrogen. General expectation that there will be little penetration into much of sector before about 2030, although some parts (e.g., airports) may be faster. Has OPEX advantages to operators so uptake could be fast if barriers can be overcome. Lifetime of plant 10–15 years. Expect to be dominant, in one form or another, by 2050.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	0% by 2030, 20% by 2040, 50% by 2050	10% by 2030, 50% by 2040, 95% by 2050	20% by 2030, 95% by 2040, 95% by 2050
Justification	Considering uptake rates informed by stakeholder engagement. Uptake dependent on industry engagement, policy drivers and cost of new infrastructure and equipment		

Biofuels in NRMM

Measure description

This measure considers the use of non-mineral liquid fuels in place of mineral diesel. In particular, these alternative fuels include various forms of biofuel such as hydro-treated vegetable oil (HVO). Use of such alternative fuels is likely to be driven by carbon emissions rather than air quality, so this measure considers the incidental effect on $PM_{2.5}$ emissions.

Evidence base and assessment of evidence

Biofuels of various kinds have been the subject of some interest for several years, and various studies have looked at their effect on $PM_{2.5}$ emissions, although there is a spread of results. Most work focusses on road diesel engines, but some studies have been carried out into NRMM.

Summary of evidence

EPA[305] suggest $PM_{2.5}$ emission reductions from biofuel blends of between zero and 47%. A review of the literature agrees that there is a spread of figures quoted, but with a consensus that biodiesels reduce particulate emissions compared to mineral diesel[306,307,308,309,310,311].

Where equipment is fitted with DPFs (e.g., Stage V equipment), the particulate emission rate will be reduced substantially beyond the reductions in cylinder emissions.

The higher cost of biofuels is a barrier, but this may reduce as production scales up and the tax regime incentivises low-carbon fuels.

Summary – Biofuels, HVO etc. in NRMM

Factor	Summary		
Benefits	Reduction of zero to 47% in particulate emissions; potential co-benefit of CO_2 emission reduction.		
Barriers	Availability. Cost.		
Investment Requirements	Fuel production and distribution.		
Policy Requirements	Policy driven by decarbonisation.		
Factors Affecting Timescales	Policy driven by decarbonisation.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	2% by 2030	5% by 2030
Justification	Reduction in emissions that may be achievable based on a number of journal articles reviewed into the subject. Uptake rates will depend on industry engagement and policy drivers as well as cost considerations for individual operators		

Prevent removal/defeat of emission control devices

Measure description

Some emissions control technologies can present running costs for operators. The most notable is that Selective Catalytic Reduction (SCR) devices for the abatement of NO_x emissions requires an input of urea or Diesel Exhaust Fluid (DEF) (often known by the brand name AdBlue). Consequently, a market has arisen for devices or services to defeat or remove these control systems. This typically also includes reconfiguring the engine management system, which would otherwise prevent the engine from running without the abatement system.

Although DPFs are not an obvious target for defeating, they are commonly packaged with SCR systems so may be removed with them.

Currently it is not illegal to remove or tamper with abatement devices after sale, and companies offering the service operate openly. This measure would criminalise such tampering, and enforce this. The Government is considering the scale of the problem and how best to take effective action.

Evidence base and assessment of evidence

The existence of companies providing removal services is well documented, but the extent to which the practice occurs is unknown.

Summary of evidence

The prevalence of removal of emissions control equipment is unknown. However, as Stage V equipment comes to dominate the fleet over the next decade, the issue will become of increasing relative importance, especially because of the very high effectiveness of DPFs. In a fleet of Stage V units, if just 1% have their DPFs removed, total $PM_{2.5}$ emissions across the fleet will double.

The reputable parts of the sector uniformly support measures to ensure that all plant meets regulated standards even after sale.

The industry's Emission Control Verification (ECV) scheme helps operators to ensure that plant not registered to meeting appropriate standards is not used. However, the ECV scheme does not control against tampering.

Summary – Prevent removal/defeat of emission control devices

Factor	Summary		
Benefits	Better compliance with $PM_{2.5}$ standards.		
Barriers	No measures to prevent practice. Enforcement may be challenging, especially if engine management systems are tampered with - hard to identify.		
Investment Requirements	Enforcement required.		
Policy Requirements	Creation and enforcement of regulations to prohibit defeat of control devices after sale. Focus will be on suppliers of defeat devices rather than plant operators.		
Factors Affecting Timescales	Increasingly important as Stage V enters the fleet. Legislation and enforcement body required. Sector considering further with DfT.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Unknown as extent of DPF removals is unknown.		

Electric transport refrigeration units (TRUs)

Measure description

TRUs are APUs covered under the NRMM regulations that provide power to operate refrigeration units on cold-chain lorries. They are normally small diesel engines, typically in the 17–25 kW power range. Until 2019 they only needed to meet the Stage IIIA standard for particulate matter, namely 0.6 g kWh^{-1}. From 2019, diesel TRUs of at least 19 kW must meet the same standards as larger engines (i.e., 0.015 g kWh^{-1} for particulate and 1×10^{12} kWh^{-1} for PN).

As with other diesel engines, these can potentially be replaced with alternative sources of power, such as electric batteries or hydrogen fuel cells.

Evidence base and assessment of evidence

Data on the number of TRUs is poor; there is no licensing. One consultee suggested that there are 30,000 units in the UK, another reference[312] states 40,000.

Summary of evidence

Plug-in electric TRUs are emerging onto the market[313,314] but are not yet mainstream or proven[312]. As well as elimination of $PM_{2.5}$ emissions from the diesel APU, these offer a substantial co-benefit in the form of reduced noise, which is important when vehicles stay overnight near residential areas.

The principal barriers are: availability of equipment; availability of charging infrastructure; and availability of charging points when needed during the plant's duty cycle.

Summary – Electric transport refrigeration units (TRUs)

Factor	Summary		
Benefits	Elimination of $PM_{2.5}$ emissions from this source. Co-benefits for noise, carbon, NO_x. Possible OPEX reductions.		
Barriers	Availability of equipment, infrastructure. Fitting charging time into duty cycle.		
Investment Requirements	Purchase of plant and charging infrastructure. Improved data required. Currently poor understanding of number, size, duty cycles of TRUs.		
Policy Requirements	Policy measures to be developed and enforced on the basis of new data gathered.		
Factors Affecting Timescales	Availability of plant and infrastructure. Fleet turnover timescale about 10–15 years.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	1% by 2035	1% by 2030
Justification	Reduction in emissions (from NRMM source) that may be achievable based on the literature reviewed, depending on industry engagement and policy drivers		

Precision equipment for improving construction efficiency

Measure description

Many construction tasks need to be achieved with high levels of accuracy but delivering this is largely down to the skill of the operator. For example, laying a road may require several passes, with a survey after each pass to determine whether the result is satisfactory yet or where further work is needed.

High-precision equipment carries the potential to do the work in fewer passes, by using spatial positioning systems to know exactly where the plant is working and what the exact requirements are at that specific location. By reducing the number of passes and the amount of rework, plant running time is reduced and emissions saved.

Evidence base and assessment of evidence

The measure is currently subject to commercial development. Stakeholder engagement suggested that developments specific to construction are generally commercially sensitive and early in development.

Summary of evidence

This measure is likely to develop in the long term, driven by cost benefits from more efficient working practices. Benefits are currently rather speculative but could be substantial in certain parts of the construction sector.

Highways England (HE) is working on a Connected Autonomous Plant project[315] to automate construction activity and develop common standards to help equipment to connect and collaborate. HE estimates that it could produce productivity savings of 20–25% in relevant areas by 2035.

Autonomous vehicles may also have a role to play. The controlled environment of a construction site makes this practical in principle.

Other sectors, such as agriculture, are working on similar developments. There is opportunity for technology transfer.

Summary – Precision equipment for improving construction efficiency

Factor	Summary		
Benefits	Highly uncertain. Potential for significant reductions but only in certain parts of the construction sector.		
Barriers	Considerable research and development needed. Substantial upfront costs.		
Investment Requirements	Substantial research and development needed. Likely to be delivered privately, driven by long-term competitive advantage.		
Policy Requirements	Possible support for research and development. Support technology transfer between sectors, e.g. agriculture.		
Factors Affecting Timescales	Long-term prospect. Currently at early R&D stage.		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Too uncertain at this stage to quantify benefits		

Hybrid generators

Measure description

Diesel generators are an important form of NRMM on construction sites and similar facilities, providing electricity for lighting, temporary offices and similar services. Hybrid generators use the diesel engine (and optionally renewable sources such as a wind turbine or solar panel) to charge a battery, from which the electricity is drawn as required. This allows the generator to operate at its optimum load when called to charge the battery, and then shut down or idle when not needed. This compares with a conventional diesel generator, where the engine needs to run at a rate that varies with load, and so is seldom operating at its most efficient setting.

A related issue concerns the use of appropriately-specified plant (especially but not only generators). Where plant hired to perform a range of tasks, it may have to operate under a range of loads. The contactor will need to hire a unit capable of meeting the highest load, even if that is a relatively infrequent demand. This may be exacerbated if the hire company is unable to provide the requested size, and has to supply something larger. The result is that the plant item may spend much of its time operating at well below its design load, reducing efficiency.

Evidence base and assessment of evidence

Hybrid generators are generally available on the market. Claims by manufacturers mainly relate to fuel efficiency and CO_2 reductions, but $PM_{2.5}$ emissions may be taken to be approximately proportionate. However, there seems to be little independent measurement of these claims.

Summary of evidence

Hybrid generators are generally available on the market, at higher cost than conventional generators. Claims for fuel efficiency improvements over conventional diesel generators are typically in the range of a few tens of percent[316,317,318], but this will depend on strongly on use and duty cycle.

Although the cost of hybrid generators is greater than for a conventional generator, it is considerably cheaper than installing the infrastructure for a fully electric system.

Desouza *et al*[292] measured $PM_{2.5}$ emissions from generators and found that emissions per kW were consistently lower at higher loads. This implies that emissions will be reduced by running at peak load for shorter periods to charge a battery and then turning off, than by running at lower loads continuously. The effect is strong enough to outweigh the loss of efficiency from charging and discharging the battery. This is considered to be good evidence of the qualitative value of this measure.

This measure mitigates the practice of using inappropriately sized equipment (due to variable demands, availability at time of hire, etc.) which causes engines to be used at inefficient loads much of the time. Hybrid generator can be used at most efficient setting.

This is likely to be a transition measure prior to adoption of fully alternative power sources (fully electric, hydrogen).

Summary – Hybrid generators

Factor	Summary		
Benefits	Estimated reduction in $PM_{2.5}$ emissions of several tens of percent from these plant items, but these are currently understood to result in a small proportion of total NRMM emissions Co-benefits for noise, NO_x, CO_2. Potential OPEX savings.		
Barriers	Increased CAPEX. Resistance to uptake from operators.		
Investment Requirements	Fleet replacement costs.		
Policy Requirements	There has been no Stage IIIB or IV for generators, so Stage V is a step change. Driven primarily by fuel costs and decarbonisation agenda.		
Factors Affecting Timescales	Equipment replacement lifecycles. Transition measure prior to adoption of fully alternative power sources (fully electric, hydrogen).		
Ambition Scenario	**Medium**	**High**	**Speculative**
Input for emissions modelling	N/A	N/A	N/A
Justification	Covered by electric and/or hydrogen powered NRMM measure		

5. Recommendations

5.1 Summary of Measures

In summary, 60 of the measures discussed above have been selected to be employed in the medium, high and speculative scenarios under which future $PM_{2.5}$ concentrations are to be modelled. The timescales and uptake rates of these measures are summarised in Figure 5-1 which illustrates the greater, and earlier, uptake of measures in the speculative scenario.

An important theme identified in the process of this study was the benefit that numerous measures that are currently proposed to reduce carbon emissions will have on $PM_{2.5}$ concentrations. This is mainly a result of reduced fossil fuel combustion. The importance of infrastructure improvements in facilitating a transition to a wider use of electricity and hydrogen was a recurring issue in the stakeholder engagement. There may also be some approaches to decarbonisation that could increase $PM_{2.5}$ emissions, for example, the increased combustion of biomass which may be required for industrial decarbonisation into the 2030s.

Another important consideration in terms of the $PM_{2.5}$ concentrations to which people are exposed is the location of sources relative to areas of population. The information obtained in this study is used to inform national scale modelling to consider the general effect on $PM_{2.5}$ concentrations rather than concentrations at particular locations. There are certain measures identified which can be employed in specific locations to reduce the highest concentrations in the country. Examples of such measures include the provision of shoreside power at ports, electric power infrastructure at train stations and targeted car scrappage schemes. The application of local measures is expected to be defined by the precise definition of the $PM_{2.5}$ targets through considerations such as the size of spatial aggregation and treatment of hotspots.

5.2 Recommendations

Several important themes were identified in the stakeholder engagement process that apply across sectors. One of these was that many of the measures will rely on alternative power sources to those used at present (e.g. electricity and hydrogen). The development of infrastructure is therefore essential for the successful implementation of such measures. Another theme was that where vehicles or equipment are replaced by newer versions with lower emissions, any benefits in terms of reduction in population exposure would be reduced if the old equipment is displaced to other parts of the country. Replaced equipment should ideally be withdrawn from use.

The literature review and stakeholder engagement for this project has identified several areas where further research would be beneficial to better quantify $PM_{2.5}$ emissions and therefore better prioritise measures to reduce concentrations. Programmes are already in place for investigating many of these aspects and that new information will be emerging over the coming years.

The main factors highlighted as requiring further research are as follows:

- Emissions from domestic, commercial and industrial wood combustion. There are varying estimates of the amount of wood burnt for domestic use and there is debate about the proportions of emissions from wood combustion from domestic and commercial or industrial sources. The magnitude of small-scale industrial wood combustion needs to be better understood in order to better quantify emissions and develop measures to reduce emissions. Better quantification will enable measures to be targeted appropriately.
- Emissions from domestic and commercial cooking. The contribution of these sources is not currently quantified in national emission inventories. Evaluation of these sources would enable

better consideration of measures, which could have a particular benefit for $PM_{2.5}$ concentrations in urban areas.

- Emissions from brake, tyre wear and road abrasion. A great deal of research is underway in this area and findings from this research will provide more information on the relative contributions of each source. This is of particular importance as non-exhaust emissions becomes the dominant source of emissions from road traffic. Greater understanding in how composition and manufacture of tyres will enable better information and/or regulation to reduce emissions.
- In relation to non-exhaust emissions, the effect of the increased weight of BEVs needs to be further evaluated. Minimising non-exhaust emissions could be an important policy driver to reduce vehicle weights in future.
- Rail brake and track wear. Further research is required to understand the magnitude of these sources and if there is potential for reducing emissions if measures are developed.
- Aviation brake and tyre wear. Further research is required to understand the magnitude of these sources and if there is potential for reducing emissions significantly if measures are developed.

wood.

Figure 5-1 Summary of Measures for Modelling (uptake rate by year)

		Medium				High				Speculative			
Work Package	Measure Title	2025	2030	2040	2050	2025	2030	2040	2050	2025	2030	2040	2050
Domestic/Commercial combustion	Retrofitting active open fires to Ecodesign appliances	0%	0%	0%	0%	10%	20%	50%	50%	0%	0%	0%	0%
Domestic/Commercial combustion	Retrofitting all older stoves to Ecodesign appliances	0%	0%	0%	0%	0%	0%	0%	24%	0%	0%	24%	24%
Domestic/Commercial combustion	Ban installation and phase out stove/open fires in urban areas	0%	0%	0%	0%	5%	15%	15%	15%	39%	60%	65%	68%
Domestic/Commercial combustion	Restrict/ban on outdoor burning	0%	0%	0%	0%	10%	40%	60%	100%	20%	60%	100%	100%
Domestic/Commercial combustion	Improve fabric standard of homes	0%	8%	8%	8%	0%	14%	14%	14%	0%	19%	19%	19%
Domestic/Commercial combustion	Ban installation of oil and gas boilers in homes	10%	27%	58%	100%	10%	27%	58%	100%	10%	27%	58%	100%
Domestic/Commercial combustion	Ban installation of oil and gas boilers in buildings	0%	0%	80%	100%	0%	0%	100%	100%	0%	100%	100%	100%
Urban Mobility	Aggregated Measures affecting car vkm	5%	10%	10%	10%	10%	15%	30%	30%	15%	25%	50%	60%
Urban Mobility	Freight Consolidation and urban HGV restrictions	0%	0%	0%	0%	20%	50%	50%	50%	50%	100%	100%	100%
Urban Mobility	Zero Emission Last Mile Deliveries	5%	33%	33%	33%	30%	66%	66%	66%	100%	100%	100%	100%
Urban Mobility	Rail Freight	0%	0%	0%	0%	25%	50%	50%	50%	5-%	100%	100%	100%
Road Transport Technology	Exhaust Emission Regulations	0%	0%	0%	0%	0%	7%	49%	56%	0%	13%	89%	100%
Road Transport Technology	Checks for Defective DPFs	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%
Road Transport Technology	Regenerative Braking (EV)	5%	13%	60%	97%	5%	13%	60%	97%	5%	13%	60%	97%
Road Transport Technology	Brake Wear Emission Regulations	0%	0%	0%	0%	0%	4%	25%	28%	0%	13%	89%	100%
Road Transport Technology	Tyre Composition and Wear	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	50%	100%
Road Transport Technology	Vehicle Condition (Wheel Alignment and tyre pressure)	0%	0%	0%	0%	0%	100%	100%	100%	100%	100%	100%	100%
Road Transport Technology	Road Composition	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	50%	100%
Road Transport Technology	Zero Emission Buses	0%	0%	0%	0%	0%	10%	30%	100%	0%	10%	100%	100%
Road Transport Technology	Zero Emission HGVs	0%	0%	0%	0%	0%	0%	50%	100%	0%	20%	100%	100%
Shipping	Fuel switch to LNG	0%	10%	10%	10%	0%	15%	15%	15%	0%	15%	15%	15%
Shipping	Fuel switch to Biofuels	0%	5%	10%	5%	0%	10%	20%	10%	0%	10%	20%	10%
Shipping	Fuel switch to Ammonia / Hydrogen	0%	5%	10%	50%	0%	5%	15%	60%	0%	10%	20%	70%
Shipping	Hybrid vessels	0%	5%	10%	20%	0%	10%	20%	10%	0%	10%	30%	20%
Shipping	Electric vessels	0%	20%	40%	60%	0%	30%	50%	70%	0%	40%	60%	80%
Shipping	Fuel efficiency	0%	20%	40%	50%	0%	30%	50%	70%	0%	40%	60%	80%
Shipping	Renewable power	0%	5%	10%	20%	0%	8%	15%	30%	0%	10%	20%	50%
Shipping	Shoreside power	0%	5%	20%	60%	0%	8%	30%	75%	0%	10%	50%	90%
Shipping	DPF	0%	45%	0%	0%	0%	90%	0%	0%	0%	90%	0%	0%
Shipping	SCR/EGR (Nox only)	0%	45%	0%	0%	0%	90%	0%	0%	0%	90%	0%	0%

		Medium				High				Speculative			
Work Package	Measure Title	2025	2030	2040	2050	2025	2030	2040	2050	2025	2030	2040	2050
Rail	Traction Decarbonisation	0%	10%	50%	80%	0%	10%	60%	100%	0%	10%	60%	100%
Rail	Exhaust Treatment (SCR, DOC, DPF) / re-engining	0%	20%	50%	10%	0%	20%	20%	0%	0%	20%	20%	0%
Rail	Hybridisation	0%	20%	50%	10%	0%	20%	20%	0%	0%	20%	20%	0%
Rail	Rail Eco-Driving / traffic optimisation	100%	100%	100%	100%	100%	100%	0%	0%	100%	100%	0%	0%
Aviation	New aircraft main engine technology	0%	0%	0%	0%	0%	0%	20%	50%	0%	0%	30%	100%
Aviation	Reduced sulphur in aviation fuel	0%	0%	0%	0%	0%	5%	40%	75%	0%	25%	50%	100%
Aviation	Aircraft operator measures to reduce engine running time on the ground	0%	10%	10%	10%	0%	80%	80%	80%	0%	100%	100%	100%
Aviation	Airport and ATC measures to reduce engine running time on the ground	0%	0%	0%	0%	0%	66%	66%	66%	0%	100%	100%	100%
Aviation	Alternatively powered APUs	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	50%	50%
Aviation	Low-emission ground support equipment (GSE)	0%	10%	30%	50%	0%	20%	50%	100%	0%	30%	60%	100%
Aviation	More efficient use of ground support equipment (GSE)	0%	20%	20%	20%	0%	50%	50%	50%	0%	100%	100%	100%
Agriculture	Slurry storage cover	50%	60%	60%	60%	50%	60%	60%	60%	50%	60%	80%	100%
Agriculture	Slurry storage acidification	0%	0%	0%	0%	25%	25%	25%	25%	25%	25%	25%	25%
Agriculture	fertiliser change / Urease Inhibitor/ Urea fertiliser ban	60%	60%	60%	60%	100%	100%	100%	100%	100%	100%	100%	100%
Agriculture	fertiliser change / Improved application methods	0%	0%	0%	0%	0%	0%	0%	0%	80%	80%	100%	100%
Agriculture	low emission spreading	50%	50%	50%	70%	60%	70%	80%	100%	100%	100%	100%	100%
Agriculture	Livestock housing - Existing housing (pig/ poultry)	0%	100%	100%	100%	0%	0%	0%	0%	0%	0%	0%	0%
Agriculture	Livestock housing - New housing - (pig/poultry)	0%	0%	0%	0%	0%	20%	50%	50%	0%	20%	50%	50%
Agriculture	Livestock housing - New Beef / dairy cattle	0%	0%	0%	0%	0%	0%	25%	25%	0%	25%	65%	65%
Agriculture	change in livestock diet	0%	0%	0%	0%	0%	60%	60%	60%	60%	60%	60%	60%
Agriculture	Fuel choice and usage for farm equipement	25%	50%	100%	100%	50%	80%	100%	100%	80%	100%	100%	100%
Agriculture	Change in food consumption	0%	0%	0%	0%	0%	0%	0%	40%	0%	0%	0%	100%
Industry	Decarbonisation of Refineries	0%	25%	75%	100%	0%	25%	75%	100%	0%	50%	100%	100%
Industry	Sinter Plant Bag Filters	100%	100%	100%	100%	100%	100%	100%	0%	100%	100%	100%	100%
Industry	Sugar Industry Fuel Switching	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Industry	Medium Combustion Plant Directive (MCPD) - increasing stringency of limits for plants above 1MW	5%	20%	50%	100%	20%	50%	100%	100%	50%	100%	100%	100%
Industry	Monitoring and improved fugitive emissions capture	0%	0%	100%	100%	0%	100%	100%	100%	100%	100%	100%	100%
Industry	NRMM Stage V – Diesel Engines	25%	50%	100%	100%	50%	80%	100%	100%	80%	100%	100%	100%
Industry	Industrial Decarbonisation (natural gas use)	53%	70%	88%	96%	53%	70%	88%	96%	53%	70%	88%	96%
Industry	Industrial Decarbonisation (biomass use)	88%	100%	29%	3%	88%	100%	29%	3%	88%	100%	29%	3%
Construction	Retrofit to Stage V standard	0%	0%	0%	0%	0%	0%	0%	0%	100%	100%	100%	100%
Construction	Training for behavioural changes	0%	100%	100%	100%	0%	100%	100%	100%	0%	100%	100%	100%
Construction	Electric/hydrogen NRMM	0%	0%	20%	50%	0%	10%	50%	95%	0%	20%	95%	95%
Construction	Biodiesels, HVO etc. in NRMM	0%	0%	0%	0%	0%	20%	20%	20%	20%	50%	50%	50%
Construction	Electric TRUs	0%	0%	0%	0%	30%	80%	100%	100%	50%	100%	100%	100%

Figure shows list of measures to be used in modelling and assumed uptake rates by year of each measure in 2025, 2030, 2040 and 2050 in Medium, High and Speculative scenarios. Uptake rates of some measures reduce as other measures affecting the same source become more important. Uptake rates are higher in the Speculative scenario than the High scenario and higher in the High scenario than the Medium scenario.

Appendix A
Interviews Carried Out

Work Package	Organisation	Interview Date
Agriculture	Environment Agency - Agriculture sector	23/12/2020
Agriculture	National Farmers' Union (NFU)	11/01/2021
Agriculture	Ricardo	14/01/2021
Agriculture	Natural England	18/01/2021
Agriculture	Centre for Ecology and Hydrology (CEH)	21/01/2021
Agriculture	Rothamsted University	21/01/2021
Agriculture	Natural England	22/01/2021
Aviation	Manchester Metropolitan University Centre for Aviation, Transport and the Environment	08/01/2021
Aviation	Ricardo	13/01/2021
Aviation	Ecolyse	13/01/2021
Aviation	Heathrow Airport	18/01/2021
Aviation	Rolls Royce	18/01/2021
Aviation	NATS	02/02/2021
Construction	Cold Chain Federation	18/12/2020
Construction	Construction Plant Hire Association (CPA)	05/01/2021
Construction	Caterpillar	07/01/2021
Construction	Imperial College London Environmental Research Group (ERG)	11/01/2021
Construction	HS2	13/01/2021
Industrial	BEIS	18/12/2020
Industrial	Oil and Gas UK	21/12/2020
Industrial	Environment Agency - Food and Drink Manufacture	22/12/2020
Industrial	Environment Agency - Metals sector	22/12/2020

Work Package	Organisation	Interview Date
Industrial	BEIS	22/12/2020
Industrial	Glosfume	22/12/2020
Industrial	Environment Agency - Pulp, paper, textiles sector	23/12/2020
Industrial	BEIS – Clean Electricity	05/01/2021
Industrial	Environment Agency - Refineries	06/01/2021
Industrial	Chemical Industries Association (CIA)	06/01/2021
Industrial	Environment Agency - Combustion sector	08/01/2021
Industrial	UK Onshore Operators Group	08/01/2021
Industrial	UK Petroleum Industry Association	08/01/2021
Industrial	Cummins / AMPS	13/01/2021
Industrial	Mineral Products Association	14/01/2021
Industrial	Industrial & Commercial Heating Equipment Association (ICOM)	15/01/2021
Industrial	Environment Agency - LA	15/01/2021
Industrial	Environment Agency - Incineration	15/01/2021
Other Urban Combustion	BEIS	12/01/2021
Other Urban Combustion	Association of Manufacturers and suppliers of Power generating Systems (AMPS)	13/01/2021
Other Urban Combustion	Industrial & Commercial Heating Equipment Association (ICOM)	15/01/2021
Other Urban Combustion	Imperial College London	15/01/2021
Other Urban Combustion	EA	15/01/2021
Other Urban Combustion	Defra	18/01/2021
Other Urban Combustion	SIA - Stove / Industry Alliance	18/01/2021
Other Urban Combustion	Defra	19/01/2021
Other Urban Combustion	Heat pumps association	21/01/2021

Work Package	Organisation	Interview Date
Other Urban Combustion	University of Birmingham	22/01/2021
Rail	RSSB	05/01/2021
Rail	Network Rail	07/01/2021
Rail	RIA	22/01/2021
Rail	RDG	25/01/2021
Rail	DfT	03/02/2021
Road Traffic	DfT	07/12/2020
Road Traffic	TRL	09/12/2020
Road Traffic	Tallano Technologie	09/12/2020
Road Traffic	University of Leeds Institute for Transport Studies)	11/12/2020
Road Traffic	Emission Analytics	11/12/2020
Road Traffic	Tyre Collective	14/12/2020
Road Traffic	Arrival	14/12/2020
Road Traffic	Defra (JAQU)	15/12/2020
Road Traffic	Imperial	16/12/2020
Road Traffic	Tyre Watch/RL Capital	16/12/2020
Road Traffic	DfT (CC Strategy)	17/12/2020
Road Traffic	DfT (Science)	17/12/2020
Road Traffic	The Society of Motor Manufacturers and Traders (SMMT)	17/12/2020
Road Traffic	TfL	18/12/2020
Road Traffic	DfT (Int. Vehicle Standards)	18/12/2020
Road Traffic	University Plymouth	05/01/2021
Road Traffic	Imperial	05/01/2021
Road Traffic	Connected Places Catapult	13/01/2021
Road Traffic	Transport & Environment	14/01/2021

Work Package	Organisation	Interview Date
Road Traffic	University of Birmingham	22/01/2021
Shipping	British Ports Association	22/01/2021
Shipping	AFC Energy PLC	28/01/2021
Shipping	DfT	26/01/2021
Shipping	Port of London Authority	28/01/2021
Urban AQ	ADEPT	15/01/2020
Urban AQ	DfT	07/12/2020
Urban AQ	Mode Shift	09/12/2020
Urban AQ	Transport Planning Society	09/12/2020
Urban AQ	Imperial College London	10/12/2020
Urban AQ	Royal Town Planning Institute (RTPI)	11/12/2020
Urban AQ	University of Leeds Institute for Transport Studies	14/12/2020
Urban AQ	Campaign for Better Transport	14/12/2020
Urban AQ	Sustrans	16/12/2020
Urban AQ	DfT (CC Strategy)	17/12/2020
Urban AQ	GLA	18/12/2020
Urban AQ	TfL	18/12/2020
Urban AQ	Transport for Quality of Life	06/01/2021
Urban AQ	University of Western England	08/01/2021
Urban AQ	UWE	13/01/2021
Urban AQ	Connected Places Catapult	13/01/2021
Urban AQ	DfT (walking and cycling)	15/01/2021
Urban AQ	City Science	15/01/2021
Urban AQ	Centre for Cities	18/01/2021
Urban AQ	Imperial	18/01/2021

Appendix B
Workshop Reports

Domestic/Commercial Combustion

Attendees

Guild of Master Chimney Sweeps, Imperial College London, Environment Agency, Industrial & Commercial Heating Equipment Association, Stove Industry Alliance, Federation of British Chimney Sweeps, The Association for Decentralised Energy, HETAS, BEIS, Woodsure, Oftec, Defra, Veissmann, Mr Soot Chimney Services

Summary of Stakeholder Views

Energy Efficiency (new and existing homes, non-domestic buildings)

Benefits

- The co-benefits of measures to improve energy efficiency were highlighted, including reduced NO_X emissions.
- There was some debate regarding the benefits to $PM_{2.5}$ concentrations from reduced gas consumption given the relatively low emission factors. It was argued that efficient combustion of gas should not lead to particulate formation and that the emission factor for gas should be limited to secondary particulate formation from emitted NOx. However, the consensus was that gas combustion is an important source of $PM_{2.5}$ (as recognised in the NAEI).
- It was noted that the reductions in $PM_{2.5}$ emissions presented do not appear very ambitious.
- Several stakeholders mentioned that improvements in energy efficiency are strongly perceived as increases in comfort rather than just reduction in costs.
- Advantage of local space heating v whole house heating.

Barriers

- Several stakeholders mentioned cost barriers to improved energy efficiency.
- Switch from gas to electrical heating will increase demand on electricity network and will require an increase in generating capacity. If gas boilers are phased out because of regulation then new electric powered technology may not cope with high heat requirements of industrial process or hot water requirements of non-domestic buildings such as hotels, leisure centres.
- Ventilation was discussed as a key consideration with regards to energy efficiency measures. There are trade-offs between insulation/air tightness and ventilation (related to health of occupants) which need to be carefully considered. May need forced ventilation v natural ventilation.
- A stakeholder raised concern that the lack of requirement for a secondary heat source in the Future Homes standards will not allow consumer choice and could disadvantage households in fuel poverty. The absence of a chimney would discourage choice for the consumer as it would entails plan to install a low carbon wood burning system. Furthermore, if secondary heating was required (e.g., for fuel poverty alleviation) this would most likely be electric heating, which

could place additional burden on the electricity infrastructure.

Investment Requirements

- Programmes to retrofit homes and buildings.

Policy Requirements

- Policies to encourage retrofit of homes and buildings to improve energy efficiency.

Factors Affecting Timescales

- Several stakeholders mentioned that trigger points such as change of tenancy/property sale can be used to push uptake of energy efficiency solutions. On this basis, timescales depend on the housing market.

Transformation of heating away from fossil fuels

Benefits

- Whilst the potential benefits of reduced use of fossil fuels were recognised by the group, there was a general consensus that there is unlikely to be a one-size-fits-all solution for homes. The good attributes of several heating sources need to be combined. For example, using solar heating as a complement to gas, or wood stoves as a complement to heat pumps.
- The use of hydrogen as part of the heating mix was also highlighted by several stakeholders (although this would also produce NO_X, potentially more than methane as it burns at hotter temperature).
- It was highlighted that district heating (and economies of scale) has potential to support the transition away from fossil fuel use.
- It was confirmed that a transition from fossil fuels to biomass (wood) whilst good for climate change would not address issues of $PM_{2.5}$.

Barriers

- Cost for new appliances. Plus other issues like disruption for installation of new appliances, convenience, trust in other types of technology, noise of alternatives (e.g. air pumps) and perceived attractiveness of alternatives.
- Barriers associated with gaps in the supply chain for non-fossil fuel systems were mentioned by several stakeholders. There is a need for the scaling up of manufacturing and a significant increase in the number of trained installers. It also requires the distribution network to be more gas tight than for methane and significant upgrade might be needed
- There is a lack of consumer awareness/acceptance around that issues and that the transition to low carbon heating will require some disruption.

Investment Requirements

- Homeowners will bear the costs of new equipment.
- This can be supported by government grants and subsidies (reduced over time) RHI and Green Homes Grant followed by Clean Heat Grant.
- Funding mechanisms to support growth of large-scale heat networks i.e. Green Heat Network Fund.

- The example of Scandinavia was discussed, where local heat networks tend to be publicly owned by local government. Municipal ownership of heat networks in the UK would require the Treasury to change its rules on local government finance.

Policy Requirements

- Introduction of regulations are needed to give a clear signal to supply chain to invest in retraining installers and increase awareness of low carbon heating technologies.
- Introduction of regulations to phase out fossil fuel heating in existing buildings off the gas grid i.e., oil/LPG from 2025 (forthcoming BEIS consultation expected Spring 2021).
- It was discussed that the above measure would have a large impact on some rural areas with no connection to gas network. So this group could be important in developing workable solutions that can then be more widely implemented. It was discussed that LPG has little impact on $PM_{2.5}$, but oil fired central heating systems does. In off grid areas, LPG is used for cooking and oil for heating.
- Clarity is required regarding zoning policies and place-based deployment of low carbon heating solutions (~2025).
- A stakeholder raised that given the engineering/financial challenges of major infrastructure redesign or strengthening needed for electricity (heat pumps) and hydrogen boilers, policy should be designed to recognise this and promote innovation, including new generation clearSkies accredited low emission low carbon secondary heating from wood burning stoves.

Factors Affecting Timescales

- Development of the manufacturing base and supply chain.
- Timing of introduction of regulations to phase out fossil fuel heating off the gas grid.
- It was discussed that a reduced demand for gas, together with biomethane and 20% added hydrogen might be enough to sustain a gas network, instead dismissing entirely the possibility of gas as a public utility.
- Development of technology for hydrogen boilers rather than gas boilers. If gas disappears as a utility, the infrastructure could be used to some extent for hydrogen if it is invested in and improved. Hydrogen is a very small molecule and will leak much more easily than methane which is a key public safety issue.
- Trigger points relating to the awareness of the existing high carbon system to drive uptake of low carbon solutions.

Uptake of heat pumps

Benefits

- There was consensus that heat pumps have zero $PM_{2.5}$ emissions, however there was agreement that heat pumps are unlikely to me*et al*l heating needs and other systems would be required.
- Ground source heat pumps would be the preferred solution for houses with gardens.
- Combinations of systems are likely to be required compared to traditional boiler-based systems.

Barriers

- Cost to homeowners is likely to be prohibitive.
- There was doubt that the high levels of heat pumps discussed can be achieved, for several reasons, including the need for changes in consumer behaviour/culture (e.g., heat pumps not providing a focal point) and lots of homes not being suitable (e.g., space required and pipe/radiator systems).
- Noise disturbance from air source heat pumps was mentioned by several stakeholder.
- Difficulty in retrofitting gas central heating to heat pumps.
- It was raised that heat pumps are a steady state heating system and UK weather is not steady state, hence the need for additional local space heating for a complete heating solution the public will buy into. It should also be noted that in some cases there are issues with retrofitting heat pumps in terms of the requirement for larger radiators or underfloor heating - which will not be appropriate in all cases. It was raided that role of complementary low carbon secondary heating should not be discouraged in policy e.g., deprecation of chimney installation.

Investment Requirements

- Investment by homeowners. Ground source heat pumps could become mandatory for new builds of homes with gardens.
- Investment by the government in relation to policy decisions.
- Investment in education of the public and suppliers in relation to a suitable mix for different homes.
- Investment in training engineers for installation and maintenance.

Policy Requirements

- Green Heat Networks Fund as a mechanism for large-scale heat pump deployment.
- Timescales from the Government on the phase-out of gas boilers.
- Policies supported by subsidies to reduce costs, build supply chains and increase consumer awareness.

Factors Affecting Timescales

- Decisions on heat network zones.
- Decision on role of hydrogen for heating of existing buildings on the gas grid.
- Decisions on implementation of zoning to inform suitable place-based solutions i.e., heat network zones (to be consulted on in 2021), electrification, hydrogen etc.

Phasing out sale of wet wood and traditional coal

Benefits

- There was agreement that reductions in burning of wet wood and traditional coal will reduce $PM_{2.5}$ emissions, however, there was debate about the scale of the issue and consensus that a large portion of this is unlikely to be from domestic sources (e.g., commercial kitchens).

Barriers

- The main barrier was considered to be the difficulty of regulation. For example, this could be at the point of sale, or at properties, businesses where the burning is carried out.

- Wood can be dried in kilns, which is also associated with environmental impacts. The production of wood fuel could be regulated and emissions controlled. Quality standards could be put in place for the fuel and Environmental permits could be required.
- There is a concern that the use of these fuels will be displaced from domestic to commercial uses. There is need to bring non-domestic burning into regulations.

Investment Requirements

- The need to build on the existing grassroots Burnright campaign was highlighted. This provides tools and resources to educate and engage chimney sweeps to engage and educate their customers.
- Education from local authorities on the environmental issues is required. This includes factors such as seasoning of wood. Public should be referred to educational tools such as the Burnright website, the Defra Burn Better campaign, educational videos on the SIA (www.stoveindustryalliance.com) and clearSkies (www.clearskiesmark.org), and the Competent Person Schemes websites such as Hetas.

Policy Requirements

- Several stakeholders highlighted the importance of Government support to help engage chimney sweeps so that they deliver information and inform their customers in how to get it right.
- There was consensus that the contribution of outdoor burning needs to be better quantified and policies developed accordingly.
- It was mentioned that the RHI requires people to buy a BSL registered fuel to demonstrate sustainability. BSL is to be adapted to include fuel quality as well. This will help to ensure that the fuel used is the right fuel for the boiler. So, banning wet wood use is not necessary, it is about using the correct wood for boiler (i.e., matches that on the emissions certificate). RHI does not exert control over emissions unless plant is otherwise regulated.
- There is a need for a sustainable biomass policy that covers all aspects of biomass use from sustainable production, land use, carbon neutrality / offsetting and air quality from combustion. It is only by considering all aspects of biomass life cycle that all environmental impacts can be taken into account.

Factors Affecting Timescales

- There was agreement that the timescales for this measure to deliver benefits will depend upon both education of consumers and enforcement of policies.

Reducing emissions from domestic combustion of solid fuel

Benefits

- There was agreement that modern appliances result in much lower emissions and are much more efficient (e.g., modern stoves will burn about a quarter of the amount of wood of an old stove). Ecodesign wood burners produce 90% less particulate matter than an open fire. The GLA advises 70% of wood burnt in London is on open fires. Upgrading these to Ecodesign appliances would reduce emissions from domestic wood burning in London by up to 63%.
- It was discussed that open fires are a lot less efficient than newer stoves (20% v up to 80%), and that they also produce more indoor air pollution.

- There was much debate about the scale of emissions from domestic burning as current estimates rely on incorrect assumptions (e.g., the about of wood consumed) and the lack of distinction between indoor and outdoor burning.
- No-burn days were discussed and there was consensus (based on studies in other countries) that these have little effect on pollution on high-pollution days.

Barriers

- The lack of understanding about the scale of emissions and the source apportionment on specific sources that would enable policies to be correctly targeted.
- It was stated that the current NAEI emissions factors (EF's) applied to wood burning stoves are not fit for purpose: they are three times the Ecodesign limits. They don't distinguish between open fires and Ecodesign stoves; they don't distinguish the fuel burnt – for example the difference between wet and dry wood. There needs to be appropriate EF for unregulated outdoor burning, whether bonfires, outdoor pizza ovens, barbecues, incinerators, chimneys etc.
- It was also stated that policy makers need greater accuracy of measuring PM's - 2 wavelength aethalometers measuring a single chemical tracer, levoglucosan, are not accurate enough or capable of distinguishing different sources; research is required to ensure correct targeting of policy and regulatory measures.
- Lack of knowledge/education about open fires compared to wood burners. The cultural desire to see open fire despite heat efficiency, cost efficiency arguments/facts.
- Important heating source for fuel poverty.

Investment Requirements

- Tax rebates or grant systems to encourage purchase of modern appliances. However, it was noted that financial incentivisation alone is not enough. Policies to halt the sale of unsuitable appliances, and scrappage schemes for replacement of unsuitable appliances are required.
- A recurring theme was the need to educate consumers about the environmental benefits, health benefits, extended chimney life and fuel savings of Ecodesign compliant stoves. Chimney sweeps, installers, servicing companies, fuel retailers can help with the education of people and how they can burn in a more environmentally responsible way.
- Need for better database/records of appliances so that older appliances and bad fuels can be removed.
- Further research into outdoor burning and non-domestic sources to better define the scale of the issue.

Policy Requirements

- New regulations for the chimney sweep industry is required so that chimney sweeps have the training required to deliver advice on the best systems.
- Requirements for regular maintenance, and if necessary, updated of appliances.
- Support for purchase of Ecodesign compliant models (e.g., VAT reduction).
- Labelling of appliances to support education (e.g., clearSkies label which combines Ecodesign and Defra Exemption but also identifies appliances going beyond Ecodesign, Hetas solid fuel approval scheme).

- Regulations for outdoor burning (potentially included under domestic burning at present in emission inventories).
- It was mentioned that the future role of biomass for domestic heating could be limited to rural areas and those buildings that are not suitable for a heat pump. If biomass is used for district heating, the emissions can be controlled through environmental permitting thus mitigating this risk.

Factors Affecting Timescales

- Development of policies needs further research into the sources of Particulate Matter from wood burning (e.g., determine contribution from unregulated outdoor burning - bonfires, incinerators, Barbeques, outdoor pizza ovens, etc.).
- Uptake will depend on timescales for working with the industry to educate users and retailers.

Reducing emissions from commercial cooking

Benefits

- There was consensus that the benefits of measures to manage emissions from commercial cooking are very difficult to quantify as the scale of the emission source and the prevalence of measures to reduce emissions is unknown.

Barriers

- Lack of evidence on the scale of the issue.
- Difficulty in regulating numerous small businesses.
- Wood-fired restaurants and takeaways are not required to have filters or a device that is Defra approved.
- ESP costs are prohibitive for small businesses, particularly ones which are currently wood-burning restaurants.

Investment Requirements

- More research into the scale of emissions from commercial cooking. This could involve use of aetholometers to trace wood combustion.
- Investment in filters/ESP by restaurants/takeaways.
- Investment in enforcement by government/local authorities.

Policy Requirements

- Policies to require restaurants/takeaways to use filters/ESP.

Factors Affecting Timescales

- Timescales will be determined by research because the scale of the issue is unknown.
- Benefits will also be determined by the enforcement regime developed and funding provided.

Regulation of biomass combustion plants <1MW

Benefits

- It was highlighted that the benefits of regulating these plants could be significant as there are ~11,000 biomass projects with Renewable Heat Incentive (RHI) funded plants with an aggregate of ~ 3 GWth. These are typically small boilers in public buildings/offices/small industrial installations with an average size of 250 kW. These appliances burn 50-60 kg of wood.
- These installations do not require a permit at the moment and it is possible that wet wood no longer sold for domestic use could be transferred to these plants. It is likely that waste wood of inappropriate grades is being used in these small appliances.

Barriers

- Regulation is challenging as it is difficult to prove and cost of prosecution would outweigh any benefits.
- Poor quality installations leading to frequent cycling of the boiler (e.g., over specified or buffer tank too small). Low seasonal efficiency and increased emissions as a result, even with the right fuel.

Investment Requirements

- Investment in enforcement which would be covered by permit fees.
- Operator investment in permit application.

Policy Requirements

- It was mentioned that this requires no change to primary legislation, but would require a change to secondary legislation to include the new processes. Also requires a new PPG and application fee.
- Introduction of maintenance and fuel quality standards from 2022 for biomass boilers.
- Strict requirements in relation to $PM_{2.5}$/NOX when applying for subsidy for biomass boilers under Renewable Heat Incentive (RHI) and planned successor policy (Clean Heat Grant).
- It was mentioned that the RHI requires people to buy a BSL registered fuel to demonstrate sustainability. BSL is to be adapted to include fuel quality as well. This will help to ensure that the fuel used is the right fuel for the boiler. So banning wet wood use is not necessary, it is about using the correct wood for boiler (i.e. matches that on the emissions certificate).
- Non-domestic RHI now requires biomass operators to comply with new fuel quality standard in order to claim payments. It also requires biomass boilers to carry out mandatory annual maintenance checks. However, it does not have emissions standards.

Factors Affecting Timescales

- Will depend on policy changes and development of enforcement mechanism.

Urban Mobility (20/02/2021)

Attendees

Imperial College, City Science, UWE, Arup, TfL, Modeshift, Systra, DfT, Connected Places Catapult, RTPI, University of Oxford, Wood, Centre for cities, Defra, TRL.

Summary of Stakeholder Views

Localised Active Travel Plans

Benefits

- There was consensus on the on-benefits of active travel, including carbon emissions, mental health (including connection to a place or community), physical health and addressing inequalities. However, it was also accepted that active travel is only appropriate for a certain subset of journeys.
- In London, where a third of car journeys are under 2 miles, there may be potential for a greater reduction in vkm than 5%. Also, a 1% reduction in vkm was seen as unambitious.

Barriers

- General barrier around active travel discussed included time restrictions, lack of connectivity to onward journey plans and habits. A lack of Trip chaining and mixed-use planning that makes encourages active modes was mentioned.
- A number of barriers specific to cycling were discussed, including affordability of bikes and equipment, lack of feasibility for a portion of the population, weather conditions and perceptions on safety.
- There may be a reluctance to restrict car use to enable active travel because of the loss of car parking revenue.

Investment Requirements

- There is a need for local facilities/destinations and mixed-use planning to achieve '15 minute' neighbourhoods.
- Planning for a range of cyclists (e.g., confident commuting cyclists, less experienced cyclists, young cyclists) including segregated cycle lanes (which are key for safety and behavioural shifts), plus facilities at destination (e.g., storage, showers, changing rooms).

Policy Requirements

- There is a need to differentiate walking and cycling policies.
- Local authorities are required to develop Local Cycling and Walking Infrastructure Plans (LCWIPs) in order for them to receive infrastructure funding.
- Requirements for infrastructure, facilities and connection to local centres in new developments.
- There is a need for "sticks" (e.g., car restrictions, reduced parking at destinations) as well as "carrots".
- Policies should be linked to those associated with health, transport, planning, carbon reduction.
- Engagement with local communities is key for the success of local transport schemes.

Factors Affecting Timescales

- Timescales will depend on government funding for active travel and resourcing for transport planning capacity in local authorities.
- Timescales depend on the measures that are implemented. Due to lower infrastructure requirements, more walking can be achieved quickly. Prime Minister's Cycling and Walking Plan has an ambition of half of trips in towns and cities being taken by walking and cycling by 2030.
- Generational changes in perceptions of travel choices will determine effects (i.e., not as many 17-25 year olds are taking their driving tests now as were 20 years ago).
- Future of costs of driving may increase active travel.

Regional Transport Plans

Benefits

- These enable co-benefits such as reduced carbon emissions and better places and improved public realm.
- New and emerging mobility services integrated with traditional public transport can increase patronage on fixed scheduled service (at least up to 30%).

Barriers

- Changing behaviour and habits is not easy, particularly whilst car driving remains convenient. There can be resistance to reallocation of road space. Slow adoption of emerging mobility services due to consolidated habits in users, high car ownership and ease of parking.
- The fuel duty freeze means that costs of driving remain relatively low.
- Integration of public transport services (route, fares and timetables) still limited by deregulation of the market and lack of coopetition between operators and modes.
- Lack of political support and senior level buy-in including the need to reassess Road Investment Strategy (RIS2) in light of net zero target.
- The lack of funding required for integrated transport planning (including public transport).

Investment Requirements

- Investment in infrastructure, facilities and services, including public transport and facilities such as bicycle storage near public transport hubs. Investment also required in existing services to improve reliability and attractiveness.
- Digital integration of mobility services, using MaaS platforms.

Policy Requirements

- There was consensus on the need for high level political support and leadership alongside provision of the resources and resources and powers required to meet targets at a local level (e.g., Mayoral combined authorities). The benefits of the devolved system were highlighted.
- Workplace parking levy's can significantly alter attractiveness of private car use.
- Subsidised, or free, public transport would encourage usage.
- Review of economic calculation methods for road schemes that may overvalue benefits relative to emissions.

- Policies should be linked to those associated with health, transport, planning, carbon reduction.

Factors Affecting Timescales

- Timescales will depend on government funding for active travel and resourcing for transport planning capacity in local authorities.
- It will take a long time to change travel patterns in places that are car-dominated.
- Planning and delivery of new infrastructure for longer distance routes (rail, BRT) (Justin)
- Upgrade/expansion of existing infrastructure for longer distance routes and major infrastructure projects have very high costs and long timescales.

Zero Emission Buses

Benefits

- The co-benefits of reduced noise and carbon emissions were highlighted.

Barriers

- Significant investment requirements, including charging infrastructure.
- The electricity grid capacity in relation to increased demand for charging.
- Range and passenger capacity issues.
- Topography (hills in particular) and start and stop driving pattern reduce the appeal of EV buses to the operator because of operational costs.
- The increased weight of electric vehicles (heavier than standard vehicles) can cause increased road wear.

Investment Requirements

- Investment in the electricity grid to support charging.
- Investment in a fleet of zero emission buses and the charging/hydrogen infrastructure.

Policy Requirements

- Introduce CAZ/LEZ restrictions everywhere, or prioritisation of zero emission vehicles along particular routes.
- The need to align electric bus policy with electricity grid policies.
- The need to avoid displacement of older (bus) fleets to other cities without policies was highlighted.

Factors Affecting Timescales

- Largely determined by funding for initial investment, plus vehicle performance compared to route (length, passenger demand, terrain).

School/Workplace Travel Planning

Benefits

- As well as reducing vkm, these measures can reduce peak time congestion.
- There are co-benefits for health and well-being when journeys are undertaken by active travel.

- The benefits could be increased by wider application of such approaches to consider neighbourhoods, public transport hubs, events etc.
- Individual schemes only apply to a small subset of the population, therefore overall benefits are limited.

Barriers

- The potential safety issues around active travel (e.g., cycling in busy streets) were discussed.
- Employers have little control over availability of the public transport infrastructure that will determine the effects of measures such as this.
- Other than for new developments travel Plans are not mandatory.

Investment Requirements

- Dedicated funding for local authorities to support schools/businesses with Travel Plans, plus funding for schools/workplaces to implement measures identified in their Travel Plan.
- Infrastructure on key routes (e.g., separated bike lanes).
- Engagement to encourage behaviour change (e.g., walk to school, Modeshift Stars and Bikeability).

Policy Requirements

- The planning system should be used, for example through having active travel to schools mandatory in planning developments. The requirements to deliver Travel Plans rather than just write them should be strengthened. The responsibility for delivery needs to be made clear.
- Works best alongside policies that discourage car use (e.g., reduced number of parking spaces) or encourage shared or sustainable travel (e.g., awards/benefits).
- Policies should be linked to those associated with health, transport, planning, carbon reduction.

Factors Affecting Timescales

- Effectiveness will be dependent on wider schemes for active travel (e.g., connections between schools, homes and workplaces).

Changes in Work Patterns

Benefits

- Several stakeholders highlighted the challenges in quantifying the benefits. Home working lowers travel demand but may increase demand for deliveries and increase leisure trips. It may also increase emissions from buildings.

Barriers

- Lack of digital connectivity (particularly in rural areas).
- Permitted development rights may mean that local authorities have reduced ability to manage changed in building use (e.g., risk that everything shifts to residential).
- Wide-scale home working may have implications for the cost-effectiveness of public transport.

Investment Requirements

- Planning for flexible co-working spaces in local communities to reduce commutes to larger, central offices.

Policy Requirements

- Planning policy which promotes plan-led approach to mixed land use so can protect co-working spaces from shift to more 'profitable' uses such as pure residential.

Factors Affecting Timescales

- None discussed.

Land Use Planning

Benefits

- There was agreement in the benefits of using land use planning to enable a significantly higher number of trips to be taken by active travel. This will reduce the energy intensity and carbon emissions of transport.
- The co-benefits such as public health, equality, reduced congestion and better places were highlighted. Several stakeholders mentioned the co-benefits to retail, including Increased foot fall, dwell time and more lively urban areas.
- The opportunity to build on changes brought about by COVID-19 (e.g., closure streets to traffic, widening pavements and allowing more space for pedestrians) was highlighted.

Barriers

- Potentially a lack of political will to reduce car use, there may be a related perception that homes without car parking spaces will not sell.
- Measures that work in dense areas may not be appropriate for other areas.
- Expansion of permitted development rights could increase the volume of development essentially taking place outside of any real planning controls (e.g., more change of use from industrial/commercial to residential in unsustainable locations)
- Several stakeholders mentioned the difficulty engaging with transport operators at local plan-making stage and a lack of modelling land use impact of transport investment decisions (esp. re carbon and air quality impacts) due to the complexity of the issue.
- There is weak planning policy and guidance on the location and design of new developments with regard to sustainable transport.
- Many new developments received planning permission a number of years ago. As such they are proceeding under old planning guidelines.

Investment Requirements

- A more active role for Homes England in unlocking funding to support plan objectives and allocating funding to exemplar schemes that raise bar for accessibility.
- Active Travel England will require investment and will function as a statutory consultee within the planning system.
- Better connections (walking/cycling) between homes, schools, retail, office, hospitality.
- The need for funding for LAs for both quick win and long-term active travel and integrated public transport networks (capital and revenue).

Policy Requirements

- Housing developers have to be required to include infrastructure that makes walking and cycling attractive.
- Several stakeholders mentioned that parking policy is a key tool. Parking provision should be reduced where alternative options are available.
- Guidance on new housing developments on greenfield sites away from public transport links.
- Explicit support for 15-minute neighbourhood principles in the new National Planning Policy Framework and exception test for development that cannot show conformity with these principles.
- Planning policy to ensure that land designated for growth and renewal is accompanied by clear transport outcomes (mode shift etc.).
- Several stakeholder highlighted the need for integrated transport and land use planning by developing and examining local plans and local transport strategies in tandem, with common vision, objectives and metrics. It was also suggested that local plans could be developed in order to meet defined transport goals.
- Planning policy for new development to demonstrate net zero transport emissions (e.g., through expanding Future Homes Standard to include transport).

Factors Affecting Timescales

- The planning reform timetable will determine when new local plans are prepared.
- The Planning Practice Guidance (PPG) system in the 1990s and 2000s including policies on brown field sites and mixed land use delivered stabilisation in car use. This indicates the timescales over which benefits can be achieved (10-20 years).
- Timescales will depend on government funding for active travel and resourcing for transport planning capacity in local authorities.
- There was agreement that changes will not deliver immediate benefits and it will take a long time to fix current land-use problems. Changes may be evolutionary rather than revolutionary and limited by changes of building/space usage.
- The timeframes will be affected if Local Plans and accompanying transport strategies are subject to legal challenge on conformity with the Climate Change Act.

Shared Mobility

Benefits

- The benefits of having fewer vehicles doing more vkm could result in a cleaner fleet than could be afforded otherwise.
- Several stakeholders commented that shared mobility could lead to reduced car ownership, reducing vkm as those who own cars are more tempted to use that vehicle for shorter journeys.
- Shared mobility would be useful to supplement to public transport for infrequent, longer journeys.
- Could be used as part of community transport, as seen in some examples in Scotland, or on particular sites like industrial estates (e.g., examples of Demand Responsive Transport).

Barriers

- The added complexity (car not being on doorstep) could reduce popularity.
- May not cater for practical needs of drivers/passengers (e.g., seats for children).
- There is a need to ensure that empty vehicles do not circulate.
- May not reduce vkm if shared rides are used as second cars rather than removing first cars.

Investment Requirements

- Blended public transport / shared mobility with public support (e.g., shared small buses with no fixed route booked on app).
- Vehicles, infrastructure for parking and recharging.

Policy Requirements

- Measures to incentivise shared journeys were discussed (e.g., shared vehicle lanes, higher tax on private vehicles.

Factors Affecting Timescales

- Schemes are run commercially, so expansion may be driven more by profitability than providing a social good.
- Schemes for particular sites/areas can be planned and implemented within a couple of years.

Financial Mechanisms

Benefits

- It was agreed that measures such as the London ULEZ/ Congestion charge have led to significant improvements in air quality by encouraging fleet upgrades. Measures encouraging the use of Euro 6 and zero emission vehicles will deliver significant benefits.
- Schemes provide local authorities/transport authorities with revenue which can then be ring-fenced and reinvested in active travel and public transport.
- It was mentioned that road pricing is the easiest way to encourage large scale modal shift, in part as they communicate the true cost to society of travel.

Barriers

- Vocal motorists opposing schemes and politicians avoiding antagonising this group.
- Several stakeholders mentioned that schemes could discriminate against the poor.
- Confusion if local schemes are not co-ordinated with each other.

Investment Requirements

- The cost of the infrastructure for the charging system (e.g., ANPR or a seamless national app).

Policy Requirements

- Road user charging can only work if co-ordinated at a national level.
- End the freeze on fuel duty to make driving less attractive.
- Schemes need to be able to levy different charges on different roads. Charges could vary based on the congestion and pollution in an area.

- Need to consider social inequalities.

Factors Affecting Timescales

- Based on policy decisions.
- It was mentioned that road pricing (or equivalent) may be inevitable as EVs become mainstream and fuel duty income is reduced.

Freight Consolidation and Urban HGV Restrictions

Benefits

- Co-benefits such as noise reduction and more attractive urban spaces for everyone were discussed.
- Several stakeholders mentioned that there are many examples of freight consolidation centres being successfully operated for a number of years.
- Several stakeholders mentioned that emissions per kg of goods transported may be lower in HGVs than using numerous LGVs.

Barriers

- Benefits may be reduced by increased LGV vkm due to online shopping and demand from food and parcel industry.
- It was mentioned that rail freight options with lower emissions (particularly in urban areas) are available. Use of electrified rail lines for freight in urban areas could be particularly beneficial.
- The lack of planning for freight, including the availability of land in the right places.

Investment Requirements

- Changing from current freight networks will add costs.

Policy Requirements

- Strong strategic / cross-boundary governance to allocate sites for consolidation centres.
- Policies need to ensure that "out of town" centres that people need to drive to are not encouraged.
- Strong, clear local transport policies and engagement with the industry are vital. Contingent on local transport policies
- Several stakeholders emphasised the importance of using the rail network for freight.

Factors Affecting Timescales

- Several years required to plan and build freight consolidation centres.

Zero Emission Last Mile Deliveries

Benefits

- Several stakeholders mentioned improvements in the urban environment due to reduced ICE delivery vehicles.
- It was mentioned that this need to be considered alongside the increase in home working and the changing logistics requirements.

Barriers

- Systems that allow slot booking can lead to sub-optimal delivery plans. Benefits would also be reduced if there are significant numbers of missed deliveries leading to additional trips.
- Perceived lack of data to understand the magnitude movements associated with last mile delivery. New data source such as mobile network data at trip-chains level are largely unexplored but remove the barrier of data owned by freight operators.
- Availability of land for distribution hubs.

Investment Requirements

- Several stakeholders highlighted the need for infrastructure including more urban consolidation/distribution centres to allow e-bike deliveries.
- Investment in vehicles (e.g., £2m invested through E-Cargo Bike Grant programme doubled the size of the e-cargo fleet).

Policy Requirements

- Policies needed to restrict the proliferation of ICE delivery vehicles.
- Requirement in planning policy to allocate and safeguard land for last mile consolidation.
- Changes to road space allocation.
- Allowance for competition (i.e., multiple providers).
- Policies need to level up the country by ensuring that there is also access to services in rural areas.

Factors Affecting Timescales

- Development of infrastructure.
- It was mentioned that the Prime Minister has committed to piloting compulsory freight consolidation schemes in one or two small historic city centres with narrow and crowded streets.

Road Transport Technology (21/01/2021)

Attendees

Tyre Collective, Imperial College, T&E, TRL, Highways England, TfL, DfT, Defra, Connected Places Catapult, Highways England, Emissions Analytics, University of Leeds ITS, Arrival, Enodamus, BTMA, Tallano

Summary of Stakeholder Views

Exhaust Regulations

Benefits

- Sales of standard new ICE cars and vans is ending (for the most part) in 2030 limiting the benefit of this measure, as regulations would be only likely to come into force in 2026-2028. However, sale of plug-in hybrids or full hybrid cars and vans will be allowed between 2030 and 2035. Therefore, any $PM_{2.5}$ limit will still be effective in limiting emissions from such vehicles.
- The benefits in terms of total $PM_{2.5}$ emissions could be minimal, leaving a small window for purchase of new ICE cars before sale is prohibited. Benefits would also be minimal as there is virtually zero $PM_{2.5}$ emitted by modern petrol or diesel cars already.
- Euro 7 limits and test requirements are subject to negotiation so there is a large amount of uncertainty on possible benefits.
- Reduction in a PN limit would not necessarily reduce actual emissions (if they already meet this limit).
- Future emission standards would be likely to reduce NO_X emissions and therefore secondary aerosol formation.

Barriers

- Depending on the agreed Euro 7 regimes there could be a number of technical barriers to be overcome in ensuring low emissions under certain operating conditions. For Euro 7 the intention is to move away from lab testing and go to full Real Driving Emissions (RDE) testing.

Investment Requirements

- Investment is required to introduce and enforce new regulations.
- Technology developments mean that remote sensing could be used as an alternative enforcement mechanism.

Policy Requirements

- The UK needs to make a decision on alignment with Euro standards as these will not automatically apply.
- Several stakeholders raised the point that policies to remove older vehicles may be more effective at reducing exhaust $PM_{2.5}$ emissions (e.g., London ULEZ).

Factors Affecting Timescales

- As sales of standard new ICE cars and vans is ending (for the most part) in 2030, and Euro 7 standards are only likely in 2026-2028 if the decision is taken to implement them in the UK, there is a limited window for benefits.

- This window may be limited further as people may chose not to purchase new ICE cars in 2026-2028 as there may be concerns that the technical support may reduce after 2030. This would affect uptake rates of cars meeting new standards.

Particle Number Checks in MOT

Benefits

- Several stakeholders highlighted that the benefits of this measure may be lower than presented as DPF failure rates may not be as high as the reported 5-10%. The NAEI includes failure rates of around 1%.

Barriers

- There was consensus that the MOT system in the UK would make it highly challenging to implement this measure at MOT test centres. There are around 20,000 to 30,000 of these in the UK, which would all need new testing equipment and staff training. An alternative raised by several stakeholders was remote sensing at the roadside to identify vehicles with failed or removed DPF (e.g., http://caresproject.eu). The Westminster Commission for Road Air Quality (www.wcraq.com) is also working in this area.
- The measure places pressure on the consumer rather than encouraging OEMs to reduce DPF failure rates.

Investment Requirements

- Further research into the link between Particle Number and $PM_{2.5}$ (and Ultra Fine Particulates (UFP)) to fully understand the potential impacts.
- Further investment in remote sensing approaches and standards if this is to be a viable alternative.
- Development of more efficient filters and vehicles.

Policy Requirements

- Policy development to prioritise MOT or remote sensing approach.

Factors Affecting Timescales

- Given the number of MOT centres, widescale rollout would take many years. Alternatively, develop remote sensing methods.

Regenerative Braking

Benefits

- Several stakeholders highlighted the benefits of regenerative braking delivered through changing driving styles. The number is braking events is optimised and the fuel economy is improved. It was mentioned that electric CAVs could help maximise the benefits in this way.
- The benefits will depend on the frequency in which regenerative braking is used as opposed to friction braking. The greater benefits may therefore be seen in urban areas. It was agreed that more research is required on this.
- Regenerative braking produces a reduction in brake temperature and changes the dominant emission mode from $PM_{2.5}$ to PM_{10}.

Barriers

- May not be as effective for HDVs due to power constraints as regenerative systems cannot recover energy at the required rates at present.

Investment Requirements

- More research is definitely required. There are several ongoing international efforts, including the upcoming research project by DfT (which will feed into the work of UNECE PMP), which will cover this aspect as well.

Policy Requirements

- Supported by policies encouraging the uptake of BEVs.

Factors Affecting Timescales

- The sale of petrol/diesel cars from 2030 (and other policies in favour of BEV uptake) will lead to increased uptake of BEVs.
- Introductions of CAVs onto the road will enhance the benefits.

Deweighting of BEVs to reduce tyre/road wear

Benefits

- Stakeholders agreed that this measure would be likely to reduce tyre wear emissions and also reduce resuspension, however, it was also highlighted that BEVs are supplied with specific tyres that are designed for the forces applied and these have lower wear rates.
- Reducing weight would also lower energy consumption and increase range.
- Benefits will depend on changes in vehicle occupancy rates, which could increase and work against the trend in lowering weight through battery improvements. On the other hand, when infrastructure improvements and familiarisation with the benefits of electric vehicles may mean that range anxiety is reduced in future and there is a preference to purchase smaller, lighter BEVs.

Barriers

- Several stakeholders raised the issue of the tension between vehicle weight and range. Until battery energy efficiency improves significantly, performance improvements are likely to be used to increase range.
- Advanced lightweight materials are likely to have high costs
- Several stakeholders pointed out that vehicle safety features add weight to vehicles.

Investment Requirements

- Development of lightweight materials.
- Research into the correlation between vehicle weight, torque, tyre wear and driving habits.

Policy Requirements

- Tyre wear rate emission standards for tyre models and types.
- Several stakeholders suggested that policies to encourage certain vehicle types in urban areas may be more appropriate. For example, incentivising smaller, lighter, low speed, low acceleration vehicles and deterring larger, heavier SUVs. It was also suggested that this could

be achieved through policies related to vehicle range, where city runabouts would be subject to different tax rates than vehicles designed for high mileage.

Factors Affecting Timescales

- There may be a tipping point sometime in the future where battery efficiency has improved to deliver sufficient range and OEMs can begin to reduce vehicle weight.

Connected Autonomous Vehicles

Benefits

- Stakeholders agreed that CAVs would deliver changes in driving style, reducing incidences of harsh braking (and potentially braking in general) and acceleration and lowering energy consumption, thereby lowering emissions.
- Several stakeholders mentioned that CAVs may increase vkm and congestion by making trips low cost and low effort. It was also mentioned that even if CAVs reduce congestion, this may increase the popularity of driving and increase vkm.
- The technology may deliver most benefits in closed systems such as airports where the journey is known ahead of time and there are minimal disruptive factors and events.

Barriers

- The need for harmonisation of different technical systems.
- The technology may not be appropriate everywhere. For example, it may be better suited to motorways and not to densely populated urban areas.

Investment Requirements

- High levels of investment in technology and infrastructure required to make CAVs feasible.
- Full network investment will need to be aligned between the Strategic Road Network (SRN) and local roads.

Policy Requirements

- Policies to enable harmonisation of different systems (e.g., different manufacturers).

Factors Affecting Timescales

- Benefits may only be achieved once a large proportion of the fleet is enabled.
- Uptake may be encouraged by benefits in productivity whilst travelling.

Brake Wear Emission Regulations

Benefits

- Stakeholders agreed that this measure would be beneficial given the importance of brake wear emissions as a source.
- Euro 7 limits and test requirements are subject to negotiation so there is a large amount of uncertainty on the possible benefits likely to be achieved. Some stakeholders consider that initial regulations may be light-touch (focusing on removing of worst materials for example), whilst others think that stringent regulations can be brought in.
- Sales of standard new ICE cars and vans is ending (for the most part) in 2030 limiting the benefit of this measure, as regulations would be only likely to come into force in 2026-2028.

However, sale of plug-in hybrids or full hybrid cars and vans will be allowed between 2030 and 2035. Therefore, any $PM_{2.5}$ limit will still be effective in limiting emissions from such vehicles when they have friction brakes.

- Combining formulation, regenerative braking and collection at source could achieve close to zero brake wear emissions.

Barriers

- The lack of a harmonised measurement method and the difficulty in assessing emissions from real world conditions.
- The need to ensure that braking safety performance is maintained.

Investment Requirements

- Development of a harmonised testing method for brake wear emissions.
- Development of technologies for collection at source (e.g., technology developed by Tallano Technologie), which will add efficiency in reducing brake wear emissions.

Policy Requirements

- Finalisation of a harmonised, industry-wide brake wear emission measurement methodology.
- Determination of a suitable brake wear emissions limits. It was suggested that brake wear emissions limits should be at least as tight as exhaust limits in mg/km/vehicle.
- The need for type approval regulations for components (e.g., pads and discs) was also highlighted. It is understood that both component and whole vehicle level are being considered for type approval regulations.

Factors Affecting Timescales

- As sales of standard new ICE cars and vans is ending (for the most part) in 2030 and Euro 7 standards are only likely in 2026-2028 there is a limited window for benefits as friction brakes are only used for a small portion of braking events in BEVs.

Tyre Composition

Benefits

- There was consensus that regulating emissions from tyres would have significant benefits through reductions in both atmospheric $PM_{2.5}$ concentrations and microplastic pollution. There remains debate regarding how much ambient $PM_{2.5}$ is from tyre wear emissions.
- It was agreed that, ultimately, when testing regimes are available, regulations should be used to place the responsibility on the industry to produce tyres with lower emissions. The manufacturing process, and not just the composition is important in determining wear rates and emissions.
- Tyre wear is heavily influenced by road surface quality. High levels of grip for road safety do not necessarily correlate with high levels of tyre wear.

Barriers

- Tyre manufactures may not want to produce slower wearing tyres that reduce the need for replacement.
- Several stakeholders emphasised that friction is a key part of the function of a tyre and safe functioning must be maintained.

- It may be difficult to encourage consumers to purchase lower wear tyres as upfront cost is still a key factor in the purchasing decision.
- The lack of harmonised standards on measuring tyre wear $PM_{2.5}$ emissions.
- Concern was raised regarding the potential double regulation of tyre wear particles through both component type approval and vehicle approval.
- The lack of awareness of the issue and information on tyre durability on tyre labels.

Investment Requirements

- Raising public awareness of the issue.
- Development of better materials, compositions and manufacturing methods.
- Further investigation into long-term health effects of tyre particles.

Policy Requirements

- A harmonised methodology of for measurement of tyre wear emissions needs to be developed.
- Emissions could be controlled either through setting of emission limits (potentially relating to types) or by using labelling to encourage the purchase of low emission tyres.
- Several stakeholders emphasised that care must be taken to ensure newly developed tyres comply with applicable chemical regulations.
- The need for greater clarity on wear rates and emissions to enable regulatory/purchase decisions.

Factors Affecting Timescales

- Governed by the research required to develop a harmonised testing regime, and also the time required to test the huge range of tyres currently in the market.
- The tyre industry is developing a robust, reliable and reproducible test method to measure tyre abrasion rate reflective of European usage. It is anticipated that this will support a regulatory minimum standard for tyre abrasion resistance by the mid-2020s. Other international efforts, such as an upcoming DfT project and EU-funded LEON-T project will cover this topic as well and will work to similar timelines.

Vehicle Condition (Wheel Alignment and tyre pressure)

Benefits

- Several stakeholders mentioned that Tyre Pressure Monitoring System already exist for new vehicles (Every new car sold in the EU from 2014). These may however only provide warning for abrupt changes in pressure, rather than gradual deflation.
- It was mentioned that 50% of commercial fleets are already running on service contracts from tyre manufacturers which monitor, and correct, tyre pressure issues. This enables operators to be more fuel efficient. The take-up of these contracts is minimal amongst smaller fleets (fewer than 20 vehicles) that together represent 50% of heavy commercial vehicles on the UK roads. This represents a considerable untapped opportunity but government support is needed to overcome the obstacles to wider uptake.
- Potential to use RFID chips to improve consumer maintenance (wear & pressure) and increase benefits.

- Driver behaviour was also discussed as an associated measure that could reduce emissions. The potential for making driver behaviour a component of road charging to incentivise modified driver behaviour (e.g., reduced harsh braking) was discussed.

Barriers

- Getting vehicle users to take action upon identifying any issues with wheel alignment and tyre pressure.

Investment Requirements

- TPMS only becomes mandatory for new heavy commercial vehicles from 2022. Easy-to-install wireless retro-fit TPMS packages are widely available at low cost, offering improved safety and environmental performance.
- One stakeholder highlighted the work of the Pew Charitable Trust[135] which suggests that to reduce microplastic pollution, the tyre industry, supported by government research programmes, should invest in innovation and redesign.

Policy Requirements

- Tyre condition checks should be included as part of standard vehicle checks.
- Government policy around tyre stewardship on smaller HDV fleets (fewer than 20 vehicles) including performance of replacement tyres, maintaining tyre condition and correct inflation.

Factors Affecting Timescales

- Difficult to quantify as testing regime/key metrics are not yet established.

Road Composition

Benefits

- Some stakeholders consider that abrasion of the road itself is not significant compared to tyre wear. Others cited reports showing that particles are typically a 50:50 mix of tyre and road-related materials.

Barriers

- Any benefits that could be delivered could be offset by increased vehicle mass contributing to increased road wear rates (see deweighting of electric vehicles).
- There was agreement that it is vital to ensure that the safety properties of roads (related to friction) are not compromised. However, it was mentioned that it is important to ensure that surfaces do not provide more friction than necessary. Other trade-offs, for example noise, where also mentioned.

Investment Requirements

- Resurfacing roads on a wide scale would have significant investment requirements.

Policy Requirements

- There is a need for further research into the interaction of road and tyre materials before policy specific to $PM_{2.5}$ can be developed.

Factors Affecting Timescales

- The timescale associated with a programme of road resurfacing would be significant.

Road treatment to reduce resuspension

Benefits

- Road surface wetness (including through meteorological conditions) plays an important role in determining concentrations of $PM_{2.5}$ from non-exhaust emission sources.
- Treatments other than washing and sweeping were mentioned. Rhinophalt is a surface dressing to harden roads and reduce wear. Calcium magnesium acetate (CMA) has been applied in some exampled to reduce resuspension.

Barriers

- There may be safety hazards associated with washing (e.g., to bikes/motorbikes).
- The labour costs of regular washing could be significant.
- Given the resource requirements, washing/CMA application may only be practical for small areas (e.g., city centre).
- It was also discussed that any benefits from regular street washing/sweeping might well be counteracted by several disadvantages, such as emissions from the regular/intensive use of the washing vehicles themselves.

Investment Requirements

- Investment in teams to wash/sweep roads on a regular basis.

Policy Requirements

- Some stakeholders suggested that the benefits relative to the labour requirements mean that this measure is not suitable to be implemented through policy decisions.

Factors Affecting Timescales

- None mentioned.

Shipping (27/01/2021)

Attendees

Shell / MarRI-UK., Kongsberg Maritime, Magnomatics, Imperial College London, Portsmouth International Port, Johnson Matthey, UK Chamber of Shipping, UK Major Ports Group, Smart Green Shipping, Society of Maritime Industries, DfT, British Ports Association, UCL, Condor Ferries, Columbia Threadneedle Investments.

Summary of Stakeholder Views

General points / introduction

- Wood team note that the selection of measures for discussion in the workshop was guided to an extent by the DfT Clean Maritime Plan (CMP), as this sets out what can be considered in both 'realistic' and 'ambitious' scenarios in terms of policy intervention and decarbonisation targets, but also aims to allow a more specific discussion on the potential for $PM_{2.5}$ reductions.
- It was emphasised that NOx emissions from shipping is also very important as this heavily impacts secondary $PM_{2.5}$ levels (i.e., primary $PM_{2.5}$ is less of an issue than NOx emissions in the overall picture).
- The consideration of stricter and/or expanded emission control area (ECA) for NO_x and SO_2 could be considered (e.g. covering the Irish Sea) to tackle this. It was noted that in the context of this study, this is difficult to consider as a definitive 'measure' as the other technical measures considered in this discussion (e.g., alternative fuel, electrification, efficiency improvements etc) will be implemented to comply with the stricter ECA requirements. The implementation of a stricter or expanded ECA must therefore be viewed as a potential driver for the uptake of the technical measures highlighted below.

Alternative Fuels

Benefits

- Fuel cell technology offers a significant improvement in thermal efficiency but they still need batteries for smoothing. Fuel cells are a viable option for addressing air quality issues while also addressing GHG emissions.
- Existing fuel technologies are available, and come with lower infrastructure costs e.g., they can use existing fuel tanking.
- Some fuel alternatives come with low modification costs for vessel propulsion systems.
- The potential for LNG in the shipping sector for reducing air pollutant emissions was highlighted. Some highlight that LNG almost eliminates PM and significantly reduces NO_x, eliminates SO_x and significantly reduces CO_2 emissions. LNG also reduces shipping running and maintenance costs (engine maintenance halved).
- However, others indicate that LNG is not a suitable option for decarbonisation (e.g., the DfT CMP does not envisage this being heavily supported in the future, unless from a renewable/bio-source). The potential issue of 'methane slip' was also raised in this context.
- Use of alternative fuels could help achieve net zero by 2050 as several options produce very low $PM_{2.5}$ emissions. In the DfT CMP, ammonia is projected as a major contributor to this transition and represents the major bulk of fuel mix in 2050.
- The switch to low S Fuel in the short term will allow DPF and other exhaust technology to be implemented.

Barriers

- Alternative fuels often come at a higher cost and engine warranties do not often cover alternative fuels.
- There is a lack of engagement from IMO on air quality. From several actors within the shipping industry, procrastination and conflict is delaying uptake of today's cleanest fuels.
- Ports will not want to provide all fuels (costs/space), and it is currently uncertain which fuel will be favoured in the future. There is a lack of clarity on demand signals to support this infrastructure.
- Furthermore, there is the potential for stranded assets associated with investing in new fuels and their infrastructure (e.g., LNG fuelled vessels), and a risk relating to fuels favoured for decarbonisation vs air quality improvements. Noted that the DfT strategy does not envisage support for LNG fuel in the shipping sector.
- Ammonia slip associated with storage and transfer of ammonia has not been quantified at this stage and ammonia is also associated with NO_x emissions. The fuel transition may need to be accompanied by appropriate exhaust treatment/scrubber technology (added cost).
- Shipowners are holding back in replacing current fleet as they don't see a favoured option so far.
- Some argue that the negative views of LNG are the same as promoting 'doing nothing'. There are also issues with allowing LNG bunkering in certain ports and risks associated with bunkering LNG at ports with low temperatures. There is also the risk of methane slip occurring when using LNG technologies.
- It is uncertain what the future training needs are for future seafarers with alternative fuels.
- There was some discussion around the potential use of nuclear power for powering vessels. It was noted that this would have significant benefits in terms of reducing air quality emissions, which if the material is managed correctly, could outweigh the overall risks.
- However, it was noted that there are significant risks around handling and disposal, and arguments over the effects of piracy and safety. It was noted that public perception would be an important barrier in uptake of this as a measure. Nuclear is not envisaged as a viable option in the DfT CMP for those reasons.
- It has been noted that biofuels are not seen as a priority fuel group for shipping (similar reasons to LNG in terms of decarbonisation targets). Compared to other sectors (e.g. road transport, aviation) the shipping sector is not foreseen as a major user of biofuel in the future.

Investment Requirements

- Alternative fuels will need the infrastructure there to be able to supply it which comes at a cost. To reduce costs the alternative fuels used should “tag along” with fuels used in other sectors. Furthermore, standardisation of systems would encourage industry uptake.
- Any extra equipment used with particular fuel types is something that also requires investment in addition to the fuels themselves (exhaust treatment etc.). Anything relying on combustion will need SCR.
- Big shipping players making their future fleet decisions will have a big influence on investments for others.
- Some fuels come with a much lower investment cost than others.

- It was highlighted that LNG is seen by many as a continuing source of power for the shipping fleet in the near- and medium-term at least. For example, Brittany Ferries have finance in place for LNG bunkering in Portsmouth.
- Some locations such as the Orkney Islands are able to use hydrogen from wind turbines as they have excess of renewables, but many ports do not produce their own energy and have a high demand.

Policy Requirements

- There is a need for regulatory acceptance of novel ideas.
- Currently it is believed that the IMO is not fully engaged with air quality, and their support (in terms of setting standards) would be required (e.g., $PM_{2.5}$ is not currently addressed directly). Similarly, it is believed that the UK government should be more active in setting policy in this area.
- There are potential compliance risks associated with setting new policy.
- Others agree that regulation is essential to drive change and they agree that it is needed now but highlight that policy can't lead what is technical possible. Policy regarding setting tighter standards is required – such as advances on Tier 3 standards – seen as a key driver for industry development.
- Others highlight that all ports should have the same regulations. For example, at the moment Liverpool has lower standards than Felixstowe.
- In order to build momentum within air quality policy development there is a need for a club of partners to push with as the Air pollution agenda is currently slow.
- A tighter NO_x standard could bring forward alternative fuels as the costs of alternative fuels become more comparable to synthetic fuels and exhaust treatment.
- As noted above – it was considered that the ECA should be expanded – this would be a significant driver towards take up of technologies (fuel, electrification etc) for emission reduction.
- Policy around safety of fuel distribution, storage and handling is also important – e.g., HSE regulations about fuel handling.
- IMO rule set for advanced biofuels – could be a driver towards uptake of biofuels in the sector.
- There should be a lower tax on alternative fuels to encourage its use.
- The public perception of risk associated with possible use of nuclear power in shipping was also raised as something that could be addressed through policy.

Factors Affecting Timescales

- Both fleet and infrastructure have ~30 year life so what is built now needs to be compatible with operation in 2030s - stranded asset and tech lock in are real risks. This is why it has been indicated that LNG is not an option.
- However, others indicate that LNG will likely be important in the short term before 2035, as vessels and infrastructure are available (and on order) now, so could be taken up to some extent without major policy support.
- It was indicated that the timescales displayed on the mural boards seemed pessimistic and that air pollution could be addressed earlier.

Electrification of the vessel fleet

Benefits

- Wood team noted that the measure broadly covers different things – hybrid, battery power and electric propulsion – we've grouped all that together for the discussion.
- It was highlighted that battery/hybrid solutions are more appropriate for ships with varied operational profiles.
- There are other efficiencies associated with shaft line orientation and mass balance in vessel.

Barriers

- There is a resistance to moving away from today's technologies (ICE).
- There is a high cost of the machinery to overcome – key barrier for operators
- DfT CMP measure was developed with quite aggressive battery assumptions – a very ambitious scenario.
- It was raised that electrification of vessels is not competitive with liquid fuels (e.g., volume and cost of storage).
- Only 1 to 2 hour journeys possible at the moment meaning radical battery improvements are required to extend this. As a result, this measure cannot be used with deep sea fleets (although viable for tug boats, cruise ships and ferries).
- The training needs of future seafarers relating to electrification technology.
- Shoreside network capacity.
- The potential savings brought about by hybrid shipping may be limited in the long term.
- The exact location of a harbour (i.e., remote or not) may be limiting when it comes to the installation of the infrastructure needed for electrification.

Investment Requirements

- There is a massive initial capital investment with no reasonable business plan showing pay back without the input of societal costs of not doing so.
- Further investment and research is required for this to be applicable for more than just short-sea trips.
- There are high Infrastructure costs associated with the supply of electricity to ports and in large enough quantities.
- The use of containerised battery bank that could be swapped out (short trips) (a more modular approach) could disperse investment costs.
- Flow battery technology is available today but it needs new design for ship which requires investment.
- Through early piloting, it can be seen that upscaling can offer significant (estimated 80%) cost reductions.
- There are the additional costs associated with training for seafarers working with this new technology.

Policy Requirements

- There is a need for better definitions e.g., what is hybrid? (noted that CIMAC is working on a definition).
- Wider policy aspect concerning the sources of electricity provided for vessel electrification from the grid – need to support clean and renewable sources of electricity to ensure the emissions are not simply transferred to another sector.
- Targets for hybrid use / might not be as effective as an emission reduction.
- There is a need for a ruleset to allow 100% electric to be included in design and operation which would allow a level playing field.
- Incentives are needed for investment - e.g., capital allowances, exemptions from some of the per unit taxes.
- One of the biggest challenges for emissions is ships at anchor. It was suggested that mandating that ships switch to renewable sources of energy when at anchor could be beneficial e.g., batteries, fuel cells etc.

Factors Affecting Timescales

- The timescale of electrification of vessels will be determined by battery development timescales.
- The supply of trained/qualified crew will also influence the timescales of implementation.
- To reduce these timescales, it could be mandated that ships are berthed without using fossil fuels. Alternatively, a changeover to electrical systems could be an option but it may require a new build to try this out as the machinery plant will be significantly different to a conventional ship.
- Three Horizons Model was discussed (Diane Gilpin to provide further details).

Improved fuel efficiency measures

Benefits

- Wood team noted that the measure covers both technical and operational efficiency as a way to reduce fuel consumption and associated emissions.
- Improved fuel efficiency measures could bring about an improvement in air quality.
- Fuel savings brought about by improved fuel efficiency are really important as they can extend the range of any fuels used in combination with these measures.
- Air lubrication and a reduction in speed were identified as being important fuel efficiency measures as well as derating. However, derating is more expensive but has lower fuel consumption.
- Potential opportunity for the UK ship building sector regarding the delivery of new types of vessel and technologies.

Barriers

- It was noted that while there is the potential for cost savings via fuel efficiency technologies (wind/hull coatings), these measures face significant barriers to uptake through lack of demonstrators/Innovation funding.

- However, the effectiveness of fuel efficiency measures depends on its interaction with the fuel technology itself and some will be more effective than others for different types of vessel.
- Noted that there is little incentive for additional retrofit on top of what is already installed to comply with minimum standards for efficiency.
- Noted from DfT that the IMO (Energy Efficiency Design Index (EEDI)) sets very ambitions targets for improvements in efficient over time (40% improvement expected under BAU) – largely driven by less efficient stock being taken out of service and replaced with newer efficient vessels.
- It is expected that there will be scope for further improvement on top of this, driven largely by the climate emergency requiring greater ambition and faster adoption of zero-emission technologies.
- Others identified that parts of shipping industry have flagged issues about mandatory speed limits which may result in the need for more ships to be built. Although this was refuted as lower emissions still occur.
- Challenges of a variety of issues affecting arrival times – e.g., tides, weather conditions etc.
- Identified there is a need for a standardisation of process of ETA reporting etc.

Investment Requirements

- The investment costs for installation can be relatively substantial, but there are fuel savings which can provide a good business case.
- Noted that there is the potential for payback within ~4 years, that facilitates lease-financing and accelerates tech uptake.
- It was highlighted that more shipyards need to reduce the premium added to non-standard designs (i.e., new designs that are more efficient), as well as the potential to invest in the UK ship building sector to support the development of new vessel types.
- Ports require better use of data and sharing of this data to better manage the effects of efficiency measures. This is relatively low cost. For this to occur there should be improved coordination with shipping companies too.

Policy Requirements

- It was noted that policy and strong incentives are needed to increase the uptake of fuel efficiency measures as companies respond to policy drivers. This is supported by others who highlight that fuel efficiency reduces costs yet these measures are not being used enough. However, others noted that no policy measures would be required for this, but instead tax incentives for fuels would be more beneficial.
- Just in time arrival measures at ports are needed to reduce emissions associated with anchoring, however this is not always coordinated or supported properly.

Factors Affecting Timescales

- It was highlighted that timescales will depend on the policies themselves.
- For new international vessels timescale will relate to IMO EEDI minima.
- Complex software-based solutions based on AI and ML could be introduced as an implementation tool to optimise the efficiencies, but this comes with an undefined set of risks.

Renewably-powered vessels

Benefits

- Portsmouth has seen improved air quality under this measure.
- Lower OPEX for vessels can occur through reduced fuel usage.
- Some participants noted that this group of measures could come with a 1-10% fuel saving while others highlighted that fuel savings could be a lot greater than 10%. e.g., with Wind Ships. Could be up to 50% on new build smaller vessels.
- UK developed wind-assist technologies are 'shovel-ready', create green jobs in UK manufacturing and reduce emissions in the short term. Annual global market potential by 2050 £1,900-£2,100 GBPM pa per DfT Clean Maritime Plan).
- Technologies for this measure fit well on a tanker/bulk carrier but are of less benefit around coasts. Wind assist on smaller coastal vessels can save up to 50% fuel.

Barriers

- There is a lack of a driver at the moment and a variable return on investment.
- The high capital cost of new hulls was seen as a barrier.
- There is an urgent need to fund technology Demonstrators get the technologies accepted as standard in the global fleet, evaluated to be 10,700 ships.

Investment Requirements

- A large investment required for renewably-powered vessel e.g. a Wind Ship example given is around £20m to get a prototype.
- Investment requirement to retrofit wingsails on commercial demonstrators £5m – this is the first step towards 100% renewable powered by 2030.
- Conversion of vessels is prohibitive if electric (solar) propulsion is proposed so would need new designs.
- For several of the measures falling under the category of renewably-powered vessels, the need for ship system and design changes is apparent e.g. battery and electric systems, new hulls, which come at a cost (unspecified).
- Need both turnover and retrofit – penalty for retrofit to some extent (harder for vessels where they have higher cap ex).
- Noted that ships retrofitted with wind can offset the cost of additional capex with cost saving from fuel save – could be facilitated by lease-finance if required by ship owner.

Policy Requirements

- It was identified that international standards via the IMO are required.
- Currently, wind-assist certification is available from Class Societies.
- Others agree that these more stringent air quality standards and more expensive fuels would create a driver for renewables. Tax incentives for alternative fuels were also seen as a possible policy measure that could support the uptake of this measure.
- The need for a verification platform for measuring and reporting carbon emissions was raised.

- One of the biggest challenges for emissions is ships at anchor. It was suggested that mandating that ships switch to renewable sources of energy when at anchor could be beneficial e.g., batteries, fuel cells etc.
- Link to carbon pricing - fiscal requirement to take up renewables.

Factors Affecting Timescales

- None discussed.

Shoreside power

Benefits

- Shoreside power could lead to improvements in air quality and is a known technology.
- Shoreside power is useful for fishing fleets, leisure marine (cruise).
- It was noted that there are high benefits to costs even if damage costs (externalities) are included.
- There is an understanding that most emissions occur during manoeuvring at ports at via primary engines which are not affected by shoreside power (only auxiliary engines are replaced by shoreside power and this only constitutes 15-20% of total emissions).

Barriers

- The capital cost of infrastructure for shoreside power is high and there are no business plans that allow a return on investment from its use. However, some ports such as Southampton are to install shore power for a cruise terminal.
- It is often cheaper to run auxiliary engines than pay for electricity due to the high costs of electricity.
- There are issues with the electricity network capacity in the area around ports. Furthermore, an infrastructure must be capable of varying voltage levels as not all ships operate HV systems which adds to the cost and complexity.
- It was highlighted that shoreside power leads to higher and more 'peaky' electricity consumption profiles which, as well as energy market regulatory issues, make acquiring sufficient energy for a reasonable cost difficult.
- There is also a general lack of demand currently for this technology.

Investment Requirements

- Infrastructure and network costs are high. There is no working business case that does not include the societal costs of not using shoreside power.
- As an example of the high costs, it could cost £8m per berthside connect, with multiples of the total port cost if network reinforcement outside the gate.
- Government funding is vital for the uptake of shoreside power as can be seen from examples from around the world.

Policy Requirements

- Government policy is seen to be needed to drive port action.
- It was raised that the Government should take up CCC recommendation of financing cold ironing in ports.

- One requirement would be to replicate the Government co-investment models we see in Norway (among other countries) and we've seen indirectly occasionally in the UK.
- The requirement for mandating 'cold ironing' was raised (which is already done in certain ports in Norway). However, the problem with this is that not enough connection points are available and there are too many passenger ships at certain times of the year for this to work currently. However, others disagreed that mandating shore power should be done.

Factors Affecting Timescales

- Shore power at ports in the EU is being mandated imminently (by 2025) as part of the Green Deal.
- DfT CMP considers a target of having at least one fully electrified port by 2030 – seen as a realistic target (even conservative according to some).
- Wider application across all ports will be very dependent on adequate grid supply of (clean) electricity and installation of adequate infrastructure.

Electrification of port machinery

Benefits

- Strictly speaking sits under the NRMM sector but considered her as part of shipping sector.
- Electrification of port machinery could lead to improvements in air quality and is a known, available technology.
- Replacement of diesel would reduce direct PM emissions by >99%.
- It is a known technology for some applications and initial investment already happening (e.g., eRTGs).
- It was argued that the benefits are minimal as ports are a relatively low source of PM emissions.

Barriers

- The electricity network capacity is often insufficient for electrification of machinery (which is one of the biggest problems) and ports are often a large distance from a substation which can result in large costs.
- Electrified port machinery often has a lower performance compared to conventional diesel counterparts.
- Electrified port machinery is usually more expensive than diesel counterpart.
- Ports operate for 24 hours of the day. By introducing the need to charge equipment, productivity is lowered.
- The market is not currently mature enough to support change to electrified port machinery.

Investment Requirements

- Some participants identified that the required investments are large but not that much larger than the diesel equivalent. However, others pointed out that electrified machinery is often considerably more expensive than its diesel counterparts. However, it was also indicated that costs will reduce as ports go all electric rather than being safe with hybrid.
- There are further investment requirements related to the cost of electricity supply.

Policy Requirements

- It was raised that policies aimed at an end point, rather than at technology (e.g., power supply) may be better.
- Others highlighted that there should be support for investment decisions (e.g., green capital allowances, scrappage schemes).
- Others indicated that there should be exemptions on some of the tax elements per MWh cost to improve in use economics and investment cases.
- For any measures that are used, there should be a realistic timeframe for introductions to occur.
- Finally, not all participants agreed that policy requirements would be necessary.

Factors Affecting Timescales

- Timescales are affected by the availability of sufficiently capable kit - especially for more specialised equipment (where the UK is a small part of what manufacturers consider as a viable market).
- The timescales are also dependent on the lifetime of current diesel-powered port equipment (which could be 30+ years).
- The Ricardo NAEI update work is demonstrating that port equipment is a really low contribution to overall NRMM AQ emissions already, and detailed work in specifications identifies port equipment as less than 2% of local air quality. This is therefore seen as a much lower priority measure.

Aviation

Attendees

DfT, Spelthorne, Ecolyse, Manchester University, MMU, Luton Airport, Menzies Aviation, Heathrow Airport, Reigate and Bansted, Airbus, MAG, Sustainable Aviation, Rolls-Royce, Gatwick Airport.

Summary of Stakeholder Views

New aircraft main engine technology

Benefits

- Focus on the carbon agenda will have benefits for air quality.
- Unlikely to be significant reductions before 2030.
- From 2030 to 2050 slow reduction in $PM_{2.5}$ emissions, maybe totalling around 10% as co-benefit of CO_2-driven measures (assuming no specific regulations targeting $PM_{2.5}$).

Barriers

- Possible trade-offs in engine design between PM, fuel, NO_x. Fuel consumption/CO_2 emissions likely to be dominant driver.
- Lack of financial incentives related to low $PM_{2.5}$.
- Bigger aircraft operating longer flights will continue to use liquid fuels (mineral kerosene and/or Sustainable Aviation Fuel (SAF)) out to 2050.
- Need to consider co-benefits/concerns that people have around airports
- Important to consider trade-offs - detailed consideration of impacts/benefits.
- Regulation is by international consensus — limited UK control.

Investment Requirements

- Whole project - Napkin is currently is currently being worked on.
- Hydrogen, electric and hybrid-electric engines under development.
- More research into lubricants needed. These are potentially a source of particulates.

Policy Requirements

- Currently there is a lack of regulatory drivers relating to PM, although a newly agreed regulation for non-volatile PM (nvPM) will help drive designs.
- Regulation is by international consensus — limited UK control.

Factors Affecting Timescales

- Commercial hydrogen engines likely to be introduced for short-haul around 2030 or 2035. Electric engines likely to be limited to very small aircraft / short flights, from around 2030.
- Liquid fuel will be dominant for bigger, longer flights up to 2050.
- See A4E report on journey to net zero — due mid-February.
- Advanced combustors cannot be retrofitted.

Reduced sulphur in aviation fuel

Benefits

- Sulphur is responsible for roughly half of main-engine $PM_{2.5}$ emissions. Reducing sulphur in aviation fuel will lead to proportional reductions in this contribution.
- Potential disbenefits from extra energy consumption and costs associated with desulphurising mineral kerosene.
- Potential disbenefit from unilateral UK action, with price differentials encouraging tankering.
- May be delivered in part through increased use of SAF (which is zero-sulphur).
- Likely to be a reduction of a few percent in sulphur content by 2030 due to introduction of SAF. Greater reductions achievable by 2050 (up to 100%?).

Barriers

- Regulation is by international consensus — limited UK control.
- Lack of investment support. Need to make it clear that plants etc. can be invested in (both SAF and desulphuring mineral kerosene).
- Cost (CAPEX and OPEX).
- Availability.

Investment Requirements

- Strong investment in desulphurisation plant/SAF.

Policy Requirements

- Strong policy is required.
- Regulation/policy is by international consensus — limited UK control.
- Need to make sure that sulphur is not moved from other fuels to aviation — needs improved standards.
- Sustainable aviation fuels roadmap lists the policy asks (https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_FuelReport_20200231.pdf). Need policy signals to help investment/upscaling.
- Defra should align with DfT and BEIS on SAF policy.

Factors Affecting Timescales

- SAF uptake driven by CO_2.
- Global COP (later in 2021) target: 10% SAF by 2030.
- Existing engines may require certain level of sulphur and aromatics for lubrication. Engines currently in production mostly do not. Suggestion that all fleets capable of operating on 100% SAF (i.e. zero sulphur) by 2025–2030? Check consistency.

Aircraft operator measures to reduce engine running time on the ground

Benefits

- Cost savings, as well as CO_2 and NO_x savings.
- Some measures such as reduced engine taxiing (RET) already implemented due to benefits.
- Possible OPEX benefits but potentially substantial payback time.
- Possible $PM_{2.5}$ reductions from aircraft on the ground of the order of 10% by 2030.

Barriers

- Cost (CAPEX) for installation of PCA, FEGP.
- Limitations on RET on taxi-out due to engine warm-up/stabilisation requirements and pilot workload (safety implications).

Investment Requirements

- Implementation investment, e.g., green stands.
- Electric taxibots, pushback tugs and other equipment.

Policy Requirements

- Mandatory PCA is the only way that it will happen at some airport, because there is no economic case.
- Electricity cost is high and regulated. Mechanism for recovering costs from third parties (including infrastructure).

Factors Affecting Timescales

- Driven by investment and payback periods.
- Some measures already being undertaken (e.g., RET, reductions in APU running times).

Airport and ATC measures to reduce engine running time on the ground

Benefits

- Co-benefits for cost, CO_2, NO_x, noise.
- See carbon trade-offs paper, supporting information for DfT Aviation 2050 green paper.
- Use Sustainable Aviation Roadmap and DfT studies to consider benefits.
- Potential reductions of around 10% by 2030, ambitious level of 20% by 2050.

Barriers

- Cost of infrastructure, development and implementation.

Investment Requirements

- Collaborative Decision Making is a regulatory requirement at some airports. Quite expensive (CAPEX but savings on OPEX?).
- Business cases may detail the costs and benefits.

Policy Requirements

- More thought on Independent Parallel Approaches (IPA), particularly new aircraft.
- Push-back Control - specific example of a measure on aircraft handling on the ground. Smarter system - digital tower.
- Particular documentation emerging from Europe over the next few months - European Roadmap in February and ATAG work at global levels.
- Measures in the air - curved approaches. Near airspace changed. Better management of airspace.

Factors Affecting Timescales

- Time to develop procedures, meet regulatory requirements and implement.

Alternatively powered APUs

Benefits

- Potential elimination of $PM_{2.5}$ emissions from APUs.
- Co-benefits for CO_2, noise, NO_x.

Barriers

- Regulation is by international consensus — limited UK control.
- Preference for single fuel, i.e., all systems powered by kerosene.
- Not seen prominently as a big issue - so may not be a focus of research.

Investment Requirements

- R&D and development.
- Safety and certification.
- Costs.
- Recharging or refuelling infrastructure.
- Consider exhaust treatment (e.g., DPF) instead (weight penalty means this may be impractical).

Policy Requirements

- Regulation required.

Factors Affecting Timescales

- Unlikely to happen in currently foreseeable timescales.
- SAF more likely to be driver of zero-carbon.

Improved brake pad materials

Benefits

- Eurocontrol: Up to 63% of $PM_{2.5}$ from Brakes https://www.eurocontrol.int/sites/default/files/library/034_Aircraft_Particulate_Matter_Emission_Estimation.pdf
- Improved wear could reduce maintenance costs.

Barriers

- Regulation is by international consensus - limited UK control.
- Safety-critical. Currently brake pads are highly managed.
- Expensive carbon brake pads are required for aircraft. The manufacturers and airlines both try to protect these so though they wear as little as possible. May be small opportunities to limit low power operation but landing is a safety requirement so nothing there.
- Uncertainty in emissions estimates.
- Disbenefits if extra weight.

Investment Requirements

- R&D.
- Safety and certification.

Policy Requirements

- Regulation is by international consensus - limited UK control.

Factors Affecting Timescales

- Unlikely on foreseeable timescales.

Improved tyre materials

Benefits

- Possible reductions.

Barriers

- Regulation is by international consensus - limited UK control.
- Safety-critical. Currently highly managed.
- Uncertainty in emissions estimates.

Investment Requirements

- R&D
- Safety and certification.

Policy Requirements

- Regulation is by international consensus - limited UK control.

Factors Affecting Timescales

- Unlikely on foreseeable timescales.

Low-emission ground support equipment (GSE)

Benefits

- Potential elimination of $PM_{2.5}$. Potential reduction of around 30% by 2030, up to 100% by 2050.
- Co-benefits for CO_2, NO_x, noise, workforce exposure. (Frankfurt example of electrification to reduce NO_x levels to permit other expansion.)
- Reduced maintenance costs, greater reliability.

- Potential OPEX savings.

Barriers

- Some plant types not yet available.
- Contractual arrangements.
- Cost (CAPEX). Could be reduced by fleet sharing.
- Safety concerns, e.g., hydrogen; use of electric plant around fuel vapours. Liability and insurance concerns.

Investment Requirements

- Infrastructure for charging or hydrogen distribution.

Policy Requirements

- Removal of tax break for red diesel.
- LEZ at Heathrow.
- Strong policy signals required to encourage shift.
- Local application — international agreement not needed.

Factors Affecting Timescales

- Fleet turnover 12–15 years lifetime.
- Most plant available now but supporting infrastructure required.

More efficient use of ground support equipment (GSE)

Benefits

- Potential reductions of around 2%.
- Co-benefits for CO_2, NO_x, noise, workforce exposure. (Frankfurt example of electrification to reduce NO_x levels to permit other expansion.)
- Reduced maintenance costs, greater reliability.
- OPEX savings.

Barriers

- None discussed.

Investment Requirements

- Operator training and development of best practice.
- Use of telematics to understand usage patterns and develop improvements.
- More on stand services (fuel, fixed ground power, pre conditioned air, etc), including mobile PCA units.

Policy Requirements

- Removal of tax break for red diesel.
- Local application — international agreement not needed.

- Zoned stands to reduce GSE/driving between stands.
- Share smaller, more common GSE at stands between operators.
- Share larger, less used GSE between operators.

Factors Affecting Timescales

- Red diesel tax break ends 2022.
- Operational changes can be implemented as soon as they can be arranged.

Surface access: reduced landside car use

Benefits

- Potential reduction in car numbers using airports of the order of 10%.

Barriers

- Capacity and access. Risk of losing a third of rail access at Manchester Airport.

Investment Requirements

- Very substantial investment required to build up public transport share, including installing new infrastructure.
- Links with public transport schemes.
- Need for airports to be seen as multimodal hubs - provision of charging etc. infrastructure.

Policy Requirements

- Vehicle access charges - all three MAG airports and several others. See MAG CSR - new concept for car parking - reinvest in public transport. Small investment in schemes rather than big scheme at the moment.

Factors Affecting Timescales

- Public resistance to public transport. At many airports, limited by public transport accessibility and capacity.

Industry

Attendees

EA, MPA, BEIS, UKOOG, CIA, Tata Steel, British Steel, Make UK, Liberty Steel UK, British Sugar), Paul Hardy British Sugar, ALFED, British Glass, BCF, Energy UK, AMPS.

Summary of Stakeholder Views

Fuel Switching from Fossil fuels to BECCS

Benefits

- This measure is largely driven by major benefits it delivers in terms of carbon reduction, with $PM_{2.5}$ emission reductions as a co-benefit.
- It was agreed that benefits would be minimal if replacing gas, with greater benefits for replacing coal and oil. CCS technology requires low PM and low NOx emissions. Although it

was noted that SCR leads to ammonia slip and secondary $PM_{2.5}$ formation (albeit this should be small in comparison to NO_X emission reductions).

- It was highlighted that CCS clusters are needed to allow carbon capture from smaller combustion units and that the waste and cement sectors in particular could deliver BECCs.

Barriers

- Limited space on sites for CCS plants.
- Not yet technically viable for certain sectors (e.g., glass).
- Distance of some sites to proposed CCUS industrial clusters.
- Fuel quality issues, such as poisoning of carbon capture catalysts by biofuel impurities.
- It was highlighted that in the steel sector, coal input is as a reductant for iron ore, not principally as a fuel. Some trials have taken place replacing a small proportion of coal/coke with wood etc., but opportunities are limited.
- Emissions associated with transport and the source of biofuels. Life-cycle analysis is required.
- Unintended consequence of use of CCS. Emissions of amines with potential health effects.

Investment Requirements

- Further research required.
- It is understood that BEIS are working on CCUS Business Models.
- Development of production capacity for biofuels, as well as storage and transport infrastructure.

Policy Requirements

- Establish BAT for CCS considering all emissions.
- Policies are required on best use of biofuels, including support for biofuel transport and storage infrastructure.
- Current sustainability regulations from power sector needs to be transferred to industrial schemes to avoid unsustainable practises.
- Policies regarding the composition of scrubbing solutions.

Factors Affecting Timescales

- Likely to depend on the availability of government incentives.
- Not an option before 2030 for the glass industry. depends on investment cycles of the site and proximity to clusters. Glass furnaces are gas or gas/electric hybrid. Replacement of gas with biofuel probably good for carbon emissions, but unlikely to have benefit for particulates.
- Not considered to be a viable option for British Steel.

Fuel Switching from fossil fuels to hydrogen and electricity

Benefits

- Potential benefits although further research and trials are required. For example, GlassFutures carrying out trails with a hydrogen fired furnace. Hydrogen may be an option for certain parts of the steel process (reversing historic moves away from hydrogen because of safety concerns).

Barriers

- Uncertainty on supply outside of the clusters. Hydrogen supply to industry would need to be cost-effective and available when needed.
- Various issues with combustion parameters were discussed. For example, higher combustion temperature results in higher thermal NOx emissions which would need to be abated. The higher temperature may mean that modifications are required. There are particular issues for glass manufacture (flame luminosity and heat transfer).
- Safety concerns around hydrogen storage. Hydrogen Storage is covered by COMAH regulations. This will be off-putting for many industries as it brings a regulatory and cost burden.
- One issue raised is that production of blue hydrogen could increase net PM emissions.

Investment Requirements

- Investment in hydrogen production.
- Some upgrade of existing infrastructure materials may be needed to ensure no hydrogen embrittlement issues.

Policy Requirements

- Several stakeholders mentioned that policy is required to govern where hydrogen is used first (when the supply is at a relatively low level) and ensure that hydrogen is used at the most appropriate sites/purposes.
- Clear policies on the use of hydrogen and support regarding costs and infrastructure.
- Regulatory framework covering HSE for blue and green hydrogen.

Factors Affecting Timescales

- Investment cycles for furnaces, reducing the speed of implementation (12-20 years).
- Several stakeholders suggested that use of hydrogen is likely for refineries by around 2030 but unlikely elsewhere outside hydrogen/CCS clusters by 2030.

Fuel Switching coal-fired to gas-fired

Benefits

- Minimal for refineries as understood that all are now gas-fired.

Barriers

- Coke also required to add structure in the furnace, not just a reductant.
- Relevant to fuel switching, the use of secondary liquid fuels, as back up fuels to gas for Coal fired, works arising gases fuel (e.g., Steelworks).
- Note that in the steel sector, coal input is as a reductant for iron ore, not principally as a fuel.

Investment Requirements

- How significant is this contribution and would any investment be cost effective? Food and drink is the third largest industrial source of $PM_{2.5}$
- Use of cleaner back up fuels?

- Some plant are sufficiently close to gas grid but insufficient capacity to supply enough gas

Policy Requirements

- Food and Drink Industry BREF. (2023) - published before UK left the EU therefore would be automatically transferred to UK legislation.
- Coal to biomass more likely for off-grid low Carbon. Set standards for new biomass.

Factors Affecting Timescales

- Not discussed in detail.

NRMM Regulation / Fuel Switching for NRMM

Benefits

- It was agreed that Stage V NRMM regulations deliver significant PM emission reduction benefits (~98%) and will also reduce NO_X emissions.

Barriers

- Electrification is not likely to be feasible for the largest machines. Many stakeholders from different industries mentioned that there are no alternatives to diesel powered equipment and do not expect there to be soon.
- Performance of alternatively fuelled engines when starting and stopping a lot.
- Cost of electricity.

Investment Requirements

- Increased electricity supply and infrastructure if this is to be used on a wide scale.

Policy Requirements

- Procurement policies and new procurement contracts or construction contracts to drive the use of plant with Stage 5.
- It was mentioned that there is a lack of clarity on who has regulatory responsibility for NRMM Regulations.

Factors Affecting Timescales

- April 2022 removal of tax exemption for red diesel will be a driver for changes in NRMM. Though some stakeholders mentioned that it will only drive change if alternatives are available – not currently the case so will only add costs.

Industrial Emissions Directive

Benefits

- It was agreed that dust abatement measures will reduce primary $PM_{2.5}$ as well (although percentage reduction is likely to be lower than for larger particles).
- In general, for most industrial processes it was felt by some stakeholders that it is hard to see how $PM_{2.5}$ emissions could be reduced significant, even if more data is gathered.
- Likely to be very few opportunities to make further reductions of $PM_{2.5}$ from energy from waste (EfW) plants despite the total particulate matter limit (TPM) reducing from 10 to 5 mg/m^3, since most plants are already operating well below this (1 mg/m^3 or less) and there is no obvious

technology which could be fitted which could reduce emissions yet further. In any case, EfW plants are unlikely to be a priority as emissions are low and it is a small source in the NAEI.

Barriers

- Stakeholders agreed that there is a need to better understand $PM_{2.5}$ emissions. Particular issues mentioned were ratio to PM_{10} and relationship with VOC emissions.
- The lack of reliable stack monitoring for $PM_{2.5}$ was mentioned by several stakeholders.

Investment Requirements

- It was mentioned that investment costs for more complex technology could be excessive for certain industries.
- Potential costs to add tertiary abatement to remove the smaller particles.

Policy Requirements

- UK needs to consider policy implementation after Brexit, including continued improvements, whilst also considering competition with European industry.
- Part A processes in general have been successfully regulated and delivered significant emission reductions under the IED/BREF framework. There is a need to focus on unregulated / poorly regulated sectors.
- Several stakeholders mentioned that current emission standards in BREFs are based on total particulates rather than fine particulates. There is a need for improved consideration of $PM_{2.5}$ based on evidence that needs to be collected first.

Factors Affecting Timescales

- Several stakeholders mentioned that the UK BAT process is currently being determined (industry views are being sought in a Defra consultation) and this will affect BREF revision timetables (several of which are currently being revised including Food, Drink and Milk (FDM) Industries and changes in individual industries.
- It was mentioned that reduction in VOCs (through STS BREF BAT compliance) will result in lower $PM_{2.5}$ emissions.

Medium Combustion Plant Directive (MCPD) and specified generator regulations

Benefits

- None highlighted.

Barriers

- Several stakeholders mentioned that retrofit is expensive (SCR / SNCR) and raised concerns that it is necessary to ensure that technologies that are invested in need to be suitable for the long-term.
- The unintended consequences/impact of abatement technologies like SCR were highlighted.

Investment Requirements

- Cost of retrofitting. Is it worth it, if long-term need to change to other technologies?

Policy Requirements

- Centralised collation of emission information from MCPD testing centrally.

- Stakeholders expressed preference for equipment type approval rather than permitting for small combustion plant. There would need to be a replacement deadline included in this policy to ensure old plant is not retained in service.

Factors Affecting Timescales

- Several stakeholders mentioned that CHP & related investments are typically viewed as longer-term (20 year +) investments, so long-term thinking about the right technology choices (e.g. abatement, new technology) is required.

Regulation for plant below 1MW

Benefits

- It was mentioned that the impact of plant of this size could be very high, so benefits of regulation will be high (in particular in relation to population exposure). Others questioned the scale of benefits and whether the regulatory burden would be worth it.

Barriers

- Several stakeholders mentioned that the regulatory burden would be large, and it was also mentioned that a focus on moving away from biomass in general would be a better approach.

Investment Requirements

- Development of a regulatory regime.

Policy Requirements

- Several stakeholders mentioned that policies should focus on a general move away from biomass.
- Minimum emission height requirements to reduce exposure.
- Type approval of design as opposed to permit to operate should be considered for this power range.
- Several stakeholders mentioned the need for a registration scheme for installers and servicers with requirements for installers to be responsible for the plant to be installed correctly.

Factors Affecting Timescales

- Development of a regulatory regime.

Upgrade to different technologies / Improving existing technologies / Upgrade BAT

Benefits

- It was highlighted that the establishment of emission limits does provide a level playing field as all have to comply with them by a specific date, therefore all have to retrofit or replace technology.

Barriers

- Several stakeholders mentioned that retrofit is often expensive and challenging (e.g., space, compatibility etc.).
- Several issues with wet scrubbers were mentioned, including water treatment requirements and reduced emission temperatures.

- All technology changes proposed need to be viewed in the context of all emissions. Lowering some should not increase others (e.g., higher energy loading).
- It was also discussed that technology/investment requirements in the UK need to harmonious with other non-UK competitors in the market (e.g., EU production, production from China), otherwise the increased costs of emissions regulation in the UK will make UK industry uncompetitive.

Investment Requirements

- Abatement technologies. Several stakeholders highlighted that these can be expensive and that it is essential to make sure that investment is not stranded by future technology/policy developments (e.g., transition to hydrogen).

Policy Requirements

- Support to cover extra investment to go beyond current BAT.
- Several stakeholders highlighted the need for clear government policies on future technologies to avoid wasted investment.

Factors Affecting Timescales

- Will depend on government policy decisions.

Improve stationary sources monitoring

Benefits

- There was general agreement that reliable methods for Continuous Emission Monitoring of $PM_{2.5}$ are not available. Benefits may also be minimal as particulate emission rates are very low for a lot of industrial processes. It was mentioned that the Source Testing Association (STA) are currently looking at ways at which $PM_{2.5}$ monitoring can be improved.
- It was highlighted that there may be many sites where a lot of $PM_{2.5}$ monitoring has taken place and others where this has not been done as there have been no requirements. These sites would benefit from a better understanding of emissions.

Barriers

- Lack of Continuous Emission Monitoring (CEM) techniques.
- Additional costs of $PM_{2.5}$ monitoring if this was required for the first time.
- Costs may be disproportionate for certain industries (e.g., chemical).
- Difficulties in calibrating CEMS at low emissions levels are exacerbated in cement manufacture where the particulates are non-uniform.

Investment Requirements

- Would require investment in new monitoring techniques. The currently used light-scattering ambient monitors are cheap to install and maintain. However, a network is typically required to get useful results.
- Need to improve emission inventories using monitoring data to support policy development.

Policy Requirements

- BREFs should have an increased focus on $PM_{2.5}$. However, data and evidence are required to establish best practice.

- Requirement for sites that have never been monitored to be monitored to validate modelled assumptions. A $PM_{2.5}$ monitoring requirement could be introduced at permit review/new permits.
- Enhancement of emission inventories to target improvements. It was highlighted that many emission factors are outdated and don't reflect current abatement. The Cement sector has just agreed with EA to report $PM_{2.5}$ each year under PI reporting. This guidance is being implemented this year.

Factors Affecting Timescales

- Development and standardisation of monitoring techniques, development of new guidance and development of best practice.

Improve fugitive emissions capture

Benefits

- It was generally agreed that a focus on total particulates probably helps with $PM_{2.5}$ concentrations - drives everything down.

Barriers

- Lack of data on size fractions in the mineral industry. Impression in that road is a more important source of $PM_{2.5}$.
- Conflict with other legal requirements to allow for rapid reduction in by-product stockpiles.
- Source Apportionment is very difficult. Lots of diesel emissions recorded near roads.
- Enclosure can be expensive and increase the environmental load in other ways (e.g., energy costs). The appropriateness of any enclosures needs to be considered.
- The available $PM_{2.5}$ data from minerals sites, typically obtained using multiple optical monitors, indicates that concentrations are not so much linked to site activities as to prevailing winds in relation to local road traffic sources.

Investment Requirements

- Light-scattering monitors have been very useful in helping to manage fugitive emissions.
- A lot of policy decisions are made from NAEI rather than the EA's Pollution Inventory. For refineries sector, the NAEI assumptions are generally derived by mass balance, rather than onsite measurements. There are methodologies to use emissions factors, but it is considered that site-specific validation would be useful to obtain a more accurate understanding.
- For cement, NAEI values for stationary sources emissions of particulates are not always consistent with operator reported PI values. For some sites, emissions are overestimated and there also appears to be some double-counting. Some stakeholders consider that the NAEI methodology needs further investigation.

Policy Requirements

- It was generally agreed, given the focus on $PM_{2.5}$, that it should be included in future BREFs as it is generally lacking in current BREFs.
- Introducing a requirement for enclosures, such as for waste sites, in permits would reduce fugitive emissions. This has been successfully employed in London.

- Alignment of the EA PI with the NAEI was discussed. The PI only covers emissions from EA-regulated industries, and reflects data from operators. NAEI data, which includes LA-regulated emissions, are often estimated rather than monitored.

Factors Affecting Timescales

- Timescales for amendments to emission inventories. The EA is currently reviewing $PM_{2.5}$ data and emissions from all sectors.

Behavioural change

Benefits

- Refineries Sector transition to hydrogen (long-term) is likely to lead to significant particulate reduction from combustion of hydrocarbon. However, there is a need to be careful about NO_X emissions if hydrogen is used.
- Flue gas cleaning for CCS may require a high degree of particulate reduction.

Barriers

- It was highlighted that carbon reductions are more about technology advancement, infrastructure & distribution than behaviour.
- A concern was raised that life-cycle emissions are not considered (e.g., including imports) so policy is skewed to de-industrialisation and displacement of manufacturing (and hence emissions) overseas.
- Price of electricity is a barrier for aluminium industry electrification. High prices could destroy the industry without strong policy support.
- Huge amounts of water vapour emissions associated with hydrogen transition.

Investment Requirements

- Hydrogen is being considered for several industries (e.g., glass, cement). It was agreed that a lot of investment in the network, supply and infrastructure is required for this to be viable.
- It was agreed that electricity capacity and infrastructure development is required for wide-scale uptake.

Policy Requirements

- It was agreed that government policy decisions need to be made. It is understood that the industrial decarbonisation strategy was coming in 2021.
- Government decision on when hydrogen becomes a public utility.
- The right incentives and support are needed. There are potentially significant cost implications and so competition impacts in relation to other countries.

Factors Affecting Timescales

- Government decisions on future energy sources e.g., hydrogen. There is precedent of gas transition in the 1970s, which could inform timescales.

Energy efficiency and waste heat recovery

Benefits

- It was agreed that decisions at sites are taken in relation to costs, so they are generally energy efficient already. What has been considered possible has been implemented (e.g., pre-heating fluidising air, insulation, using CHP, switch from oil to gas).

Barriers

- It was agreed that the lack of availability of heat networks means that there is no outlet for waste heat (for example, minerals are best worked where they are found which may not be proximate to heat networks). Fragmented industries make heat networks difficult to establish. There is also a lack of funding for local authorities for heat networks.
- Some sites in energy intensive sectors are unaware of some inefficiencies - steam leaks, compressed air etc.
- Cost of Energy recovery for EAF and Large Re-heating furnaces. IEFT Feasibility concluded not currently viable in relation to IRR, Payback.
- Heat recovery can have cross-media effects due to temperature changes e.g., prevention of dioxin formation. There are also barriers in relation to SCR heat requirements.

Investment Requirements

- Investment in establishment of heat networks.
- Energy and heat surveys by independent knowledgeable auditors.

Policy Requirements

- Low interest CapEx or tax benefits to heat network projects. BEIS reported on this a few years ago.
- Government Net zero initiatives will drive energy efficiency.
- Need for better heat network policies and local support (including financial) for integration into heat network.
- IETF already available for Energy Efficiency Deployment.

Factors Affecting Timescales

- Government policies and incentives for integration into heat networks.

Construction

Attendees

Construction Products Association, University of Surrey, Construction Equipment Association, Imperial College London Environmental Research Group, Caterpillar, Mineral Products Association, Cold Chain Federation, Construction Plant-hire Association, JCB, Costain, HS2, Emissions Analytics, Energy Saving Trust, Defra, Building Research Establishment.

Summary of Stakeholder Views

New Stage V NRMM

Benefits

- There was general agreement that this measure will substantially reduce emissions of $PM_{2.5}$ from NRMM over the next 10–15 years, and will be the major driver of reductions over that timescale. Diesel particulate filters (DPM) are the only practical way to meet the particle number (PN) requirements of Stage V, and lead to consequent reductions in particle mass emissions.
- Full flow DPFs are estimated to reduce $PM_{2.5}$ mass emissions by about 95–97% (some say 90%, others 99%). However, manufacturers will tend to work to meet the regulatory limits rather than trying to go beyond them. Reductions in mass emissions are driven by requirement to reduce PN.
- Stage V also includes reductions in emissions of NO_x. Tailpipe abatement typically combines DPF and SCR.

Barriers

- Some additional cost for new plant.
- Risk of stranded assets if alternative technologies (e.g., hydrogen, electric) come to dominate. Disincentive to invest in latest equipment if it may quickly become obsolete. Hazard for early adopters being punished for trying to do the right thing.

Investment Requirements

- Some investment required, but may be largely driven by natural fleet turnover.

Policy Requirements

- Pressure from government agencies and large companies to require their contractors to meet high standards of emission control. London NRMM LEZ, HS2 requirements, etc. Expect London to require Stage V by 2030.
- Major developers see it as part of CSR and good PR, especially perhaps on contentious projects.
- Requirements for latest emission standards may be geographical (e.g., London NRMM LEZ) or per project (e.g., HS2 contracts with contractors).
- May need regulatory enforcement from local authorities.
- Expectation that natural fleet turnover will be the major driver, unless there are new policy measures.
- Annual Investment Allowance — capital expenditure offset against accounts for the year. Proposed to be reduced to £200k. But likely keeping at £1m — incentive for plant owners/contractors to invest in new equipment. Budget on the 3rd March.

Factors Affecting Timescales

- Some pre-Stage V plant already has DPFs, but not much.
- DPF technology is reasonably mature but further improvements likely as manufacturers gain experience.

- Natural fleet turnover is around 10–15 years. Lifecycle is typically around 5 years with a major hire company before being sold on to second-tier and then smaller operators, and finally often being sold overseas.
- Scope for driving faster uptake with suitable measures.
- Expect Euro 7/VII for road vehicles to be effectively duplicated as Stage VI in due course (e.g., requirement for RDE).

Retrofit to Stage V NRMM

Benefits

- Can achieve close to Stage V standard on older plant, at much lower cost than buying new plant.
- Typically, a package with improvements to NO_x emissions (SCR).
- Operators able to use older plant on projects where the highest standards are mandated.

Barriers

- Some real-world examples but still not mature. Availability for mass market not yet there. May not be a one-size-fits-all unit, so higher cost than bus/coach retrofit market.
- Only likely to be cost-effective for specialist equipment where there is not enough plant that meets latest standards to meet project demands. For more run-of-the-mill plant, hire companies can buy new plant for projects in London/HS2, and move older plant onto projects that do not demand latest emission standards.
- Needs to be certified (e.g., by EST).
- Integration with OEM engine control systems.

Investment Requirements

- Cost. Only likely to be cost-effective for specialist plant.

Policy Requirements

- General drivers for latest emission standards (see above).
- All exemptions have now expired in London LEZ.

Factors Affecting Timescales

- Some real-world examples but still not mature.
- Short window between maturity of technology and still having enough older plant to be worthwhile — limited time for payback on investment.

Training for behavioural changes

Benefits

- Co-benefits for NO_x, noise, carbon.
- Benefits for workforce occupational exposure.

Barriers

- Little interest at grassroots.

- Often rental plant, so less motivation for operators to care for it long term.
- Cheapest plant may be incorrectly specified for the required task (e.g., overpowered) and so less efficient.

Investment Requirements

- Build supporting technology into equipment, e.g., start-stop is mostly there to cut off engine when operator not in driving seat.
- Telematics to provide supporting information. Scope for gamification / competition / rewards for good operator practice.
- Rapid development and promulgation of training and best practice through existing frameworks, e.g., Supply Chain Sustainability School, Considerate Constructors Scheme, Institute of Civil Engineers, FORS.
- Operator aids e.g., GPS can improve efficiency and reduce OPEX costs.

Policy Requirements

- Scope for fuel savings is a significant driver.
- Positive reinforcement and incentives from clients.

Factors Affecting Timescales

- Imperial College developing NRMM operator's manual.
- Grassroots policy engagement and adoption of new working practices.

Remove tax break for red diesel

Benefits

- No direct benefits, but a driver for changes elsewhere.
- Raises awareness of fuel costs.
- Starts to create level playing field with other green technology and fuels.

Barriers

- Already implemented.
- Extra costs for operators may reduce ability to invest in newest equipment.
- Lack of current alternatives to diesel — extra costs with limited scope to reduce them. Especially certain sectors such as quarrying, TRUs.

Investment Requirements

- Drives investment in fuel efficiency measures.
- If plant are moving away from diesel, need investment in alternatives (plant, infrastructure, fuel/electricity distribution).

Policy Requirements

- In effect from 2022 unless postponed in 2021 budget.

Factors Affecting Timescales

- Comes into effect April 2022, but industry is budgeting and adapting already.

Electric NRMM — non-construction sites (warehouses, ports, airports etc.)

Benefits

- Potential elimination of tailpipe $PM_{2.5}$.
- Co-benefits for NO_x, CO2, noise.
- Potentially reduced OPEX.

Barriers

- Availability of specialist and large plant.
- Risk of stranded assets if alternative technologies (e.g., hydrogen) come to dominate. Disincentive to invest in latest equipment if it may quickly become obsolete. Hazard for early adopters being punished for trying to do the right thing.
- Cost (CAPEX).
- Lack of policy drivers.
- UKPN seen as a barrier.

Investment Requirements

- Lack of available grid power. Infrastructure may need additional supply to site as well as distribution around the site. However, for fixed sites this is deliverable given possibility of long-term payback.
- New plant.

Policy Requirements

- Other than diesel tax, no policy measures on horizon.
- Participants agreed that government should not try to “pick winners” between electric and hydrogen as long-term solution, but this present problems for operators trying to invest.
- Mix of opinions between participants whether hydrogen or electric was a more likely long-term replacement for diesel.
- Electric plant does not feature in NRMM LEX from 2014 — needs to be updated.
- Likely to be driven by carbon emissions rather than air quality.

Factors Affecting Timescales

- Lack of policy drivers.
- Availability of plant, CAPEX costs, infrastructure requirements.
- Lifetime of existing plant 10–15 years.

Electric NRMM — construction sites

Benefits

- Potential elimination of tailpipe $PM_{2.5}$.
- Co-benefits for NO_x, CO2, noise.

- Potentially reduced OPEX.

Barriers

- Availability of specialist and large plant.
- Risk of stranded assets if alternative technologies (e.g., hydrogen) come to dominate. Disincentive to invest in latest equipment if it may quickly become obsolete. Hazard for early adopters being punished for trying to do the right thing.
- Cost (CAPEX).
- Lack of policy drivers.
- UKPN seen as a barrier.

Investment Requirements

- Particular challenges with financial viability of installing charging infrastructure on temporary sites. More imaginative solutions required for getting energy onto site.
- New plant.

Policy Requirements

- Participants agreed that government should not try to "pick winners" between electric and hydrogen as long-term solution, but this present problems for operators trying to invest.
- Mix of opinions between participants whether hydrogen or electric was a more likely long-term replacement for diesel.
- Electric plant does not feature in NRMM LEX from 2014 — needs to be updated.
- Policy changes to make is quicker and easier to get power onto sites (internal barriers within DNOs or UK power network operators)
- Likely to be driven by carbon emissions rather than air quality.

Factors Affecting Timescales

- Lack of policy drivers.
- Availability of plant, CAPEX costs, infrastructure requirements.
- Lifetime of existing plant 10–15 years.

Hydrogen NRMM

Benefits

- Potential elimination of tailpipe $PM_{2.5}$.
- Co-benefits for NO_x, CO2, noise.
- Potentially reduced OPEX.
- Perhaps more feasible for large plant than electric.
- Scope for interfacing construction/NRMM sector with other parts of the hydrogen economy.

Barriers

- Availability of specialist and large plant.

- Risk of stranded assets if alternative technologies (e.g., hydrogen) come to dominate. Disincentive to invest in latest equipment if it may quickly become obsolete. Hazard for early adopters being punished for trying to do the right thing.
- Cost (CAPEX).
- Lack of policy drivers.
- UKPN seen as a barrier.

Investment Requirements

- Infrastructure for generation and distribution of hydrogen.
- New plant.

Policy Requirements

- Participants agreed that government should not try to "pick winners" between electric and hydrogen as long-term solution, but this present problems for operators trying to invest.
- Mix of opinions between participants whether hydrogen or electric was a more likely long-term replacement for diesel.
- Likely to be driven by carbon emissions rather than air quality.

Factors Affecting Timescales

- Lack of policy drivers.
- Availability of plant, CAPEX costs, infrastructure requirements.
- Lifetime of existing plant 10–15 years.
- Innovative solutions are being developed.
- Expect to see hydrogen plant being introduced in about 10 years, and much more common by 2050.

Biofuels, HVO etc. in NRMM

Benefits

- Expected to be approximately neutral for $PM_{2.5}$ emissions. Where plant is fitted with DPFs, emissions likely to be low.
- Benefits are mainly for carbon emissions.

Barriers

- Availability of fuel.

Investment Requirements

- Fuel production and distribution.

Policy Requirements

- Driven by carbon emissions requirements.

Factors Affecting Timescales

- Driven by carbon emissions requirements.

Prevent removal/defeat of emission control devices

Benefits

- Manages control of emissions of air quality pollutants (NOx, PM).
- Widely supported in sector.
- Prevalence highly uncertain.

Barriers

- Many providers. Not illegal, so all above board and respectable.
- Need for legislation to control practice.
- ECV does not control against tampering.
- Removal of emissions control devised reduces costs for operators, e.g., cost of Adblue.
- Enforcement may be challenging, especially if engine management systems are tampered with — hard to identify.

Investment Requirements

- OEMs required to have engine shutdown if control devices are removed.

Policy Requirements

- Legislation required. Focus will be on suppliers of defeat devices rather than plant operators.

Factors Affecting Timescales

- Legislation required. Sector is working with DfT to bring forward.

Electric TRUs

Benefits

- Co-benefits for NOx, noise, carbon.
- Possible OPEX cost reductions.

Barriers

- Availability of suitable technology. Electric may be suitable for smaller vehicles but not for articulated vehicles.
- Choice of suitable technology (electric vs hydrogen).

Investment Requirements

- Technology and operator investment required.

Policy Requirements

- Improved data required. Currently poor understanding of number, size, duty cycles of TRUs. Risk of inefficient policy measures.

Factors Affecting Timescales

- Driven largely by carbon requirements.

Precision equipment for improving construction efficiency

Benefits

- Reduced operator costs through improved efficiency and faster, high-quality project delivery.
- Co-benefits for NOx, noise, carbon.
- Autonomous vehicles may bring safety benefits on closed sites.
- Technology transfer between other sectors, e.g., agriculture.
- May be confined to specialist areas in the first instance. Potential for widespread roll-out to certain common use cases (e.g., road building).

Barriers

- Development of equipment.
- Cost of deployment.

Investment Requirements

- Development and deployment of plant and techniques. Substantial investment cost.

Policy Requirements

- Likely to be driven by competitive advantage rather than policy.
- HE leading in a Connected Autonomous Plant project - Common standards to help machinery connect.

Factors Affecting Timescales

- Development time required.
- Hard to predict due to manufacturer confidentiality.

Hybrid generators

Benefits

- Co-benefits for noise, NOx, carbon.
- More efficient that conventional diesel but without need to complex electric infrastructure.
- Mitigates the practice of using inappropriately sized equipment (due to variable demands, availability at time of hire, etc.) which causes engines to be used at inefficient loads much of the time. Hybrid generator can be used at most efficient setting.
- Smart power management systems.
- Potential for alternative fuels.

Barriers

- Concerns about alternative fuel storage on sites.
- Resistance to uptake.
- Some additional cost (CAPEX costs but OPEX savings?).

Investment Requirements

- Fleet replacement costs.

Policy Requirements

- There has been no Stage IIIB or IV for generators, so Stage V is a step change.
- Emission control standards, either by location (e.g., London LEZ) or project policy (e.g., HS2).

Factors Affecting Timescales

- Equipment replacement lifecycles.
- Likely to be a transition measures prior to adoption of fully alternative power sources (fully electric, hydrogen).

Agriculture

Attendees

National Farmers' Union, Imperial College London, JNCC, Natural England, National Association of Agricultural Contractors, Country Land and Business Association, Plantlife, Central Association of Agricultural Valuers, ADAS, WRAP, Anaerobic Digestion and Bioresources, DEFRA.

Summary of Stakeholder Views

Slurry / Manure Storage and Management

Benefits

- Several stakeholders emphasised that location is important when considering benefits. For example, covering a slurry store near a sensitive receptor (such as a sensitive ecosystem) could still be beneficial. It was highlighted that this would not necessarily reduce ammonia emissions contributing to the national total.
- Several stakeholders mentioned that slurry store covering will only be effective at reducing ammonia emissions if measures are introduced at spreading.
- It was mentioned that there is no point covering solid manures stores as emissions are low and rapid incorporation (within 12 hours of application) would be required to minimise losses at spreading.

Barriers

- Large capital input required for both retrofit and build. Needs to be done in conjunction with Farming Rules for Water rules. It may not be possible to retrofit covers so risk that money spent now will be wasted.
- Several stakeholders mentioned implementation barriers such as a shortage of agricultural building contractors, local planning restrictions, H&S requirements, challenges around irregular store shapes, challenges around cleaning sand bedding.
- Does not actually reduce ammonia. This still needs to be dealt with.
- The need to consider unintended consequences was also mentioned (e.g., other emissions resulting from changed storage conditions (higher temperatures)).

Investment Requirements

- Investment in storage purchase or retrofit.

Policy Requirements

- National policy on emission controls and local planning regulations is required, including policy to encourage farmers to invest.
- There was consensus around the need for joined-up policy. Considering this alongside spreading and in relation to other environmental factors (e.g., water quality).

Factors Affecting Timescales

- Will depend on policy development and implementation.
- Investment timescales.

Manure Management – Anaerobic Digestion

Benefits

- There was discussion about whether this measure would have much effects on overall emissions, but several stakeholders mentioned that it could help manage nitrogen and provide a method to better manage manures on farms.
- It was mentioned that the benefits in terms of emission reductions depend on feedstocks.

Barriers

- Investment costs and lack of financial incentives to encourage processing of manures and slurries (low yielding feedstock).
- Low gas yield per tonne of fresh weight leads to it being used as a top up feedstock or to ensure the 50% gas from waste requirement is met (RHI & GGSS).
- Higher N concentration in digestate may make it more difficult to handle.
- Use of food waste on farms will require regulatory permitting.

Investment Requirements

- AD plants require large investment. Not viable on small farms.
- Investment for retrofitting of stores and covers.

Policy Requirements

- Policy/regulation/incentivisation to encourage ammonia reduction technology trials/application.
- Alteration to tariff structure.
- Several stakeholders mentioned the need for integrated nitrogen policies. The recent BEIS consultation on reducing ammonia emission for GGSS was mentioned.
- Incentivising manures to be processed - France has an additional tariff for using agri manures

Factors Affecting Timescales

- Will depend on policy decisions.

- Implementation on individual farms will depend on availability of finance and investment choices.

Improved Nitrogen Efficiency / Fertiliser Changes

Benefits

- Several stakeholders mentioned that farmers want to reduce fertilizer use, rather than losing a large proportion so better efficiency will benefit farmers and the environment.
- The use of organics to soil improves soil; biology, chemistry, structure, water retention was highlighted.

Barriers

- Farmers considered switch to non-urea fertiliser to be one of the options with least barriers in Defra project LM0475. http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=20022
- Regulations for different applications was mentioned as a potential barrier.

Investment Requirements

- Several stakeholders mentioned that this is a cost-effective.
- Reinstating livestock would require significant investment - significant yield loss (including staff/training).
- It was discussed that wider changes in farming approaches would be required for wide uptake.
- Education on best practice.
- Interest in legume research and wheat taking nitrogen fixing legumes into the cycle.
- R&D in organic manures to reduce the requirement for fossil fuels.

Policy Requirements

- Urea use will be determined by outcome of current consultation on urea fertiliser use.
- Regulation to provide a level playing field for farm businesses.
- Integrated farming & fertiliser policy across issues (air, water, GHG) and channels (ELM, regulation, CSF & other advice, capital grants)
- Incentivisation for use of organic manures.
- Needs to be considered as part of a whole system.
- Farming Rules for Water should understand the actual spreading seasons & closed windows.

Factors Affecting Timescales

- Several stakeholders mentioned the Defra consultation on use of urea fertilisers. It is understood that Defra would like to see a drastic reduction in the use. Policies will determine timescales.
- Environmental Land Management Scheme (ELMS) introduced from 2022-2023 onwards will determine timescales.

- It was mentioned that this could be a long-term project and there is a need to start measuring nitrogen use efficiency.

Low Emission Spreading

Benefits

- Several stakeholders mentioned that the benefits are discussed in the Clean Air Strategy and that lots of farmers and contractors already employ low emission spreading. There is now improved understanding of volume of slurry spread, etc, resulting in better informed farming.
- The benefits for sward on improved grassland (see CSF AQ case studies) were mentioned.
- WRAP work on digestate (ADAS report) covers low emission spreading and GHG emissions.

Barriers

- Dependent on farm and field size (difficult for small farms). Also dependent on weather conditions.
- If spread in the wrong place can have high impact for odour, water and air quality (typically ecosystems impact for air).
- Access to land due to regulations can mean speed is of the essence.

Investment Requirements

- Machines are very expansive. retrofitting is cheaper when appropriate and applicable.
- Training and education for contractors. This needs to be linked to updated FACTs training to ensure agronomic advice is right. Contractors now qualify for grant funding for the first time and need equal access to training funding.

Policy Requirements

- Several stakeholders mentioned that support needs to be available to contractors who are likely to the ones who invest in equipment.
- Air shed or exclusion area for sensitive habitats.
- Incentivisation through SFI element of ELMS.
- Link to spreading window - just using low emission spreaders will not be effective if spreading is done at the wrong time of year or under the wrong conditions.

Factors Affecting Timescales

- It was mentioned that there is expected to be a requirement for all farms to be doing it by 2025 subject to funding.
- Related to ELMS introduction in 2024.

Livestock Housing

Benefits

- Where implemented near a sensitive site can significantly reduce impact to ecosystems for what are typically the primary source of emissions if housing is not regulated (e.g., dairy/cattle or sub-permit threshold farms <40k birds or <750 pigs) but less so if regulated.
- It was mentioned that the ranges in benefits presented are huge. Technology appropriate to the building is required.

- Animal health benefits.

Barriers

- Need to ensure any measures meet both air and water regulations.
- Availability of suppliers and fitters for low emission flooring.
- Planning considerations/ permissions required for improvements.
- As with all measures, farmer don't gain the benefits, so policy/investment support is required.

Investment Requirements

- Automatic scrapers and low emission flooring now available in Countryside Stewardship.
- Monitoring to link to fans/adapt to changing emissions. Manure drying equipment.
- It was mentioned that this is probably one of the more expensive options being looked at and one that will be constrained by speed of refurbishment/cost and scale of investment.

Policy Requirements

- Extension of environmental permitting regulations.
- Planning requirement.
- Code of Good Agricultural Practice support.
- Policy clarification post-Brexit is required. There is a need to support viable farming businesses.

Factors Affecting Timescales

- Flooring - established technology in the Netherlands but availability an issue. but can be retrofitted.
- Clean Air Strategy timelines for regulation will leave a gap for incentives. Once regulated, there is limited likelihood for incentives for this regulated activity. There will be farms not in regulation (e.g., small or certain activity on farm).
- Changes cannot be made quickly because of the cost. Huge number of buildings that could be affected. Animal housing not regularly changed because of large investment.

Changes in Livestock Diet

Benefits

- Benefits likely to be greater if it can be shown that this will reduce feed costs.
- It was mentioned that Harper Adams University is doing research in this area.

Barriers

- Requires higher level of management.
- Several stakeholders mentioned uncertainty over how feeds impact growth and health. Impacts on growth could impact efficiency & other ruminant emissions.

Investment Requirements

- Stakeholders mentioned that this is potentially an easier win as long as profitability is not adversely affected. e.g., a lot cheaper than air scrubbers.

- Research is vital to make this work.

Policy Requirements

- Farmers will need to see a cost reduction and a benefit to production. May need a policy instrument to encourage feed makers to make the transition to lower protein feeds.

Factors Affecting Timescales

- The need to develop a strong evidence base showing that changed diet is beneficial for farmer and livestock.

Incineration of Poultry Litter

Benefits

- There was general agreement that this measure might not offer much benefit as any benefits will be offset as nitrogen will enter the atmosphere anyway. Nitrogen should be treated as an asset to manage and potentially use in arable farming (via exchange networks).

Barriers

- Several stakeholders mentioned the loss of a manure resource under this measure.
- Transport costs (moving something bulky and low value).
- Disposal of particulate from bag filters.

Investment Requirements

- Lifecycle analysis of poultry litter and where it is more useful / economic efficient to use it.
- Small scale on farm incineration and heat recovery equipment.
- It was mentioned that CHP units will only be viable for large farms.

Policy Requirements

- Regulation of emissions to reduce contribution overall rather than solely EQS/effects-based level.
- Needs policy drivers to say that litter cannot be spread it this measure is to be employed. It was highlighted that policy is vital if this is to happen as there will not be a cost case otherwise.
- Policies to help exchanges rather than incineration. (e.g., straw for muck).

Factors Affecting Timescales

- Further research is required in the benefits.
- Should be possible to instigate fairly quickly.

Beed / Dairy Cattle Regulations

Benefits

- Some stakeholders considered it better to manage slurry etc. rather than imposing new regulations.

Barriers

- Cost of new infrastructure (a particular concern as many beef farmers lose money).

Investment Requirements

- Grave doubts over whether beef production, in particular, could handle the extra costs.

Policy Requirements

- Again, stakeholders emphasised the need for joined-up/long term thinking on policies.
- It is understood that the EA is currently developing BAT for dairy/cattle.

Factors Affecting Timescales

- Depends on BAT proposed. This can be complex. It was mentioned that this was better defined for pig and poultry.
- Decisions on what size farm is regulated and then ability to implement (e.g., contractor availability, farmer able to fund, feasible for site).
- Changes to buildings will take a long time due to investment cycles.

Fuel Choice and Usage for Equipment and Vehicles

Benefits

- Cost case/efficiency and ease of use will determine the benefits/uptake.
- Stage V emission standards will significantly decrease PM emissions.

Barriers

- Doubts were expressed about the availability of non-diesel alternatives for farm machinery.
- Trade-offs if adaptations to reduce NOx from combustion results in ammonia emissions instead (e.g., through catalysis).
- Subsidised red diesel.
- Infrastructure requirements for electricity/hydrogen. Convenience of operation is vital for efficient farm operation.
- Biomethane for transport fuel.

Investment Requirements

- Investment in new equipment is very expensive.
- Power supply is a big issue. Not available in rural areas.
- There is a strong second-hand market in farm kit so the impact on this needs to be factored in.

Policy Requirements

- Subsidy to remain for agriculture for red diesel.
- Need a long timescale to signal change to equipment suppliers.

Factors Affecting Timescales

- It was highlighted that the replacement cycle is key. Replacement cycles will depend on the specific piece of equipment, farm size, use of contractors. Most machines cost £100k+ and some pieces of equipment are substantial fixed investments (e.g., grain dryers could last for decades). Turnover can be quite rapid for others (e.g., combine harvester after 4 years). Contractors will keep equipment while it is operation and under warranty. They can also focus on new innovations in the industry. Leasing is also important as companies are likely to have a high turnover. Equipment could be replaced every two years, but this could also take a lot longer.

- Requirements from customers e.g., around carbon supply chain.
- Long-term infrastructure requirements for electricity/hydrogen.

Change in Land Use

Benefits

- It was mentioned that this covers a huge range of alternative land uses so it is difficult to comment.
- Increased biodiversity & ecosystem services.
- Stakeholders mentioned a variety of co-benefits, including agro-forestry and animal health, economic benefit and others ecosystem services. It was mentioned that this could be one tool for some particularly vulnerable sites with a land management contract in place.
- Potential disbenefit around carbon emissions for transport.

Barriers

- Land can be productive and managed correctly, rather than just doing nothing with the land. It was agreed that it is essential to maintain productive land to produce food.
- Loss of production so incomes go down.

Investment Requirements

- Communicating benefits of the measure.

Policy Requirements

- Locally appropriate solution (need advice/evidence) and associated with monitoring and incentives. Could be contractually agreed for sensitive sites (e.g., management of SSSIs).
- Regenerative farming and habitat restoration objectives linked to land use measures.
- Several stakeholders mentioned the use of public money for public goods, such as ELMS payments for environmental management, biodiversity benefits etc. It was agreed that to change land, use income streams will need to be replaced.

Factors Affecting Timescales

- Will depend on policies and incentives.

Behaviour Change in Food Consumption

Benefits

- There was much debate around whether there are any benefits of this measure. It was highlighted that it assumes that people consume British meat, so land would be free up and carbon emissions reduced in the UK. It was mentioned that there is an associated need to reduce food waste throughout the system.

Barriers

- Several stakeholders mentioned that there is a lack of evidence of the benefits to emissions of this measure.

- It was mentioned that if red meat and dairy consumption is replaced by pork and chicken consumption there are issues associated with intensive farming and associated ammonia emissions.

Investment Requirements

- Communication to public about benefits of change and accounting for their actions so they can see benefit.
- Full analysis of the nitrogen cycle and carbon footprints. Transport costs need to be accounted for.

Policy Requirements

- Need to consider all of the measures as a policy package and include carbon emissions, rather than having carbon specific policies.
- One stakeholder mentioned that UK red meat production is / can be low emission and considered that there should be encouragement of more extensive lamb and beef production.

Factors Affecting Timescales

- Stakeholders agreed that it may be difficult, and take a long time, to change the behaviour of shoppers and consumers. Price is still a key driver for supermarkets and many consumers.

Appendix C
References

Domestic/commercial combustion

[1] The Air Quality (Domestic Solid Fuels Standards) (England) Regulations 2020. Online: https://www.legislation.gov.uk/uksi/2020/1095/contents/made

[2] BEIS. National Emission Inventory (NAEI). UK emissions data selector. Online: https://naei.beis.gov.uk/data/data-selector?view=pms

[3] Defra (2019) Clean Air Strategy 2019. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770715/clean-air-strategy-2019.pdf

[4] BEIS (2016) Summary results of the domestic wood use survey. Online: https://www.gov.uk/government/publications/summary-results-of-the-domestic-wood-use-survey

[5] Mitchell, E.J.S., Cottom, J.W, Phillips, D., and Dooley, B. (2019) A Review of the Impact of Domestic Combustion on UK Air Quality. Online: https://www.auldtonstoves.co.uk/wp-content/uploads/2019/12/A-Review-of-the-Impact-of-Domestic-Combustion-on-UK-Air-Quality-1.pdf

[6] Defra (2020) Estimating UK domestic solid fuel consumption, using Kantar data. Summary of results and discussion. Annexe A of 'Burning in UK Homes & Gardens'. Online: http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=20159

[7] Kantar (2020) Burning in UK Homes and Gardens. Research Report. Prepared for Defra. Online: http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=20159

[8] Defra (2018) Consultation on cleaner domestic burning of solid fuels and wood. Online: https://consult.defra.gov.uk/airquality/domestic-solid-fuel-regulations/

[9] Defra (2019) Title: Proposed regulation of the sales, distribution and marketing of Wet wood (>20% moisture) sold in units up to 2m3, Bituminous house coal, Banning manufactured solid fuels with sulphur content over 2%. RPC Reference no: RPC-4233(1)-DEFRA. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/933097/burning-wood-consult-ia.pdf

[10] Burn Right Campaign. Online: https://www.burnright.co.uk/

[11] HETAS. Ecodesign Explained. Online: https://www.hetas.co.uk/ecodesign/

[12] Clearskies. Online: https://www.clearskiesmark.org/

[13] AQEG (2017) The Potential Air Quality Impacts from Biomass Combustion. Online: http://aqma5.co.uk/_assets/AQEG_Biomass_Combustion_report_Defra_2017.pdf

[14] A J Scott (2005) Real-life emissions from residential wood burning appliances in New Zealand. Online: https://www.researchgate.net/publication/343303613_Real-life_emissions_from_residential_wood_burning_appliances_in_New_Zealand#pf39

[15] EPUK (2013) Solid Fuel and Air Quality. An Update for Local Authorities. Online:

https://www.environmental-protection.org.uk/wp-content/uploads/2013/07/Solid-Fuel-and-Air-Quality-Update-for-LAs-final-060413.pdf

[16] Defra (2020) Summary tables of estimates of UK domestic solid fuel users and solid fuel use. Annexe B of 'Burning in UK Homes & Gardens'. Table 4.1. Online: http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=20159

[17] Climate Change Committee (2018) Biomass in a low-carbon economy. Online: https://www.theccc.org.uk/publication/biomass-in-a-low-carbon-economy/

[18] Stove Industry Alliance. Ecodesign Legislation & Implications. Online: https://stoveindustryalliance.com/sia-ecodesign-ready-appliances/ecodesign-legislation-implications/

[19] Defra. Burn Better Campaign. Online: https://uk-air.defra.gov.uk/library/burnbetter/

[20] Chakraborty R, Heydon J, Mayfield M, Mihaylova (2020) Indoor Air Pollution from Residential Stoves: Examining the Flooding of Particulate Matter into Homes during Real-World Use. Online: https://www.mdpi.com/2073-4433/11/12/1326

[21] Institute of Health Equity (2020) Sustainable health equity: Achieving a Net-Zero UK. Online: https://d423d1558e1d71897434.b-cdn.net/wp-content/uploads/2020/11/Sustainable-Health-Equity-Achieving-a-Net-Zero-UK-report-FINAL.pdf

[22] GLA (2020) London Atmospheric Emissions (LAEI) 2016. Online: https://data.london.gov.uk/dataset/london-atmospheric-emissions-inventory--laei--2016

[23] GLA (2019) PM2.5 in London: Roadmap to meeting World Health Organization guidelines by 2030. Online: https://www.london.gov.uk/sites/default/files/pm2.5_in_london_october19.pdf

[24] Imperial College London. National and urban scale modelling: the UKIAM model. Online: https://www.imperial.ac.uk/environmental-policy/research/projects-centres-networks-affiliations/iau/iam/ukiam/

[25] Kitiwiroon N, Beevers S and Williams M (2019) The WHO air quality guideline for PM2.5. CMAQ modelling of future scenarios. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/930113/annex2-pm25-kings-college-report.pdf

[26] Fountoukis C, *et al*. (2016) Simulating the formation of carbonaceous aerosol in a European Megacity (Paris) during the MEGAPOLI summer and winter campaigns. Online: https://acp.copernicus.org/articles/16/3727/2016/

[27] Ots R, *et al*. (2016) Model simulations of cooking organic aerosol (COA) over the UK using estimates of emissions based on measurements at two sites in London. Online: https://acp.copernicus.org/articles/16/13773/2016/

[28] Purified Air (2007) The Principle of Electrostatic Precipitators. Online: https://planning.islington.gov.uk/NorthgatePublicDocs/00459537.pdf

[29] Discount Canopy Shop Ltd. FusionAir ESP 3000. Online: https://www.fusionhot.co.uk/apps/webstore/products/show/8034319

[30] CanopyUK. Electrostatic Precipitators ESP 4500E. Online: http://www.canopydirect.uk.com/index.php?route=product/product&product_id=437

[31] MHCLG (2021) Future Buildings Standard Consultation IA. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/953664/201209_Future_Buildings_Standard_consultation_IA.pdf

[32] Climate Change Committee (2020) The Sixth Carbon Budget. Online: https://www.theccc.org.uk/wp-content/uploads/2020/12/The-Sixth-Carbon-Budget-The-UKs-path-to-Net-Zero.pdf

[33] BEIS (2020) Energy Consumption in the UK (ECUK, End uses data tables, Table U2. Online: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk

[34] Climate Change Committee (2020) The Sixth Carbon Budget. Buildings. Online: https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Buildings.pdf

[35] BEIS (2020) National Atmospheric Emissions Inventory (NAEI) Breakdown of UK GHG emissions by source and greenhouse gas.

[36] MHCLG (2021) Consultation outcome. The Future Homes Standard: changes to Part L and Part F of the Building Regulations for new dwellings. Online: https://www.gov.uk/government/consultations/the-future-homes-standard-changes-to-part-l-and-part-f-of-the-building-regulations-for-new-dwellings

[37] MHCLG (2021) The Future Homes Standard: 2019 Consultation on changes to Part L (conservation of fuel and power) and Part F (ventilation) of the Building Regulations for new dwellings. Summary of responses received and Government response. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/956094/Government_response_to_Future_Homes_Standard_consultation.pdf

[38] MHCLG (2020) Future Homes Standards Impact Assessment. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/836925/REQUEST.pdf

[39] BEIS (2020) Subnational Electricity and Gas Consumption Statistics. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/946968/sub-national-electricity-and-gas-consumption-summary-report-2019.pdf

[40] HM Government (2020) Energy White Paper. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/945899/201216_BEIS_EWP_Command_Paper_Accessible.pdf

[41] MHCLG (2020), English Housing Survey 2018: stock condition. Online: https://www.gov.uk/government/statistics/english-housing-survey-2018-stock-condition

[42] Building Services Research and Information Association (BSRIA) (2017) Global boiler market heats up as the UK is no longer the largest market. Online: https://www.bsria.com/uk/news/article/global-boiler-market-heats-up-as-the-uk-is-no-longer-the-largest-market/

[43] UCL. UK TIMES. Online: https://www.ucl.ac.uk/energy-models/models/uk-times

[44] HM Government (2020) The Ten Point Plan for a Green Industrial Revolution. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf

[45] National Grid ESO (2020) Future Energy Scenario. Online: https://www.nationalgrideso.com/document/173821/download

Urban Mobility

[46] GLA (2020) AIR QUALITY IN LONDON 2016-2020 London Environment Strategy: Air Quality Impact Evaluation. Online: https://www.london.gov.uk/sites/default/files/air_quality_in_london_2016-2020_october2020final.pdf

[47] DfT (2020) Gear Change A bold vision for cycling and walking. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/904146/gear-change-a-bold-vision-for-cycling-and-walking.pdf

[48] Transport for Quality of Life (2020) Impact of the Local Sustainable Transport Fund: Synthesis of Evidence. Online: https://www.transportforqualityoflife.com/u/files/180817%20Evaluation%20and%20Synthesis%20of%20LSTF%20FINAL.pdf

[49] Chapman *et al* (2018) A Cost Benefit Analysis of an Active Travel Intervention with Health and Carbon Emission Reduction Benefits. Int. J. Environ. Res. Public Health 2018, 15, 962. Online: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5982001/pdf/ijerph-15-00962.pdf

[50] TRL (2019) Healthy mobility and road safety. Online: https://trl.co.uk/publications/healthy-mobility-and-road-safety

[51] Royal Town Planning Institute (2021) Net Zero Carbon Transport The role of spatial planning and place-based solutions

[52] Institute of Health Equity (2020) Sustainable Health Equity: Achieving A Net-Zero UK. Online: https://d423d1558e1d71897434.b-cdn.net/wp-content/uploads/2020/11/Sustainable-Health-Equity-Achieving-a-Net-Zero-UK-report-FINAL.pdf

[53] TfL (2020) Streetspace for London. Online: https://tfl.gov.uk/travel-information/improvements-and-projects/streetspace-for-london

[54] European Commissions (2004) Reclaiming city streets for people Chaos or quality of life? Online: https://ec.europa.eu/environment/pubs/pdf/streets_people.pdf

[55] Greater Manchester Spatial Framework (2019) Transport Topic Paper. Online: https://www.greatermanchester-ca.gov.uk/media/1742/transport-topic-paper-w-cover-web.pdf

[56] Massot *et al* (2006) Potential for Car Use Reduction through a Simulation Approach: Paris and Lyon Case Studies. Transport Reviews Volume 26. Online: https://www.tandfonline.com/doi/abs/10.1080/01441640500124787

[57] Transport for Greater Manchester (2019) Greater Manchester Transport Strategy 2040 Draft Delivery Plan. Online: https://assets.ctfassets.net/nv7y93idf4jq/2GBbEBM4hm68q9qqvdal1T/97f7b3d51ef9b312b756cd15bd0b008c/190128_Delivery_Plan_2020-2025_Draft_MASTER_final.pdf

[58] Birmingham City Council (2020) Financial Plan 2020-2024. Online: https://www.birmingham.gov.uk/downloads/file/16189/financial_plan_2020_to_2024

[59] Bloomberg (2020) The 15-Minute City—No Cars Required—Is Urban Planning's New Utopia. Online: https://www.bloomberg.com/news/features/2020-11-12/paris-s-15-minute-city-could-be-coming-to-an-urban-area-near-you

[60] MHCLG (2019) National Planning Policy Framework https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/810197/NPPF_Feb_2019_revised.pdf

[61] IPCC (2014) AR5 Climate Change 2014: Mitigation of Climate Change Chapter 12: Human Settlements, Infrastructure and Spatial Planning. Online: https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter12.pdf

[62] RTPI (2018) Settlement Patterns, Urban Form & Sustainability an Evidence Review. Online: https://www.rtpi.org.uk/media/1836/settlementpatternsurbanformsustainability2018.pdf

[63] VTPI (2020) Land Use Impacts on Transport How Land Use Factors Affect Travel Behavior. Online: https://www.vtpi.org/landtravel.pdf

[64] National Research Council (2009) Driving and the Built Environment: The Effects of Compact Development on Motorized Travel, Energy Use, and CO2 Emissions -- Special Report. Chapter: 3 Impacts of Land Use Patterns on Vehicle Miles Traveled: Evidence from the Literature. Online: https://www.nap.edu/read/12747/chapter/5

[65] Marler (2006) DISTILLATE PROJECT F Appendix C Land use: development densities & mix. http://www.distillate.ac.uk/outputs/Deliverable%20F%20Appendix%20C.pdf

[66] Aditjandra, Mulley, Nelson (2013) The influence of neighbourhood design on travel behaviour: Empirical evidence from North East England. Transport Policy 26. Online: https://www.researchgate.net/publication/271888919_The_influence_of_neighbourhood_design_on_travel_behaviour_Empirical_evidence_from_North_East_England

[67] HM Treasury (2020) Spending Review 2020. Online: https://www.gov.uk/government/publications/spending-review-2020-documents/spending-review-2020

[68] Modeshift STARS (2021) What is a Travel Plan. Online: https://www.modeshiftstars.org/about/travel-planning/

[69] DfT (2020) National Travel Survey: England 2019. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/906276/national-travel-survey-2019.pdf

[70] Transport for Quality of Life (2004) Smarter Choices – Changing the Way We Travel. Workplace Travel Plans. Online: https://www.transportforqualityoflife.com/u/files/Smarter_Choices_Changing_The_Way_We_Travel_chapter3.pdf

[71] European Commission (2013) Quantifying the Effects of Sustainable Urban Mobility Plans. Online: https://www.eltis.org/sites/default/files/trainingmaterials/quantifying_the_effects_of_sustainable_urban_mobility_plans.pdf

[72] Plymouth City Council (2019) Plymotion Outstanding Statistics for 2018/2019. Online: https://www.plymouth.gov.uk/sites/default/files/Plymotion%20Oustanding%20statistics%20FINAL.pdf

[73] Isle of Wight Council (2019) Access Fund Programme Evaluation 2018/19. Online: https://www.iow.gov.uk/documentlibrary/view/access-fund-programme-evaluation-2018-19

[74] DfT (2020) Statistical data set Mode of travel. Online: https://www.gov.uk/government/statistical-data-sets/nts03-modal-comparisons

[75] DfT (2017) Commuting trends in England 1988 – 2015. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/877039/commuting-in-england-1988-2015.pdf

[76] Institute of Health Equity (2021) Sustainable Health Equity: Achieving A Net-Zero UK. Online: https://d423d1558e1d71897434.b-cdn.net/wp-content/uploads/2020/11/Sustainable-Health-Equity-Achieving-a-Net-Zero-UK-report-FINAL.pdf

[77] Lokesh, K., Anable, J., Marsden, G., Walker, R., McCulloch, S., and Jenkinson, K. (2020). Decarbonising Transport: Travelling Less and the Role of Online Opportunities', Local Government Association: London. Online: https://www.local.gov.uk/sites/default/files/documents/5.90%20travelling%20less_02.pdf

[78] Global Action Plan (2020) Remote Work Press Release. Online: https://www.globalactionplan.org.uk/files/remote_work_press_release.pdf

[79] Giovanis (2018) The relationship between teleworking, traffic and air pollution. Atmospheric Pollution Research

Volume 9, Issue 1. Online: https://www.researchgate.net/publication/317565238_The_relationship_between_teleworking_traffic_and_air_pollution

[80] International Transport Forum (2016) Shared Mobility Innovation for Liveable Cities. Online: https://www.itf-oecd.org/sites/default/files/docs/shared-mobility-liveable-cities.pdf

[81] Stettler (2018) The UK private road transport system: how and why is it changing? Government Office for Science. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/761927/Privateroadtransport.pdf

[82] Commission on Travel Demand (2019) Shared mobility – where now, where next? Second report of the Commission on Travel Demand. Online: https://www.creds.ac.uk/wp-content/uploads/CREDS-Shared-mobility-comm-report-WEB.pdf

[83] DfT (2018) Road Traffic Forecasts 2018. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/873929/road-traffic-forecasts-2018-document.pdf

[84] Ipsos (2019) Shared Mobility Ipsos MORI report for the Department for Transport. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/935389/Shared-Mobility-Report-accessible.pdf

[85] TfL (2008) Central London Congestion Charging Impacts monitoring Sixth Annual Report, July 2008. Online: http://content.tfl.gov.uk/central-london-congestion-charging-impacts-monitoring-sixth-annual-report.pdf

[86] GLA (2019) Central London Ultra Low Emission Zone – Six Month Report. Online: https://www.london.gov.uk/sites/default/files/ulez_six_month_evaluation_report_final_oct.pdf

[87] TfL (2017) Mayor's Transport Strategy: Supporting Evidence Outcomes Summary Report. Online: http://content.tfl.gov.uk/mts-outcomes-summary-report.pdf

[88] Centre for London (2019) Green Light: Next Generation Road User Charging For A Healthier,

More Liveable, London. Online: https://www.centreforlondon.org/wp-content/uploads/2019/04/Next-Generation-Road-User-Charging.pdf

[89] Transport & Environment (2018) Roadmap to Decarbonising European Cars. Online: https://www.transportenvironment.org/sites/te/files/publications/2050_strategy_cars_FINAL.pdf

[90] TfL (2007) Central London Congestion Charging Scheme: ex-post evaluation of the quantified impacts of the original scheme. Online: http://content.tfl.gov.uk/ex-post-evaluation-of-quantified-impacts-of-original-scheme.pdf

[91] House of Commons Library (2020) Research Briefing Taxation of road fuels. Online: https://commonslibrary.parliament.uk/research-briefings/sn00824/#:~:text=The%20two%20main%20categories%20of,(as%20of%20September%202019)

[92] GLA (2018) London Environment Strategy. Online: https://www.london.gov.uk/sites/default/files/london_environment_strategy_0.pdf

[93] TfL (2019) Freight and servicing action plan. Online: http://content.tfl.gov.uk/freight-servicing-action-plan.pdf

[94] Allen, Browne, Woodburn, Leonardi (2015) A Review of Urban Consolidation Centres in the Supply Chain Based on a Case Study Approach. Supply Chain Forum 15. Online: https://www.researchgate.net/publication/284550829_A_Review_of_Urban_Consolidation_Centres_in_the_Supply_Chain_Based_on_a_Case_Study_Approach

[95] Catapult Transport Systems (2018) Consolidating Public Sector Logistics Operations for the DfT. Online: https://s3-eu-west-1.amazonaws.com/media.ts.catapult/wp-content/uploads/2018/07/13095627/Public-Sector-Logistics-Consolidation_On-Line-Report-web.pdf

[96] National Infrastructure Commission (2019) Better Delivery: The Challenge for Freight Freight Study final report. Online: https://nic.org.uk/app/uploads/Better-Delivery-April-2019.pdf

[97] The Centre for Sustainable Road Freight (2019) Decarbonising road freight for Government Office for Science. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/780895/decarbonising_road_freight.pdf

[98] OECD (2020) Non-exhaust Particulate Emissions from Road Transport An Ignored Environmental Policy Challenge. Online: http://www.oecd.org/environment/non-exhaust-particulate-emissions-from-road-transport-4a4dc6ca-en.htm

[99] Lokesh, K., Anable, J., Marsden, G., Walker, R., McCulloch, S., and Jenkinson, K. (2020). Decarbonising Transport: Travelling Less and the Role of Online Opportunities', Local Government Association: London. Online: https://www.local.gov.uk/sites/default/files/documents/5.90%20travelling%20less_02.pdf

[100] Rail Delivery Group (2019) Rail Freight: Delivering for Britain. Online: https://www.raildeliverygroup.com/files/Publications/2019-05_rail_freight_delivering_for_britain.pdf

[101] MDS Transmodal (2019) Rail freight forecasts: Scenarios for 2033/34 & 2043/44. Produced for Network Rail. Online: https://www.networkrail.co.uk/wp-content/uploads/2019/04/Rail-freight-forecasts-Scenarios-for-2033-and-2043.pdf

[102] DfT (2016) Rail Freight Strategy. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/552492/rail-freight-strategy.pdf

Road Transport Technology

[103] TfL (2017). Proposed changes to the ULEZ (start date and emissions standards) Consultation and information document. Online: https://consultations.tfl.gov.uk/environment/air-quality-consultation-phase-3a/user_uploads/ulez-changes---stage-3a---con-and-info-doc---final-v1.0.pdf

[104] GLA (2020) Central London Ultra Low Emission Zone – Ten Month Report. Online: https://www.london.gov.uk/sites/default/files/ulez_ten_month_evaluation_report_23_april_2020.pdf

[105] Ricardo (2018) Cambridge Clean Air Zone Feasibility Study – Appendices. Online: https://consultcambs.uk.engagementhq.com/1836/documents/2050

[106] Defra (2016) Committed Clean Air Zone Impact Assessment. Online: https://consult.defra.gov.uk/airquality/implementation-of-cazs/supporting_documents/161012%20%20CAZ%20Impact%20Assessment%20%20FINAL%20consultation.pdf

[107] Defra (2020) Emissions Factors Toolkit. Online: https://laqm.defra.gov.uk/review-and-assessment/tools/emissions-factors-toolkit.html

[108] Air Quality News (2020) Clean Air Zones – Postponed or cancelled. Online: https://airqualitynews.com/2020/07/06/clean-air-zones-postponed-or-cancelled/

[109] TfL (2021) ULEZ Car and motorcycle scrappage scheme. Online: https://tfl.gov.uk/modes/driving/ultra-low-emission-zone/car-and-motorcycle-scrappage-scheme

[110] Coventry City Council (2020) Mobility Credits. Online: https://www.coventry.gov.uk/mobilitycredits

[111] Samaras, Hausberger, Mellios (2020) Preliminary findings on possible Euro 7 emission limits for LD and HD vehicles. Online: https://circabc.europa.eu/sd/a/fdd70a2d-b50a-4d0b-a92a-e64d41d0e947/CLOVE%20test%20limits%20AGVES%202020-10-27%20final%20vs2.pdf

[112] Transport Policy. China Light Duty Emissions. Online: https://www.transportpolicy.net/standard/china-light-duty-emissions/#:~:text=Nationwide%20Standards,China%205%20(Euro%205).&text=The%20China%206%20standard%2C%20with,emission%20standards%20around%20the%20world.

[113] Transport Policy. California Light Duty Emissions. Online: https://www.transportpolicy.net/standard/california-light-duty-emissions/

[114] DfT (2020) Government takes historic step towards net-zero with end of sale of new petrol and diesel cars by 2030. Online: https://www.gov.uk/government/news/government-takes-historic-step-towards-net-zero-with-end-of-sale-of-new-petrol-and-diesel-cars-by-2030

[115] TNO (2017) Investigation into a Periodic Technical Inspection (PTI) test method to check for presence and proper functioning of Diesel Particulate Filters in light-duty diesel vehicles – part 2. Online: https://www.tno.nl/en/focus-areas/traffic-transport/roadmaps/sustainable-traffic-and-transport/sustainable-mobility-and-logistics/improving-air-quality-by-monitoring-real-world-emissions/emissions-of-particulate-matter-from-diesel-cars/

[116] GOVERNMENT GAZETTE Official publication of the Kingdom of the Netherlands (2019) Order No IENW/BSK-2019/202498 of the Minister for the Environment and Housing of 21 November 2019 amending the Vehicles order to enable inspection of particulate filters with a particle counter and to apply certain other technical amendments https://ec.europa.eu/growth/tools-databases/tris/en/search/?trisaction=search.detail&year=2019&num=328

[117] TSI. Emission Testing: Periodic Technical Inspection. Online: https://tsi.com/resources/emission-testing-within-periodic-technical-inspect/

[118] Audic and Stettler (2019). Remote sensing of diesel particulate filter failures using portable exposure measurements

[119] TNO (2016) Diesel Particulate Filters for Light-duty Vehicles: Operation, Maintenance, Repair, And Inspection. Online: https://www.tno.nl/en/focus-areas/traffic-transport/roadmaps/sustainable-traffic-and-transport/sustainable-mobility-and-logistics/improving-air-quality-by-monitoring-real-world-emissions/emissions-of-particulate-matter-from-diesel-cars/

[120] TNO (2020) Follow-up research into the PN limit value and the measurement method for checking particulate filters with a particle number counter. Online: https://www.tno.nl/en/focus-areas/traffic-transport/roadmaps/sustainable-traffic-and-transport/sustainable-mobility-and-logistics/improving-air-quality-by-monitoring-real-world-emissions/emissions-of-particulate-matter-from-diesel-cars/

[121] OECD (2020) Non-exhaust Particulate Emissions from Road Transport An Ignored Environmental Policy Challenge. Online: https://www.oecd-ilibrary.org/deliver/4a4dc6ca-en.pdf?itemId=/content/publication/4a4dc6ca-en&mimeType=pdf

[122] Exxon Mobil. EV Question Corner. Online: https://www.exxonmobilchemical.com/en/products/butyl/electric-vehicle-butyl-campaign/electric-vehicle-tires

[123] Continental. Electric vehicle tyres – Everything you need to know. Online: https://www.continental-tyres.co.uk/car/all-about-tyres/tyre-essentials/electric-vehicle-tires

[124] Timmers and Achten (2016) Non-exhaust PM emissions from electric vehicles. Atmospheric Environment 134. Online: https://www.researchgate.net/publication/297889793_Non-exhaust_PM_emissions_from_electric_vehicles

[125] Beddows and Harrison (2020) PM10 and PM2.5 emission factors for non-exhaust particles from road vehicles: Dependence upon vehicle mass and implications for battery electric vehicles. Online: https://www.researchgate.net/publication/343896949_PM10_and_PM25_emission_factors_for_non-exhaust_particles_from_road_vehicles_Dependence_upon_vehicle_mass_and_implications_for_battery_electric_vehicles

[126] Nordic Council of Ministers (2020) Reducing the Release of Microplastic from Tire Wear: Nordic Efforts. Online: http://norden.diva-portal.org/smash/get/diva2:1515089/FULLTEXT01.pdf

[127] Air Quality Expert Group for Defra (2019) Non-Exhaust Emissions from Road Traffic. Online: https://uk-air.defra.gov.uk/assets/documents/reports/cat09/1907101151_20190709_Non_Exhaust_Emissions_typeset_Final.pdf

[128] Ricardo E&E (2018) The Contribution of Brake Wear Emissions to Particulate Matter in Ambient Air. Online: https://www.vda.de/dam/vda/publications/2017/FAT/FAT-Schriftenreihe_301.pdf

[129] Interview with Tallano regarding TAMIC. Online: https://www.tallano.eu/en

[130] Mann + Hummel (2018) MANN+HUMMEL Successfully Tests Brake Dust Particle Filter. Online: https://www.mann-hummel.com/en/the-company/current-topics/press-releases/mann-hummel-successfully-tests-brake-dust-particle-filter/

[131] Fieldhouse and Gelb (2016) New Developments of an On-Vehicle Brake Pad Waste Collection System. SAE International Journal of Passenger Cars - Mechanical Systems 9. Online: https://www.researchgate.net/publication/323475357_New_Developments_of_an_On-Vehicle_Brake_Pad_Waste_Collection_System

[132] EEA (2019) Air quality in Europe — 2019 report. Online: https://www.eea.europa.eu/publications/air-quality-in-europe-2019

[133] VTI (2020) Microplastics from tyre and road wear A literature review. Online: http://vti.diva-portal.org/smash/get/diva2:1430623/FULLTEXT02.pdf

[134] Norwegian Institute for Water Research (2020) Microplastics in road dust – characteristics, pathways and measures. Online: https://niva.brage.unit.no/niva-xmlui/handle/11250/2493537

[135] The Pew Charitable Trusts (2020) Breaking the Plastic Wave A Comprehensive Assessment of Pathways

Towards Stopping Ocean Plastic Pollution. Online: https://www.pewtrusts.org/-/media/assets/2020/10/breakingtheplasticwave_mainreport.pdf

[136] Tyre Collective. Our Device. Online: https://www.thetyrecollective.com/

[137] European Parliament (2020) New EU rules on labelling of tyres. Online: https://www.europarl.europa.eu/RegData/etudes/BRIE/2018/625144/EPRS_BRI(2018)625144_EN.pdf

[138]DVSA (2021) MOT testing guide A handbook to scheme administration Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/950978/mot-testing-guide.pdf

[139] Dimensions (2019) Auto-Align - Reduction of tyre and road wear through wheel alignment monitoring. Online: https://app.dimensions.ai/details/grant/grant.8470028

[140] Penkała, Ogrodnik and Rogula-Kozłowska (2018) Particulate Matter from the Road Surface Abrasion as a Problem of Non-Exhaust Emission Control. Environments 5. Online: https://www.mdpi.com/2076-3298/5/1/9/pdf

[141] Gustaffson (2018) A Review of Road Emission Measurement Studies: Identification of Gaps and Future Needs

[142] Querol, Amato, Robusté, Holman and Harrison (2018) Non-Exhaust Emissions an Urban Air Quality Problem for Public Health; Impact and Mitigation Measures. Chapter 11 - Non-technological Measures on Road Traffic to Abate Urban Air Pollution. Online: https://www.sciencedirect.com/science/article/pii/B978012811770500011X

[143] Stern *et al* (2019) Quantifying air quality benefits resulting from few autonomous vehicles stabilizing traffic. Transportation Research Part D: Transport and Environment Volume 67. Online: https://www.sciencedirect.com/science/article/abs/pii/S1361920918304383

[144] Rafael *et al* (2020) Autonomous vehicles opportunities for cities air quality. Science of the Total Environment Volume 712. Online: https://www.sciencedirect.com/science/article/abs/pii/S0048969720300565#:~:text=The%20autonomous%20scenario%20promoted%20an,30%25%20for%20both%20air%20pollutants.

[145] Center for American Progress (2016) The Impact of Vehicle Automation on Carbon Emissions Where Uncertainty Lies. Online: https://www.americanprogress.org/issues/green/reports/2016/11/18/292588/the-impact-of-vehicle-automation-on-carbon-emissions-where-uncertainty-lies/

[146] Rojas-Rueda *et al* (2020) Autonomous Vehicles and Public Health. Annual Review of Public Health 241. Online: https://www.annualreviews.org/doi/pdf/10.1146/annurev-publhealth-040119-094035

[147] International Transport Forum (2015) Urban Mobility System Upgrade How shared self-driving cars could change city traffic. Online: https://www.itf-oecd.org/sites/default/files/docs/15cpb_self-drivingcars.pdf

[148] Victoria Transport Policy Institute (2020) Autonomous Vehicle Implementation Predictions Implications for Transport Planning. Online: https://www.vtpi.org/avip.pdf

[149] Connected Places Catapult (2020) Market Forecast for Connected and Autonomous Vehicles. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/919260/connected-places-catapult-market-forecast-for-connected-and-autonomous-vehicles.pdf

[150] DfT (2020) A better deal for bus users. Online: https://www.gov.uk/government/publications/a-better-deal-for-bus-users/a-better-deal-for-bus-users#:~:text=In%20a%20package%20worth%20%C2%A3,bus%20strategy%20and%20funding%20settlement.&text=We%20also%20want%20to%20create,to%20zero%20emission%20capable%20buses.

[151] HM Treasury (2020) Spending Review 2020. Online: https://www.gov.uk/government/publications/spending-review-2020-documents/spending-review-2020#departmental-settlements

[152] GLA (2018) London Environment Strategy. Online: https://www.london.gov.uk/sites/default/files/london_environment_strategy_0.pdf

[153] GLA (2021) Cleaner Buses. Online: https://www.london.gov.uk/what-we-do/environment/pollution-and-air-quality/cleaner-buses

[154] GLA (2021) Improving Buses. Online: https://tfl.gov.uk/modes/buses/improving-buses

[155] DfT (2020) Annual bus statistics: England 2019/20. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/929992/annual-bus-statistics-year-ending-march-2020.pdf

[156] Energy Saving Trust (2021) Clean Vehicle Retrofit Accreditation Scheme. Online: https://energysavingtrust.org.uk/service/clean-vehicle-retrofit-accreditation-scheme/

[157] Climate Change Committee (2020) The Sixth Carbon Budget Surface Transport. Online: https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-Surface-transport.pdf

Shipping

[158] Department of Transport, 2019. Maritime 2050: Navigating the Future, https://www.gov.uk/government/publications/maritime-2050-navigating-the-future

[159] DfT, 2019a. Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution, Maritime Emission Reduction Options, A Summary Report for the Department for Transport

[160] DfT, 2019b. Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution, Economic Opportunities from Low and Zero Emission Shipping. Technical Annexes

[161] DfT, 2019c. Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs

[162] DNV GL (2016) Global maritime energy efficiency partnerships (GLOMEEP) programme and Energy Efficiency Appraisal Tool https://glomeep.imo.org/resources/appraisal-tool/ and report https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/Final%20EE%20Appraisal%20Tool%20Report.pdf.

[163] Kollamthodi, S. *et al*. 2016, The role of natural gas and biomethane in the transport sector. Report by Ricardo Energy & Environment for Transport and Environment (T&E).

[164] Hansson, J. *et al*. (2020) The Potential Role of Ammonia as Marine Fuel—Based on Energy Systems Modeling and Multi-Criteria Decision Analysis. Sustainability 2020, 12, 3265; doi:10.3390/su12083265

[165] https://brittanyferriesnewsroom.com/brittany-ferries-and-repsol-extend-their-agreement-for-the-delivery-of-lng-for-long-haul-spanish-routes/

[166] https://www.orkney.gov.uk/Service-Directory/Renewable/h2-in-orkney-the-hydrogen-islands.htm

[167] DfT, 2019a. Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution, Maritime Emission Reduction Options, A Summary Report for the Department for Transport

[168] Sofras and Prousalidis, 2015. Developing a new methodology for evaluating diesel—electric propulsion, https://www.tandfonline.com/doi/pdf/10.1080/20464177.2014.11658123

[169] European Commission, 2015. GHG emission reduction potential of EU-related maritime transport and on its impacts, https://ec.europa.eu/clima/sites/clima/files/transport/shipping/docs/report_ghg_reduction_potential_en.pdf

[170] Royal Academy of Engineering. 2013. Future ship powering options : Exploring alternative methods of ship propulsion. https://www.raeng.org.uk/publications/reports/future-ship-powering-options

[171] DfT, 2019b. Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution, Economic Opportunities from Low and Zero Emission Shipping. Technical Annexes

[172] Notter, Gauch, Widmer, Wäger, Stamp, Zah and Althaus, 2010. Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles, https://pubs.acs.org/doi/10.1021/es903729a

[173] Sofras and Prousalidis, 2015. Developing a new methodology for evaluating diesel—electric propulsion, https://www.tandfonline.com/doi/pdf/10.1080/20464177.2014.11658123

[174] Department for Business, Energy & Industrial Strategy, 2020. Quarterly Energy Prices 2020 Annual Domestic Bills Estimates Supplement United Kingdom, 2020, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/956490/QEP_Q3_2020_Revision.pdf

[175] Department of Transport, 2019. Maritime 2050: Navigating the Future, https://www.gov.uk/government/publications/maritime-2050-navigating-the-future

[176] DNV GL (2016) Global maritime energy efficiency partnerships (GLOMEEP) programme and Energy Efficiency Appraisal Tool https://glomeep.imo.org/resources/appraisal-tool/ and report https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/Final%20EE%20Appraisal%20Tool%20Report.pdf.

[177] https://www.imo.org/en/OurWork/Environment/Pages/Technical-and-Operational-Measures.aspx#:~:text=Energy%20Efficiency%20Design%20Index%20(EEDI),-

[178] Rehmatulla, N., Parker, S., Smith, T. and Stulgis, V., 2015. Wind technologies: Opportunities and barriers to a low carbon, https://www.researchgate.net/publication/289995860_Wind_technologies_Opportunities_and_barriers_to_a_low_carbon_shipping_industry

[179] Chowdhury, Rahman, Chowdhury, and Nuthammachot, 2020. An overview of solar photovoltaic panels' end-of-life material recycling, https://www.researchgate.net/publication/338195279_An_overview_of_solar_photovoltaic_panels'_end-of-life_material_recycling

[180] Maddox Consulting, 2013. Analysis of market barriers to cost effective GHG emissions, https://ec.europa.eu/clima/sites/clima/files/transport/shipping/docs/market_barriers_2012_en.pdf

[181] Frontier Economics (2019) Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/816018/scenario-analysis-take-up-of-emissions-reduction-options-impacts-on-emissions-costs.pdf

[182] Wang, H. *et al*., 2015, Costs and benefits of shore power at the Port of Shenzhen, Report for International Council on Clean Transportation. https://theicct.org/publications/costs-and-benefits-shore-power-port-shenzhen

[183] California Air Resources Board. 2019. Control Measure for Ocean-Going Vessels At Berth : Cost Analysis Inputs and Assumptions for Standardized Regulatory Impact Assessment. https://ww2.arb.ca.gov/sites/default/files/classic/ports/shorepower/meetings/051419/costassumptions.pdf

[184] Guo *et al*., 2015. A Short Review of Treatment Methods of Marine Diesel Engine Exhaust Gases, 9th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC) and the 3rd

International Conference on Building Energy and Environment (COBEE), Procedia Engineering 121 (2015) 938 – 943.

[185] Cederqvist, H and Holmgren, C. 2011, Investment vs. operating costs: a comparison of automatic stacking cranes and RTGs. Port Technology International. https://www.porttechnology.org/wp-content/uploads/2019/05/064-066.pdf

[186] DfT, 2019b. Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution, Economic Opportunities from Low and Zero Emission Shipping. Technical Annexes.

Rail

[187] Kitanov and Podol'skii (2008) Analysis of Eddy-Current and Magnetic Rail Brakes for High-Speed Trains. The Open Transportation Journal. Online: https://benthamopen.com/contents/pdf/TOTJ/TOTJ-2-19.pdf

[188] RSSB (2020) Eddy-Current Track Brakes (ECTB). Online: https://www.rssb.co.uk/en/what-we-do/key-industry-topics/adhesion/changes-to-train-design/eddy-current-track-brakes

[189] Network Rail (2020) Traction Decarbonisation Network Strategy Interim Programme Business Case. Online: https://www.networkrail.co.uk/wp-content/uploads/2020/09/Traction-Decarbonisation-Network-Strategy-Interim-Programme-Business-Case.pdf

[190] RSSB (2020) Air Quality Strategic Framework. Online: https://www.rssb.co.uk/en/research-and-technology/sustainability/Air-quality

[191] Hart (2020) Traction Decarbonisation Network Strategy – Presentation. https://www.thepwi.org/technical_hub/technical_hub_files/section_meeting_presentations/19_november_2020_-_traction_decarbonisation__steven_hart

[192] Rail Industry Decarbonisation Taskforce (2019) Final Report to the Minister For Rail. Online: https://www.rssb.co.uk/research-and-technology/sustainability/Decarbonisation/Decarbonisation-our-final-report-to-the-Rail-Minister

[193] Pons, Williams, Norris, Cornwell and Brown (2019) Air Quality Improvement Measures – Cost and Feasibility Study for the Rail Industry. Online: https://www.sparkrail.org/Lists/Records/DispForm.aspx?ID=26223

[194] Rail Delivery Group (2018) Long Term Passenger Rolling Stock Strategy for the Rail Industry. Online: https://www.raildeliverygroup.com/files/Publications/2018-03_long_term_passenger_rolling_stock_strategy_6th_ed.pdf

[195] Luijt, van den Berge, Willeboordse and Hoogenraad (2017) 5 years of Dutch eco-driving: managing behavioural change. Transportation Research Part A, Volume 98

[196] EMEG. Neville Hill Depot – 850V Shore Supplies. Online: https://www.emeg.co.uk/case-studies/neville-hill-depot/

Aviation

[197] European Union Aviation Safety Agency (2020) ICAO Aircraft Engine Emissions Databank. v28. https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank

[198] B Underwood *et al* (2010) Heathrow Airport Emission Inventory 2008/9. AEAT/ENV/R/2906.

[199] K Sarsfield (2020) Pipistrel Velis Electro earns first all-electric aircraft type certification. https://www.flightglobal.com/news/pipistrel-velis-electro-earns-first-all-electric-aircraft-type-certification/138779.article

[200] P Wolfsteller (2020) Sweden's Heart Aerospace presents all-electric regional aircraft. https://www.flightglobal.com/airframers/swedens-heart-aerospace-presents-all-electric-regional-aircraft/140307.article

[201] The Engineer (2016) Fuel cell aircraft HY4 makes maiden flight. https://www.theengineer.co.uk/fuel-cell-aircraft-hy4-makes-maiden-flight/

[202] ICAO (2016) White Paper on Air Quality Aviation Impacts on Air Quality: State of The Science. Online: https://www.icao.int/environmental-protection/Documents/ScientificUnderstanding/EnvReport2016-WhitePaper_LAQ.pdf

[203] Committee on Climate Change (2020) The Sixth Carbon Budget: The UK's path to Net Zero

[204] Sustainable Aviation (2020) Decarbonisation road-map: a path to net zero.

[205] A King (2012) Ultra-low sulfur jet fuel on the radar. https://www.chemistryworld.com/news/ultra-low-sulfur-jet-fuel-on-the-radar/4985.article

[206] Sustainable Aviation (2020) Sustainable aviation fuels road-map

[207] Heathrow Airport (n.d.) Heathrow Air Quality Strategy 2011–2020

[208] Gatwick Airport (n.d.) Air quality management action plan

[209] Sustainable Aviation (n.d.) UK aviation and air quality

[210] Ricardo (2018) Heathrow Airport 2017 Emission Inventory

[211] Alexander Kugele *et al* (2005) Aircraft Particulate Matter Emission Estimation through all Phases of Flight. EEC/SEE/2005/0014. https://www.eurocontrol.int/sites/default/files/library/034_Aircraft_Particulate_Matter_Emission_Estimation.pdf

212 Heathrow Airport (2018) Emissions strategy and action plan. https://www.heathrow.com/content/dam/heathrow/web/common/documents/company/heathrow-2-0-sustainability/futher-reading/heathrow-emissions-strategy.pdf

213 K Sadler (2015) Frankfurt Airport expands fleet of electric vehicles. https://www.internationalairportreview.com/news/20875/frankfurt-airport-expands-fleet-of-electric-vehicles/

Agriculture

214 HM Government (2019) Farm practice survey February 2019 – greenhouse gas mitigation practices. Online: https://www.gov.uk/government/statistics/farm-practices-survey-february-2019-greenhouse-gas-mitigation-practices

215 Catchment Sensitive Farming – Reducing ammonia by effective nutrient management planning on dairy farm. Online: http://publications.naturalengland.org.uk/publication/5523097291849728?category=5100549248909312

216 Catchment Sensitive Farming – Reducing ammonia emissions through Integrated Nutrient Planning with Anaerobic Digestion. Online: http://publications.naturalengland.org.uk/publication/5218507572903936?category=5100549248909312

217 Catchment Sensitive Farming – Reducing Ammonia Emissions from Slurry Storage on Dairy Farms. Online: http://publications.naturalengland.org.uk/publication/5421995640750080?category=5100549248909312

218 Institute of Occupational Medicine (2018) Rapid evidence assessment of interventions to improve ambient air quality – Agriculture/ Rural Interventions. Online: https://www.researchgate.net/profile/James_Stewart-Evans/publication/331773629_A51_180907_REA4_-_Agriculture_IOM_REPORTpdf/data/5c8b88f192851c1df942302e/A51-180907-REA4-Agriculture-IOM-REPORT.pdf?origin=publication_list

219 Long-range transboundary air pollution (2014) Options for ammonia mitigation – guidance from the UNECE Task Force on Reactive Nitrogen. Online: http://www.clrtap-tfrn.org/content/options-ammonia-abatement-guidance-unece-task-force-reactive-nitrogen

220 Ricardo Energy and Environment (2019) Ammonia futures: understanding implications for habitats and requirements for uptake of mitigation measures – Stakeholder feasibility workshops and supporting review. Online: https://uk-air.defra.gov.uk/library/reports?report_id=995

221 Ricardo Energy and Environment (2017) Ammonia emissions from agriculture – updating the agriculture model. For DEFRA (unpublished)

222 DEFRA (2018) Code of Good Agricultural Practice (COGAP) for Reducing Ammonia Emissions. Online: https://www.gov.uk/government/publications/code-of-good-agricultural-practice-for-reducing-ammonia-emissions/code-of-good-agricultural-practice-cogap-for-reducing-ammonia-emissions#store-and-cover-your-organic-manures

223 T. H. Misselbrook and S. L. Gilhespy, 2019 Inventory of Ammonia Emissions from UK Agriculture. Online: https://uk-air.defra.gov.uk/library/reports?report_id=977

224 Defra (2017) New Farming Rules for Water. Online: https://www.gov.uk/government/news/new-farming-rules-for-water

[225] UK Government guidance Storing silage, slurry and agricultural fuel oil (2015). Online: https://www.gov.uk/guidance/storing-silage-slurry-and-agricultural-fuel-oil

[226] UK government Clean air Strategy policy. Online: https://www.gov.uk/government/publications/clean-air-strategy-2019

[227] Defra (2019) Countryside Stewardship and air quality - LM0475. Online: http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=20022

[228] Defra Consultation (2020) Reducing Ammonia from urea fertilisers. Online: https://consult.defra.gov.uk/air-quality-and-industrial-emissions/reducing-ammonia-emissions-from-urea-fertilisers/

[229] H. ApSimon, U. Dragosits, T. Misselbrook, J. Morgan and J. Webb (2012) Report on a workshop on costs of measures to reduce ammonia emissions to the atmosphere from agriculture in the UK. Unpublished.

[230] Catchment Sensitive Farming – Reducing ammonia emissions by focusing on building design on dairy farms. Online: http://publications.naturalengland.org.uk/publication/5791522916401152?category=5100549248909312

[231] Centre for Ecology and Hydrology (CEH) (2018) AROMA – Agri-Environment Reduction Options for Mitigating Ammonia: Assessment of the effects of RDPE environmental land management schemes on air quality. Online: http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&ProjectID=20022

[232] Wang *et al* (2018) Advances in low-protein diets for swine. Journal of Animal Science and Biotechnology 9. Online: https://jasbsci.biomedcentral.com/articles/10.1186/s40104-018-0276-7

[233] Catchment Sensitive Farming – Nutritional Approaches to reducing ammonia emissions in pig diets. Online: http://publications.naturalengland.org.uk/publication/6727550909022208?category=5100549248909312

[234] Defra (2020) Farming Statistics – Crop areas and cattle, sheep and pig populations at 1 June 2020 – England. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/928464/structure-june20-eng-21oct20.pdf

[235] CBRE (2021) Urban Agriculture. Online: https://www.cbre.co.uk/research-and-reports/our-cities/urban-agriculture

[236] J. P. Newell Price, Harris D., Taylor M., Williams J. R., Anthony S.G., Duethmann D., Goodday R.D., Lord E.I., Chambers B. J., Chadwick D.R. and Misselbrook T.H. (2011) An inventory of Mitigation methods and guide to their effects on diffuse water pollution, greenhouse gas emissions and ammonia emissions from Agriculture - Mitigation methods – user guide. Online: https://www.researchgate.net/publication/268200287_MITIGATION_METHODS_-_USER_GUIDE_An_Inventory_of_Mitigation_Methods_and_Guide_to_their_Effects_on_Diffuse_Water_Pollution_Greenhouse_Gas_Emissions_and_Ammonia_Emissions_from_Agriculture

[237] Centre for Ecology & Hydrology (2018) Quantifying the impact of future land use scenarios to 2050 and beyond – Final report. Online: http://www.theccc.org.uk/wp-content/uploads/2018/11/Quantifying-the-impact-of-future-land-use-scenarios-to-2050-and-beyond-Full-Report.pdf

[238] Tim Benton (2019) Climate change and diets: a CCC discussion meeting. Online: https://www.theccc.org.uk/wp-content/uploads/2020/01/Tim-Benton-2019-Climate-change-and-diets-a-CCC-discussion-meeting.pdf

[239] National Food Strategy (2020). Online: https://www.nationalfoodstrategy.org/approach-2020/

Industry

[240] Environment Agency (2020) 2018 Pollution Inventory. Online at: https://environment.data.gov.uk/portalstg/home/item.html?id=972525652487430185a69836ec4a71ef

[241] EIPPCB (2015) Best Available Techniques (BAT) Reference Document for the Refining of Mineral Oil and Gas. Online: https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/REF_BREF_2015.pdf

[242] EIPPCB (2014) Commission Implementing Decision of 9 October 2014 establishing best available techniques (BAT) conclusions, under Directive 2010/75/EU of the European Parliament and of the Council on industrial emissions, for the refining of mineral oil and gas. Online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32014D0738&from=EN

[243] UKPIA (2020) Transition, Transformation and Innovation - Our role in the Net-Zero Challenge. Online: https://ukpia.com/media/2230/ukpia-vision-july-2019.pdf

[244] UKPIA (2019) The Downstream Oil Sector in a Low-Carbon World. Online: https://ukpia.com/media/2230/ukpia-vision-july-2019.pdf

[245] Concawe (2020) A Clean Planet for all. Impact assessment on the potential implications for our refining system and the link with Refinery 2050. Online: https://www.concawe.eu/wp-content/uploads/Rpt_20-20.pdf

[246] Concawe (2020) Exploring possible pathways for the EU refining system to contribute to a low-CO2 economy in the 2030–2050 time frame. Online: https://www.concawe.eu/wp-content/uploads/Refinery-Technology.pdf

[247] Element Energy (2020) Deep-Decarbonisation Pathways for UK Industry A report for the Climate Change Committee. Online: https://www.theccc.org.uk/publication/deep-decarbonisation-pathways-for-uk-industry-element-energy/

[248] IEA (2020) Flaring Emissions. Online: https://www.iea.org/reports/flaring-emissions

[249] EIPPCB (2012) Best Available Techniques (BAT) Reference Document: for Iron and Steel Production. Online: http://eippcb.jrc.es/reference/BREF/IS_Adopted_03_2012.pdf

[250] EA (2013) Comparison of techniques employed at Scunthorpe Integrated Steelworks with those in the BAT Conclusions for Iron and Steel Production published in the Official Journal of the European Union, 8th March 2012. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/488404/Reg_60_response_dated_02-09-13.pdf

[251] Turley (2018) Planning Statement Sinter Plant De-Dust 2020 Project Port Talbot Steelworks, Port Talbot. Online: http://appsdevweb.npt.gov.uk/iDocsPublic/ShowDocument.aspx?id=624433

[252] Tata Steel (2013) Tata Steel brings forward bag filter installation. Online: https://www.tatasteeleurope.com/ts/corporate/news/tata-steel-filter-installation

[253] TNO (2002) Potentials and costs to reduce PM_{10} and $PM_{2.5}$ emissions from industrial sources in the Netherlands. Online: https://www.infomil.nl/publish/pages/65238/potentialsandcoststoreducepm10andpm2_5emissionsfromindustrialsourcesinthenetherlands.pdf

[254] EIPPCB (2019) Best Available Techniques (BAT) Reference Document for the Food, Drink and Milk Industries. Online: https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/JRC118627_FDM_Bref_2019_published.pdf

[255] Environment Agency (2020) 2018 Pollution Inventory. Online at: https://environment.data.gov.uk/portalstg/home/item.html?id=972525652487430185a69836ec4a71ef

[256] EIPPCB (2019) Commission Implementing Decision (EU) 2019/2031 of 12 November 2019 establishing best available techniques (BAT) conclusions for the food, drink and milk industries, under Directive 2010/75/EU of the European Parliament and of the Council. Online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2019.313.01.0060.01.ENG&toc=OJ%3AL%3A2019%3A313%3ATOC

[257] ABF (2019) Associated British Foods - Climate Change 2019. Online: https://www.abf.co.uk/documents/pdfs/2019/ar2019/abfcdpclimatechange2019.pdf

[258] European Parliament (2015) Directive (EU) 2015/2193 of the European Parliament and of the Council of 25 November 2015 on the limitation of emissions of certain pollutants into the air from medium combustion plants (Text with EEA relevance) https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32015L2193

[259] The Environmental Permitting (England and Wales) Regulations 2016 https://www.legislation.gov.uk/uksi/2016/1154/contents/made

[260] Environment Agency. Medium Combustion Plant Guidance. Online: https://consult.environment-agency.gov.uk/psc/mcp-and-sg-regulations/supporting_documents/MCPD%20Guidance%20interim.%20Final.pdf

[261] Glowacki Law Firm (2016) Medium Combustion Plant Emissions Limitations https://www.emissions-euets.com/mcp-basics

[262] Defra (2019) Clean Air Strategy. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770715/clean-air-strategy-2019.pdf

[263] Defra (2016) Amendments to environmental permitting regulations to improve air quality by transposition of Medium Combustion Plant Directive and application of emission controls to high NOx generators in anticipation of

the 2020 NOx emission ceiling within the Gothenburg Protocol. Online: https://consult.defra.gov.uk/airquality/medium-combustion-plant-and-controls-on-generators/supporting_documents/Impact%20Assessment.pdf

[264] Ofgem (2020) Non-Domestic RHI tariffs and payments. Online: https://www.ofgem.gov.uk/environmental-programmes/non-domestic-rhi/contacts-guidance-and-resources/non-domestic-rhi-tariffs-and-payments

[265] BEIS (2021) Renewable Heat Incentive statistics. Online:

https://www.gov.uk/government/collections/renewable-heat-incentive-statistics#:~:text=the%20non%2Ddomestic%20Renewable%20Heat,systems%20in%20the%20domestic%20sector

[266] BEIS (2018) Renewable Heat Incentive: Biomass Combustion In Urban Areas. Consultation. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/749016/RHI-support-for-biomass-in-urban-areas-consultation.pdf

[267] BEIS (2020) Consultation outcome. Renewable Heat Incentive: biomass combustion in urban areas. Online: https://www.gov.uk/government/consultations/renewable-heat-incentive-biomass-combustion-in-urban-areas

[268] BEIS (2020) Renewable Heat Incentive: biomass combustion in urban areas. Government response to consultation. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/880346/rhi-biomass-combustion-in-urban-areas-government-response.pdf

[269] Gov UK. Biomass Suppliers List (BSL). Online: https://biomass-suppliers-list.service.gov.uk/

[270] BEIS (2020) Report: Air Quality Pollutant Inventories for England, Scotland, Wales and Northern Ireland: 1990-2018. Online: https://naei.beis.gov.uk/reports/reports?report_id=1010

[271] AQEG (2021) Fine Particulate Matter in the UK. Online: https://uk-air.defra.gov.uk/assets/documents/reports/cat11/1212141150_AQEG_Fine_Particulate_Matter_in_the_UK.pdf

[272] European Commission (2013) Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide. Online: https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/CLM_Published_def_0.pdf

[273] European Commission (2017) Best Available Techniques (BAT) Reference Document for the Non-Ferrous Metals Industries. Online: https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-01/JRC107041_NFM_bref2017.pdf

[274] IAQM (2016) Guidance on the Assessment of Mineral Dust Impacts for Planning. Online: https://iaqm.co.uk/text/guidance/mineralsguidance_2016.pdf

[275] EEA (2019) Quarrying and mining of minerals other than coal. Guidebook 2019

[276] EPA (1995) AP 42, Fifth Edition, Volume I Chapter 11: Mineral Products Industry. Sand and Gravel Processing. Online: https://www.epa.gov/sites/production/files/2020-10/documents/c11s19-1.pdf

[277] North Lincolnshire (2019) 2019 Air Quality Annual Status Report (ASR). Online: https://www.northlincs.gov.uk/wp-content/uploads/2020/03/Air-Quality-Status-Report-2019.pdf

[278] Envirosuite. Pro-active air quality and dust solution implemented at a UK steelworks. Online: https://envirosuite.com/projects/managing-air-quality-and-dust-emissions-at-a-uk-steelworks-operation

[279] HM Treasury (2020) Consultation on reforms to the tax treatment of red diesel and other rebated fuels. Online: https://www.gov.uk/government/consultations/consultation-on-reforms-to-the-tax-treatment-of-red-diesel-and-other-rebated-fuels

[280] HM Government (2020) Ten Point Plan for a Green Industrial Revolution. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/936567/10_POINT_PLAN_BOOKLET.pdf

[281] HM Government (2020) Energy White Paper. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/945899/201216_BEIS_EWP_Command_Paper_Accessible.pdf

[282] HM Government (2021) Industrial Decarbonisation Strategy. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/970229/Industrial_Decarbonisation_Strategy_March_2021.pdf

[283] Element Energy (2020) Deep-Decarbonisation Pathways for UK Industry A report for the Climate Change Committee. Online: https://www.theccc.org.uk/publication/deep-decarbonisation-pathways-for-uk-industry-element-energy/

[284] Climate Change Committee (2020) Policies for the Sixth Carbon Budget and Net Zero. Online: https://www.theccc.org.uk/wp-content/uploads/2020/12/Policies-for-the-Sixth-Carbon-Budget-and-Net-Zero.pdf

[285] Lott, Pye and Dodds (2017) Quantifying the co-impacts of energy sector decarbonisation on outdoor air pollution in the United Kingdom. Energy Policy Volume 101. Online: https://www.sciencedirect.com/science/article/abs/pii/S030142151630622X

[286] Frazier-Nash Consultancy (2018) Appraisal of Domestic Hydrogen Appliances. Online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/699685/Hydrogen_Appliances-For_Publication-14-02-2018-PDF.pdf

[287] Energy Systems Catapult (2020) Industrial Decarbonisation: Net Zero Carbon Policies to Mitigate Carbon Leakage and Competitiveness Impacts. Online: https://www.theccc.org.uk/publication/industrial-decarbonisation-net-zero-carbon-policies-to-mitigate-carbon-leakage-and-competitiveness-impacts-energy-systems-catapult/

[288] BEIS (2021) National Statistics Energy consumption in the UK. Online: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk

[289] UCL. UK TIMES. Online: https://www.ucl.ac.uk/energy-models/models/uk-times

Construction

[290] Directive 2004/ 26/EC of the European Parliament and of the Council of 21 April 2004 amending Directive 97/68/EC on the approximation of the laws of the Member States relating to measures against the emission of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery

[291] Regulation (EU) 2016/1628 of the European Parliament and of the Council of 14 September 2016 on requirements relating to gaseous and particulate pollutant emission limits and type-approval for internal combustion engines for non-road mobile machinery, amending Regulations (EU) No 1024/2012 and (EU) No 167/2013, and amending and repealing Directive 97/68/EC

[292] C.D. Desouza *et al* (2020) Real-world emissions from non-road mobile machinery in London. Atmospheric Environment 223 (2020) 117301. https://doi.org/10.1016/j.atmosenv.2020.117301

[293] Mayor of London (n.d.) Non-Road Mobile Machinery (NRMM). https://www.london.gov.uk/what-we-do/environment/pollution-and-air-quality/nrmm

[294] HS2 (n.d.) HS2 and air quality. https://www.hs2.org.uk/building-hs2/hs2-environment-facts/hs2-and-air-quality/

[295] HS2 (2020) HS2's world-first emissions retrofit solution cuts emissions and carbon and will save millions of pounds. https://mediacentre.hs2.org.uk/news/hs2s-world-first-emissions-retrofit-solution-cuts-emissions-and-carbon-and-will-save-millions-of-pounds

[296] Considerate Constructors Scheme (2018) Efficient Management of Non Road Mobile Machinery (NRMM). https://ccsbestpractice.org.uk/entries/efficient-management-of-non-road-mobile-machinery-nrmm/

[297] Construction Logistics and Community Safety (n.d.) Case Studies. https://clocs.org.uk/casestudies.php

[298] Fleet Operator Recognition Scheme (n.d.) Your route to best practice. https://www.fors-online.org.uk/

[299] Fleetmaster Group (n.d.) SAFED (Safe and Fuel Efficient Driving). https://www.fleetmastergroup.com/safed/

[300] Construction Logistics and Community Safety (n.d.) What is CLOCS. https://clocs.org.uk

[301] HM Treasury (2020) Consultation on reforms to the tax treatment of red diesel and other rebated fuels. https://www.gov.uk/government/consultations/consultation-on-reforms-to-the-tax-treatment-of-red-diesel-and-other-rebated-fuels

[302] HM Treasury (2019) Non-road mobile machinery and red diesel call for evidence: summary of responses . https://www.gov.uk/government/consultations/non-road-mobile-machinery-and-red-diesel-excluding-use-for-agriculture-fishing-vessels-home-heating-and-other-static-uses

[303] Scottish Plant Owners Association (2020) Scottish Plant Owners Association response to the Government Consultation on the Removal of Red Diesel Subsidy. https://www.spoa.org.uk/application/files/3616/0154/4283/SPOA_response_to_the_Government_Consultation_on_the_Removal_of_Red_Diesel_Subsidy.pdf

[304] CEDR (2018) CEDR Call 2015: Climate Change: DeTECToR: Decission-support Tools for Embedding Climate Change Thinking on Roads. Interim Report 2. https://trl.co.uk/projects/decision-support-tools-for-embedding-climate-change-thinking-on-roads--detector-/

[305] US Environmental Protection Agency (n.d.) Verified Technologies for SmartWay and Clean Diesel: Various Technology—Biodiesel (1-100%). https://www.epa.gov/verified-diesel-tech/various-technology-biodiesel-1-100

[306] LiRuina *et al* (2014) Effects of cetane number improvers on the performance of diesel engine fuelled with methanol/biodiesel blend. Fuel, Volume 128, 15 July 2014, Pages 180-187. https://doi.org/10.1016/j.fuel.2014.03.011

[307] Paresh D.Patel *et al* (2016) Bio fuels for compression ignition engine: A review on engine performance, emission and life cycle analysis. Renewable and Sustainable Energy Reviews Volume 65, November 2016, Pages 24-43. https://doi.org/10.1016/j.rser.2016.06.010

[308] Teemu Ovaska *et al* (2019) Effect of Alternative Liquid Fuels on the Exhaust Particle Size Distributions of a Medium-Speed Diesel Engine. Energies 2019, 12, 2050; doi:10.3390/en12112050

[309] K. Thuneke *et al* (2016) Real driving emissions of vegetable oil fuelled tractors. 24th European Biomass Conference and Exhibition, 6-9 June 2016, Amsterdam, Netherlands

[310] Ruud Verbeek (2014) Assessment of pollutant emissions with Shell GTL fuel as a drop in fuel for medium and heavy-duty vehicles, inland shipping and nonroad machines. TNO 2014 R10588

[311] G. Kadijk *et al* (2014) Projected impact of biodiesel on road transport emissions up to 2030 – background report. TNO 2014 R10715 | 1.0

[312] Road Haulage Association (2020) Response of the Road Haulage Association to HM Treasury Reforms to the tax treatment of red diesel and other rebated fuels. https://www.rha.uk.net/getmedia/da96e34a-e878-4fba-8672-6a93000af930/200930-HMT-consultation-red-diesel-ttax-Fin_1.pdf.aspx

[313] PLM (n.d.) Zero Emissions. https://www.plmtrailer.com/products-services/zero-emissions

[314] Shorepower Technologies (n.d.) Electric standby infrastructure for reefers. https://www.shorepower.com/etru/

[315] Highways England (n.d.) Connected Autonomous Plant to 2035. https://highwaysengland.co.uk/industry/innovation/connected-autonomous-plant-to-2035/

[316] Himoinsa (n.d.) Variable speed hybrid generator sets that reduce fuel consumption by 40% and extend maintenance periods up to 1000 hours. https://www.himoinsa.com/eng/news/63/product-launch/variable-speed-hybrid-generator-sets-himoinsa.html

[317] Getlithium.com (n.d.) Diesel generators for hybrid electric. http://www.getlithium.com/diesel_hybrid_off_grid_micro_grid_solar_power.html

[318] Polar Power (n.d.) Hybrid power systems. https://polarpower.com/hybrid-power-systems/