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Evaluating the variability and consistency of NO_x emission regulation between sectors†

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The emissions of nitrogen oxides (NO_x) from combustion have been regulated for several decades with substantial reductions in national totals being reported in high-income countries since the 1990s. Most technical regulation on emissions is sectoral, appliance specific, and uses metrics aligned to activity data, for example grams of NO_x per kilometre driven or grams per kilonewton thrust. It is not straightforward therefore to compare the relative stringency of emission regulation between sectors. Here we undertake a regulatory assessment placing all the key NO_x emitting sectors onto a common grams of NO_x per kilowatt hour ($g_{[NO_x]}$ kWh^{-1}) baseline, covering appliances as small as 1 kW to greater than 2 GW. This common scale facilitates meaningful regulatory comparisons and may help to inform future policy decisions. We find little regulatory consistency between sectors when viewed on a per kWh output basis, with non-road mobile machinery (NRMM), medium combustion plant (MCP), maritime and civil aviation having more permissive regulatory limits when compared to emissions from passenger cars and domestic boilers. This difference can be large for appliances with the same nominal power rating; for example, the allowable NO_x emissions for a backhoe loader are 4.3 times higher than those for a passenger car. Transparency in pollutant emissions varies considerably between sectors. Data from MCPs and the Industrial Emissions Directive (IED) are less accessible due to commercial sensitivities and the use of less definitively defined principles of 'Best Available Techniques'. Whilst electrification is likely in the long-term to eliminate some NO_x sources, it is notable that this will be in sectors that currently have more stringent regulatory limits (*e.g.* road transport, domestic heating). More permissively regulated sectors such as NRMM, MCPs and aviation are likely to retain combustion systems and will continue to emit substantial NO_x unless the adoption of low carbon fuel is accompanied by revision of NO_x emission standards.

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Environmental significance

Current regulation governing nitrogen oxide (NO_x) emissions is highly sector specific and commonly stipulated in activity-based units. To allow for comparison of relative stringencies of legislation, here we convert all units onto a common energy output scale. This is a timely analysis as the pathway to net zero will lead to an adjustment in combustion (and therefore NO_x) sources. A greater understanding of the relative NO_x emission limits is important to inform future regulatory standards for sectors likely to retain combustion regardless of future fuel decarbonisation.

1. Introduction

Nitrogen oxides (NO_x: the sum of NO + NO_2) are a class of air pollutants that have a direct impact on human health. The NO_2 molecule acts as a respiratory irritant, aggravating or leading to the development of asthma, emphysema and other respiratory complaints.[1] Additionally, NO_x contributes significantly to broader air quality problems, including the formation of secondary particulate matter,[2] the production of tropospheric ozone,[3,4] and ecological damage through nitrogen deposition.[5] In many high-income countries NO_x emissions have decreased substantially over the past three decades[6–9] as a consequence of increasing emissions abatement from multiple sectors including electrical power and transport. For example, the UK total annual NO_x emissions have reduced from ~3 Tg in 1970 to ~0.6 Tg in 2021.[10] Despite this reduction, NO_2 concentrations in the UK continue, in some locations, to regularly exceed the 2021 WHO air quality guideline value of an annual average of 10 μg m^{-3}.[11] Data gathered as part of the fifth WHO global air quality database indicated that in 2020, the annual mean average NO_2 concentration exceeded this guideline in 83 out of 92 cities within the UK.[12]

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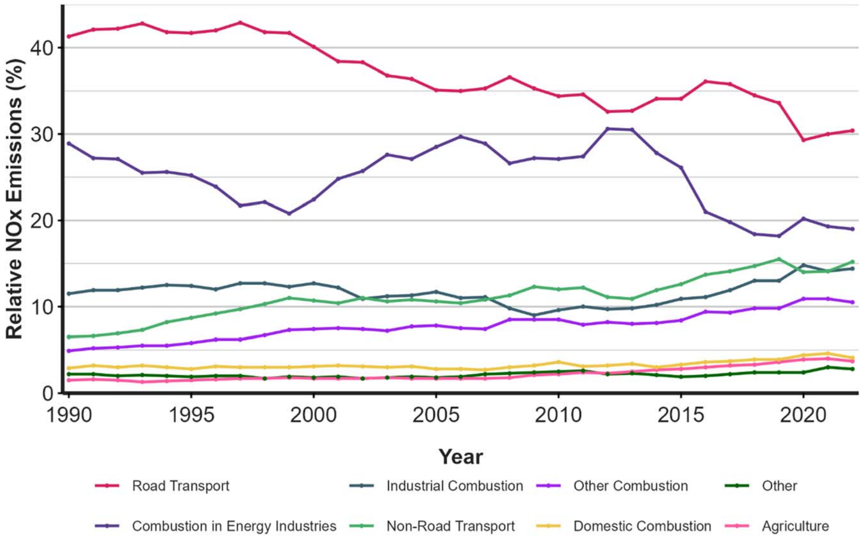

Fig. 1 Relative contributions to the overall NO_x UK emissions from seven major activity sectors over the period 1990 to 2022.[19] All other emission sources are grouped together as 'Other' and include: fugitive emissions from fuels, industrial processes and product use, military aircraft and naval shipping.

Trends in the UK since 1970

Reductions in the amount of NO_x emitted have been achieved through many different technical interventions, for example adding exhaust gas aftertreatment to combustion processes, alongside other macrotrends such as the decarbonisation of the energy supply.[13] The relative distribution of NO_x emissions between major economic sectors in the UK has changed markedly over the last 30 years; see Fig. 1. Despite an increase in the number of vehicles registered,[14] NO_x emissions from road transport have decreased in response to the introduction of progressively more stringent European emissions legislation since 1996.[15–17] Energy-related emissions of NO_x, which include both small-scale heating and large-scale electricity production, have also reduced in relative terms due to a combination of increasingly stringent emissions standards and a reduction in activity. Particularly significant in a UK context has been the post-2012 reduction in fossil fuel derived NO_x from electricity generation due to an increase in renewable production.[18] As emissions from these main sectors have dropped, other sectors, such as non-road transport and agriculture, have seen a rise in their relative share of NO_x emissions.

Fig. 1 demonstrates that the NO_x reductions delivered by different economic sectors has been somewhat variable. Current legislation for NO_x emissions is derived from multiple, seemingly disconnected, European directives and international agreements and regulations, often with very high levels of appliance specificity and granularity but with little obvious consistency between sectoral and regulatory domains. To exemplify this, there is individual regulation in place on maximum NO_x to be emitted from appliances as small as <1 kW power output for individual chainsaws,[20] to the flue stacks of >2 GW power stations.[21]

We are unaware of any analysis that places the myriad of current NO_x legislative standards on to a level playing field. Compilation of this data offers the opportunity to identify the degree to which different sectors are either over- or under-performing in delivering NO_x reductions. This is a relevant and timely analysis since the delivery of net zero will not eliminate NO_x as a pollutant. Many sectors are likely to retain combustion in some form; potentially using lower carbon or alternative fuels, such as biodiesel, sustainable aviation fuel (SAF) or hydrogen,[22,23] all of which have associated, and in some cases uncertain, air pollution implications.[24,25] The stringency of the relevant emissions legislation will therefore be crucial in determining whether the potential air quality co-benefits are realised alongside net zero greenhouse gas emissions.

Scope

This analysis examines the current legislative requirements and level of ambition for control of emissions of NO_x in the UK, but much of the insight is transferable to other European jurisdictions, and the principles are likely to be internationally applicable. This is not intended to be an assessment or revision of actual real-world emissions, but rather an examination of the regulatory perspective. We note however, that regulatory limits often define real-world emissions, since many sectors typically emit close to the maximum limits that are allowed.[26] Here we place a wide range of prevailing regulation on a 'level playing field', through conversion of activity and emission limits onto a common baseline of grams of NO_x emitted per kilowatt hour power delivered ($g_{[NO_x]}$ kWh^{-1}). When a direct conversion is not feasible or applicable, we use operational or quoted emissions. This assessment focuses on the current standards for newly marketed products or industrial installations and does not cover previous emission stages.

The regulations and directives reviewed, and their scope are shown in Table 1.

The absence of a unified regulatory framework covering all NO_x emitting activity means that a detailed analytical approach is required, with specific assumptions and methodologies

Table 1 Directives, regulations and international treaties that have been considered in this review with a brief description of their scope

Regulatory framework	Scope	Legislative reference
Ecodesign	Many household and commercial products including boilers, air heaters and stoves	2009/125/EC[27]
Non-road mobile machinery	Machinery intended for purposes other than for the transport of passengers or goods on roads, including forklift trucks, backhoe loaders, construction equipment, garden equipment; chain saws and lawnmowers	(EU) 2016/1628 (ref. 20)
Medium combustion plants	Combustion plants that have a rated thermal input of less than or equal to 1 MW and less than 50 MW	(EU) 2015/2193 (ref. 28)
Industrial emissions directive	Large industrial installations, including combustion plants, with thermal inputs greater than 50 MW	2010/75/EU[21]
Road transport	Transport on roads including cars, light commercial vehicles, heavy duty diesel engines and motorbikes	(EU) 2017/1151 (ref. 29) 595/2009/EC[30]
Aviation	Civil aviation	ICAO CAEP 8 (ref. 31)
Shipping	International shipping	MARPOL[32]

applied to each sector. To support the reader in understanding how normalisation to common units has been achieved, each emission sector is described separately and in detail. Since the methodology to derive g kWh^{-1}, the relevant assumptions, and obtained values are closely linked, we include the methodology and sectoral results together for clarity. This makes it straightforward to identify the sensitivity of calculated values to the assumptions made.

2. Ecodesign directive

The Ecodesign directive formally links a series of regulations that specify energy-efficiency and emissions requirements. This directive covers 31 energy-related product types that are commonly used in domestic and commercial settings including boilers used for space and water heating. Due to the stationary nature of these appliances, NO_x emissions may disproportionately affect those who live in densely populated areas such as cities, and potentially contribute to air quality inequalities.[33]

Emission limit values are given as mg kWh^{-1} of fuel input gross calorific value.‡ There are no assigned power ratings accompanying these limit values; emission limits are specified based solely on the product type. Therefore, to allow for collation onto a common metric, the following approach was taken to define the power rating of the appliances:

(1) Legislation was reviewed to determine whether pre-specified power ranges apply to any of the products covered by the directive. Maximum power outputs were noted where specified.

(2) A database of domestic and commercial products currently on the market matching the current standards was collated and the average power rating for different fuel inputs was calculated (full details can be found in the ESI, Table S1†). Uncertainties in these estimates were assigned based upon the standard deviation of products available on the market.

The focus of this section is household boilers due to the amount of data commercially available and the large contribution from domestic combustion to total national NO_x emissions (4% in 2022, of which 89.2% arises from space and water heating following natural gas and oil combustion).[10] The values used are shown in Table 2.

Residential oil boilers were found to have the highest allowable limits of NO_x emissions per kWh of heat released – 106 mg kWh^{-1}. Residential natural gas and liquified petroleum gas boilers produced comparatively lower emissions, 28.8 and 25.8 mg kWh^{-1} respectively, for approximately the same nominal power rating. It is notable that the emission limit value prescribed by Ecodesign legislation for 'fuel boiler space heaters and fuel boiler combination heaters using gaseous fuels' is 56 mg kWh^{-1}, higher than the average observed from the current market demonstrating the ability of new residential boilers be able to outperform their current emissions limits.

The relatively long lifespan of boilers (approximately 15 years[34]) means that new legislative changes will have a long-term impact. Since boilers are replaced relatively infrequently, real-world emissions are likely to be on average higher than those shown in Table 2, as many older appliances that are subject to less stringent regulatory limits will still be in use.

3. Non-road mobile machinery

Non-Road Mobile Machinery (NRMM) encompasses a broad range of machinery,§ from small hand-held devices, such as chainsaws, to 1000 kW excavators. The NRMM sector contributed 2.8% of total UK NO_x emissions in 2022.[35] Construction NRMM can also be an important urban source of NO_x in cities,

‡ The gross calorific value (GCV) is defined as: the total amount of heat released by a unit quantity of fuel when it is burned completely with oxygen and when the products of combustion are returned to ambient temperature; this quantity includes the condensation heat of any water vapour contained in the fuel and of the water vapour formed by the combustion of any hydrogen contained in the fuel (2009/125/EC).

§ Formally defined as 'any mobile machine, transportable equipment or vehicle with or without bodywork or wheels, not intended for the transport of passengers or goods on roads, and includes machinery installed on the chassis of vehicles intended for the transport of passengers or goods on roads'.

Table 2 Power and NO_x emissions for different fuel and different use case boilers. The standard error is calculated as $\frac{\sigma}{\sqrt{n}}$, where σ is the standard deviation, n is the number of observations, NG = natural gas and LPG = liquified petroleum gas

Fuel	Usage	Count	Mean power (kW)	Standard error power (kW)	Mean NO_x (mg kWh^{-1})	Standard error NO_x (mg kWh^{-1})
LPG	Commercial	6	71.7	14.2	54.4	5.6
LPG	Residential	21	35.3	1.5	25.8	0.9
NG	Commercial	7	82.9	16.4	34.5	0.3
NG	Residential	29	33.4	1.5	28.8	1.5
Oil	Residential	5	27.2	6.3	106.6	3.2

Table 3 NRMM emission limit values for the NRE engine category depending upon the engine type. Values marked with an asterisk denote those estimated based upon emission factors published in the EMEP/EEA guidance[36]

		Emission limit values (g kWh^{-1})			
Engine subcategory	Max power (kW)	Combined HC + NO_x	Diesel	Two-stroke petrol	Four-stroke petrol
NRE-1	8	7	6.73*	0.023*	1.54*
NRE-2	19	7	6.73*	0.021*	2.96*
NRE-3	37	4.5	4.22*	0.013*	1.61*
NRE-4	56	4.5	4.34*	0.016*	1.19*
NRE-5	130	—	0.40	0.40	0.40
NRE-6	560	—	0.40	0.40	0.40
NRE-7	1000	—	3.50	3.50	3.50

increasing individual exposure and influencing inequalities in population exposure to NO_2.

Regulation (EU) 2016/1628 introduced Stage V emission limits for NRMM engines, amending and repealing several previous directives and regulations. This regulation defines ten categories and 47 sub-categories of engine, based upon usage, power, swept volume and operational speed. Full details of these sub-categories are specified in Annex I of the regulation.[20]

Exhaust emission limits for NRMM are already given in units of grams of pollutants per kilowatt hour of useful work (g kWh^{-1}). For small lower power-rated appliances, typically ≤56 kW, this emissions limit is given as combined hydrocarbon (HC) and NO_x value. To extract estimates of the separate NO_x emissions limits, NRMM emission factors produced by the European Modelling and Environment Programme/European Environment Agency (EMEP/EEA) were used.[36] The EMEP/EEA use a tier three approach to calculate emission factors for air pollutants including NO_x, volatile organic compounds (VOCs) and CH_4. This splits the NRMM population into different machinery types, ages, and power ranges, including those where the emission limit value in Regulation 2016/1628 is not specified individually for NO_x. These emission factors are widely used by national emissions inventories including the UK National Atmospheric Emissions Inventory (NAEI).[37]

To estimate the NO_x emission limit value for power categories where pollutants are not explicitly separated, a ratio of the emission factors from the EMEP/EEA guidance was taken between the hydrocarbons, (ΣVOCs + CH_4), and NO_x and applied to the combined regulated limit value. For engines classed as non-road engines (NRE), which cover the majority of NRMM, NO_x limits are not individually specified for categories NRE-1 to NRE-4, so a regulatory 'NO_x apportionment' has been made using this ratio method, see Table 3. These values are typically higher than for the larger engines where NO_x emission limit values (ELVs) are directly specified; higher allowable limits for NO_x from smaller engines may be because of scale and a limited availability of cost-effective abatement technologies. Larger engines (56–560 kW) have more stringent emissions regulation for NO_x, presumably because economy of scale allows for the installation of aftertreatment methods such as selective catalytic reduction (SCR). Somewhat counter-intuitively however, regulation allows for a higher NO_x emission per unit of useful energy for the largest engines (power outputs greater than 560 kW); the NRE-7 ELV is 3.5 g kWh^{-1}, 8.75 times higher than the ELV for NRE-6 engines. Such anomalies are difficult to rationalise from a technical perspective.

As the emission factors in the EMEP/EEA guidance differ based upon the type of engine, the sector, and the fuel, it was necessary to compile a list of the types of equipment used and the corresponding type of engine. The NRMM sector covers a vast array of equipment and machinery types, and thus it is challenging to produce a definite list of all NRMM. A list that is provided within the 2023 EMEP/EEA guidance, which details typical power ranges and fuel type, was elected to be used due to its comprehensive coverage and sectoral separation.

From this detailed list, the machinery description was matched to the sub-categories of engine as defined in Regulation 2016/1628, see Table S2.† The fuel typically used was also considered and allowed for the assignment of a minimum and maximum NO_x emission limit value. The combined ELVs and power ratings data were plotted, see Fig. 2, where the weighted mean of the ELVs and the midpoint between specified power ratings was plotted. This compilation demonstrates an anticipated difference between emission estimates for diesel engines in comparison to either two-stroke or four-stroke petrol engines.

Other NRMM

Railways. Non-road mobile machinery also covers railcars and locomotives. Despite 70% of rolling stock in Great Britain being electric, only 32% of the track is electrified.[38] This creates significant potential for NO_x exposure, particularly at and surrounding railway stations. The age of the rolling stock is also important; as of 2018, only 10% of GB rail diesel engines conformed to the Stage V limits and 38% of units were manufactured prior to the introduction of mandatory emission regulation.[20] The Rail Safety and Standards Board conducted a fleet-wide assessment of rail emissions factors[39] to propose a new approach for estimating emissions from the rail sector. This research involved using on-train monitoring recorders alongside train loading data to develop emission factors as a function of engine operating conditions for several train classes; 66, 158, 170, 220/221, see Fig. 3.

Class 66 locomotives are classified under Regulation 2016/1628 as RLL engines, whereas classes 158, 170, 220/221 are classed as railcars, RLR. These categories have respective emission limit values of 4 g HC + NO_x per kilowatt hour and 2 g NO_x per kilowatt hour for all power outputs under Stage V regulation. The EMEP/EEA guidebook was used to estimate the typical power outputs from railcars and locomotives.[40] The method of ratio apportionment was applied to the RLL category to estimate the separated NO_x limit. These values are shown in Fig. 2.

The real-world emissions from these trains significantly exceed the Stage V emission limits, see Fig. 3. Whilst this is to be anticipated as these train classes are not subject to this recent legislation, it demonstrates the importance of ambitious foresight and consideration of the product lifespan when introducing regulation. Fig. 3 also demonstrates that the times in which engines are likely to be closest to people, *e.g.* idling at a station at low power outputs, coincides with the regime which produces the most NO_x per unit of energy. However, measurements made at Birmingham New Street station demonstrate that a multitude of factors, particularly station design and configuration, affect pollution exposure.[41]

Inland waterway vessels. Inland waterway vessels are also covered by the NRMM emissions legislation. Emission limits for Regulation 2016/1628 are also defined based upon the power output. Thus, to evaluate this sector on the common $g_{[NO_x]}$ kWh^{-1} baseline, an approach has been taken to take the midpoint of the power categories where applicable, and the minimum point in the incidents where no upper bound is defined. Definitions of these engines can be found in the ESI,

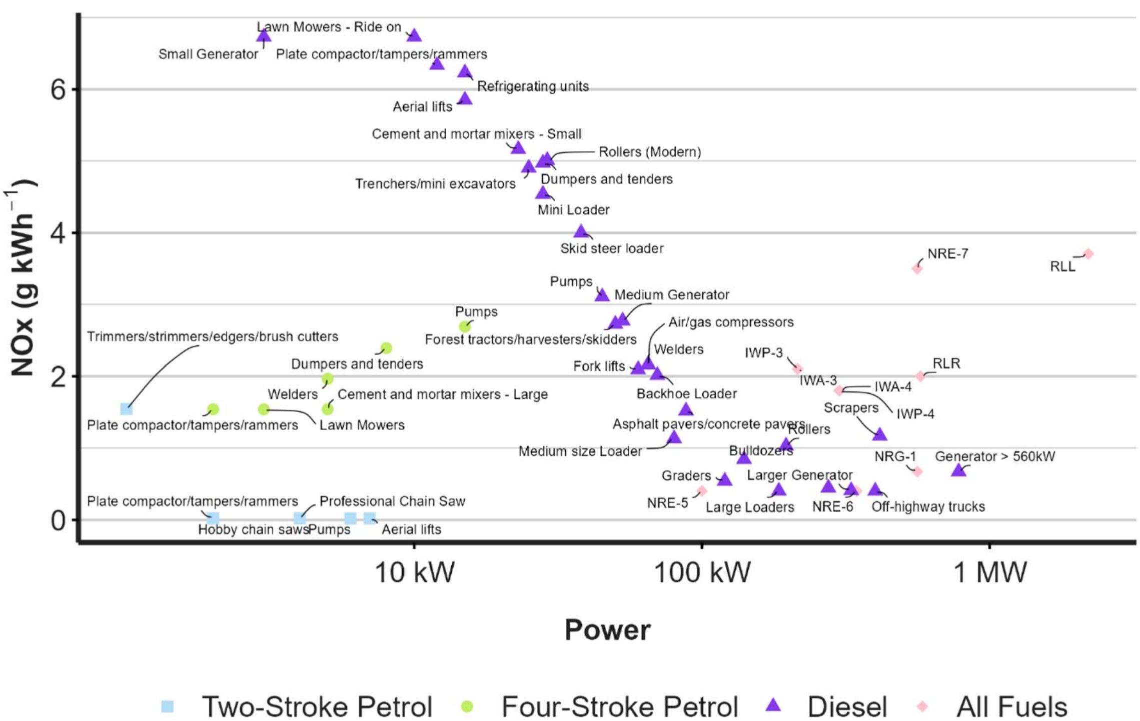

Fig. 2 NRMM products by power and NO_x emissions. Fuel and engine size specific apportionment estimates have been applied except for the cases NRE-5, NRE-6, NRE-7, NRG-1, IWP-3, IWP-4, IWA-3, IWA-4, RLR which have predefined limits specified in Regulation 2016/1628. IWP are defined as engines ≥ 19 kW exclusively used in inland waterway vessels, for their propulsion or intended for their propulsion. IWA are defined as engines ≥ 19 kW exclusively used in inland waterway vessels, for auxiliary purpose or intended for auxiliary purpose. RLR engines are those used exclusively for use in railcars and RLL engines are those used for locomotives. NRG engines are defined as engines ≥ 560 kW that are used in generating sets. NRE includes engines for non-road mobile machinery that are not included in other categories. The number following the code refers to the specified power output range, details of which are specified in Annex I of the regulation.

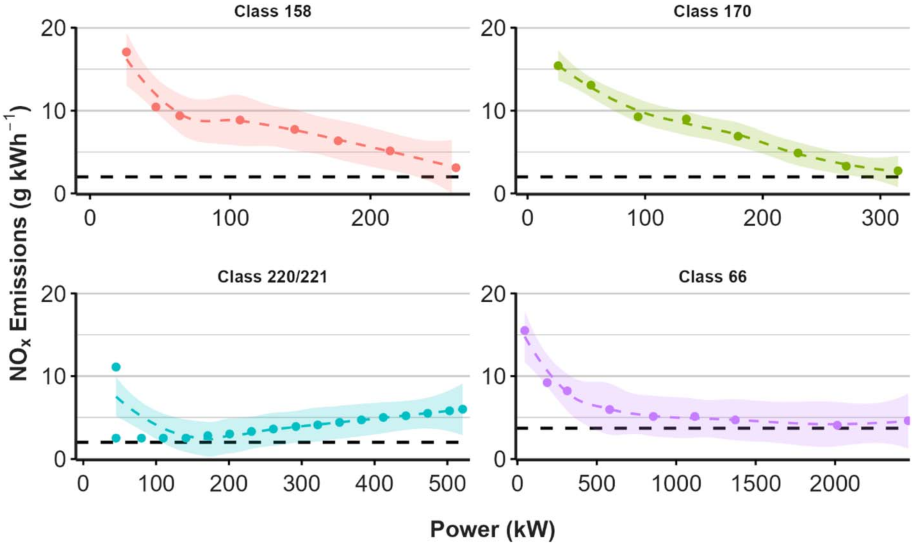

Fig. 3 Train emission factors (g kWh^{-1}) as a function of engine power including auxiliary loads (kW).[39] The NO_x Stage V emission limit is shown by the horizontal dashed line.[20] Note that this has been estimated for the class 66 (RLL) engine using the ratio apportionment method.

see Table S3.† This data is shown alongside the apportioned emission limits in Fig. 2.

It is worth noting that the EMEP/EEA also recommend building in deterioration factors to account for wear with use when compiling national emissions inventories. However, this was not incorporated here as we are simply looking at the most recent applicable NRMM standards for new appliances, meaning that these estimations are likely to represent a lower bound of the true emissions.

4. Industrial emissions directive

The Industrial Emissions Directive (IED) was adopted by the EU in 2010 under Directive 2010/75/EU[21] to control and reduce harmful emissions from large industrial installations. It covers operations that are greater than 50 MW in capacity with emission limit values that are dependent on the industrial activity, fuel and permitting date (exact details are specified in article 30(2-3) of the directive). Here, we focus upon the emissions from combustion plants, which includes major power stations. Table 4 details the combustion technologies focused upon in this review with their corresponding NO_x emission limit values in milligrams per normal cubic metre¶ (mg Nm^{-3}).

Table 4 shows that emission limits for installations fuelled by natural gas do not vary with power, whereas one might expect NO_x abatement potential to be higher at larger plant scales. Interestingly, power stations with outputs greater than 100 MW running on coal or biomass need to conform to the same emission limit value. This seems surprising from a technical perspective since less NO_x would be anticipated to be produced from biomass combustion than coal (although this exact difference is dependent upon the nitrogen content of the fuels).[42]

As IED emission limits are specified as a flue gas concentration, in units of mg Nm^{-3}, conversion to the common scale of g kWh^{-1} is challenging and requires numerous assumptions regarding the conditions of combustion to be made. It is possible to use alternative data; energy generation and emissions of NO_x from major power providers provide a degree of transparency *via* the publication of their annual environmental sustainability and governance (ESG) reports which detail the annualised operational energy and NO_x production. This contrasts with equivalent data from medium combustion plants (1–50 MW) where such information is often protected by commercial sensitivity, see Section 5.

Where available, the ESG reports were used to obtain annual energy generation and the annual NO_x emissions to then produce a value of NO_x emissions per unit of energy produced. It is worth noting that this is not considering the energy lost during onward transmission – here we are simply considering the direct output at the power plant. The total generation capacity was taken to be the rated power of the plant. Despite obvious issues with assuming full operation capacity, this metric was chosen as the power parameter instead of an annualised mean power output due to the data availability and the variability of annual fluctuations.

It is challenging to find fully disclosed data for single large power-plants, instead it is often reported on a total company basis (*e.g.* Uniper[43] and RWE[44]) with only a single power station in the UK disaggregating NO_x emissions by plant and fuel-use (Drax[45]). This should have minimal impact for the NO_x value under the assumption that NO_x emissions will be consistent across the same fuel-typed power stations, but it is more challenging to then prescribe a plant-by-plant power rating. To

¶ Where a 'normal cubic metre' is defined according to the following conditions: 273.15 K, 101.3 kPa, allowing for correction for the water vapour content of the waste gases different and a standardised O_2 content of: 6% for medium combustion plants using solid fuels, 3% for medium combustion plants, other than engines and gas turbines, using liquid and gaseous fuels and 15% for engines and gas turbines.

Table 4 Emission limits for selected power generation combustion technologies[21]

	NO_x emission limit (mg Nm^{-3})				
Power (MW)	Gas turbine	Gas engine	Gas boiler	Biomass boiler	Coal boiler
50–100	50	75	100	250	300
100–300	50	75	100	200	200
300	50	75	100	150	150

Table 5 Power plant capacity and NO_x emission limit values calculated from environmental sustainability and governance reports, separated by fuel where possible

Fuel	Year	Capacity (GW)	NO_x (g kWh^{-1})	Source
Biomass	2022	2.6	0.471	Drax
Biomass	2021	2.6	0.468	Drax
Coal	2021	1.4	0.485	Drax
Gas and coal	2022	1.0	0.328	Uniper
Hard coal	2022	1.3	0.35	RWE
Gas	2021	0.7	0.14	RWE
Hard coal	2021	1.3	0.37	RWE
Gas	2021	0.7	0.15	RWE

approximate power, the list of major power stations in the United Kingdom in operation as of the end of May 2023 was used.[13] Filtering was applied by fuel type and the mean value of the installed capacity was taken as the power estimation. See Table 5 for the collated data.

Whilst we are limited by the amount of data available, estimates demonstrate some consistency in terms of order of magnitude. Interestingly, biomass burning produces almost identical amounts of NO_x per kWh to coal at Drax power station, implying that emissions may be defined as much by the permitted regulatory limit value as what is technologically feasible. However, it is worth noting that the total amount of electricity generated from coal at Drax was significantly less than for biomass. Since 2021, energy generation from coal has been halted at Drax[46] and as of September 2024, following the closure of Ratcliffe-on-Soar power plant, coal-based electricity generation has ceased completely in the UK.[47]

Converting mg Nm^{-3} to g kWh^{-1}

Many assumptions must be made about the combustion conditions when converting between the required units. The United States Environmental Protection Agency (US EPA) provide a methodology[48] for converting emission limit values (g kWh^{-1}) to emission factors (g GJ^{-1}) and has been adopted in the EMEP/EEA guidance,[49] as well as here. The method produces estimates of emission factors based on fuel-specific standardised emission concentration and theoretical volumes of flue gas produced with the assumed stoichiometry and ideal gas behaviour at standard temperatures and pressures.

A conversion factor between $mg_{[NO_x]}\ m^{-3}$ and mg kWh^{-1} [net thermal input] was calculated using the converted emission factors (in g GJ^{-1}) within the EMEP/EEA guidance, derived from the US EPA methodology. A linear model was applied with the y-intercept held at 0. To convert this to a g kWh^{-1} [useful energy output] a further assumption must be made regarding the efficiency of power stations. Efficiency varies depending on the age, fuel, and technologies used but is typically circa 40–50%, with efficiencies rising for combined heat and power stations. The calculated conversion factors and calibrations can be found in the ESI, see Table S4.†

Testing conversion technique

Taking Drax as a 2.6 GW biomass power station, with a permit granted after 2016, means that the NO_x emission limit value is 150 mg Nm^{-3}. The calculated conversion factor is 720 for wood, with a thermal efficiency of 38%. This gives a value of 0.55 g kWh^{-1}, marginally higher, but of the same order of magnitude, as when calculated from the Environment Sustainability and Governance report (0.47 g kWh^{-1}).

$$\frac{\text{Emission limit in mg Nm}^{-3}}{\text{Fuel specific conversion factor} \times \text{efficiency}} \approx$$

$$\text{emission limit in g kWh}^{-1}$$

$$e.g.\ \frac{150}{720 \times 0.38} = 0.55$$

The major downside to this technique is the sensitivity to the efficiency. The inversely proportional relationship between efficiency and the converted estimation means that it has a large bearing on the final value. The Department for Energy Security and Net Zero publish average thermal efficiency values for gas turbine and coal fired power stations, with the most recent figures estimating mean thermal efficiencies of 49.9% and 35.8% respectively.[13] Whilst it is to be anticipated that efficiency increases with the size of power plant and thus the emission limit value in g kWh^{-1} will decrease, for this analysis we took these average values when converting the units. As this conversion technique is based on a myriad of assumptions, error bounds would be significant. Instead, we take confidence in our estimates based on close compatibility between the conversion assumptions applied here and the independent measured values derived from company ESG reports.

5. Medium combustion plants

The Medium Combustion Plant Directive (EU) 2015/2193 was introduced to cover the regulatory gap that existed between the

Table 6 Classification of medium combustion plants

Classification	Capacity (MWh)	Permit in place by	Meeting emission limit by
New	$1 < x < 50$	20th December 2018 or prior to commissioning	20th December 2018 or from date of permit issue
Existing	$1 < x < 5$	1st January 2029	1st January 2030
	$5 \leq x < 50$	1st January 2024	1st January 2025

Table 7 Emission limit values (mg Nm^{-3}) for a selection of common medium combustion plant types

	NO_x emission limit (mg Nm^{-3})				
Power (MW)	Gas turbine	Gas engine	Gas boiler	Biomass boiler	Coal boiler
1–5	50	95	100	500	500
5–50	50	95	100	300	300

Ecodesign Directive (2009/125/EC) and Industrial Emissions Directive (2010/75/EU). The regulation applies to combustion plants with a rated thermal input greater than or equal to 1 MW and less than 50 MW. Many industrial activities within the UK economy fall within this gap[50] and thus are regulated by this directive. Owners must apply for a permit and are subject to emission monitoring. Emission limits depend upon whether the MCP is existing or new (as defined in Table 6), the thermal input rating, the type of fuel burnt and whether the MCP is an engine or a gas turbine. Emission limit values additionally depend upon the location of the MCP; if located within an Air Quality Management Area (AQMA) stricter emission limit values may be in place. Like the IED, the NO_x emission limit values for MCP are given as concentrations; milligrams of NO_x per normal cubic metre (mg Nm^{-3}) and are shown in Table 7.

Taking the NO_x emission limits for gas-fired MCPs, these flue concentrations are the same as larger combustion plants covered by the IED (with an exception for gas engines where the MCP limit is 95 mg Nm^{-3} compared to the IED limit of 75 mg Nm^{-3}). This suggests limited ambition within the IED for abatement strategies to be upscaled and for installations to become more NO_x efficient as the power output increases.

To allow for comparison with the other units on the centralised plot, it was necessary to change this emission limit value from a concentration in mg Nm^{-3} to units of mg kWh^{-1}. Unlike large industrial plants where individual ESG reports may give an annual breakdown of the NO_x and energy produced, this data is not readily available for medium combustion plants. As outlined in Section 4 for the IED, the US/EPA conversion factors were used to convert emission limit values from the stated concentration in mg Nm^{-3} to units of mg kWh^{-1}.[48] The application of these values is appropriate for the emission limit range of MCPs as all emission limit concentrations were within the calibration values, see Fig. S1.†

Discerning values for MCPs is difficult owing to the confidentiality surrounding individual permit applications and the wide and varied usage of MCPs. This opacity, alongside a lack of explicit discernible limits, is a legislative flaw that may be inhibiting the principle of best available techniques. In turn, this may lead to opportunities for real progress in NO_x abatement from MCP engines being missed.

6. Road transport

Whilst the relative contribution of road transport to UK NO_x emissions has decreased from 41% to 27% (1990–2021), vehicles on the roads still represent a significant source of NO_x in the UK.[35] As a large and visible source, abatement and emission regulation for NO_x has existed within this sector since 1976.[51] The impact of road transport regulation is identifiable in the NAEI emissions inventory which shows a NO_x reduction of 83% from this sector in the period 1990–2021 irrespective of the contemporaneous expansion of the UK vehicle fleet, see Fig. S2.†[10,14]

Road transport emission limits depend upon the type, fuel and age of the vehicle. Regulation (EU) 2017/1151 delivers the latest iteration of emission limits for passenger cars and light commercial vehicles, Euro 6, and Regulation (EC) 595/2009 provides the Euro VI standards for Heavy Duty Diesel Engines (HDDEs). These two regulations will be the focus of this review.

Emission standards are given as g km^{-1} under Regulation (EU) 2017/1151, meaning that further unit conversion is

Table 8 Fuel consumption (l per 100 km),[52] activity related NO_x emission limit (g km^{-1})[29] and the estimated NO_x limit for the useful power output basis (g kWh^{-1}). LCV refers to light commercial vehicles. NB: heavy duty diesel engines (HDDEs) have emission limits already defined in grams per kWh.[30] Steady state and transient refer to the applicable emissions test cycle

Type of vehicle	Fuel consumption (l per 100 km)	NO_x (g km^{-1})	NO_x (g kWh^{-1})
Petrol cars	5.4	0.06	0.42
Diesel cars	5.0	0.08	0.46
Petrol motorcycles	4.0	0.06	0.57
Petrol LCV	4.6	0.075	0.62
Diesel LCV	6.4	0.105	0.47
HDDE – steady state	—	—	0.40
HDDE – transient	—	—	0.46

required to compare this across sectors on a power delivered basis. Additionally, limit values are not dependent on the power rating of the vehicle, thus estimations of the vehicle power are also required.

The following approach was taken to convert g km^{-1} to g kWh^{-1}:

(1) Statistics from the Department for Transport estimating average fuel consumption, in l km^{-1}, for new vehicles was used.[52] These figures are derived from testing within the laboratory and thus do not include different driving conditions, *e.g.* cold starts and different loads. The most recent data (2020) was used, and the values can be found in Table 8.

(2) The fuel consumption was then multiplied by the energy content of the fuel (kWh l^{-1}), giving units of kWh km^{-1}. The energy content of the fuel was taken to be: 10.57 kWh l^{-1} (ref. 53) and an assumption of 33% thermal efficiency for diesel and 25% for petrol was made.[54,55]

(3) Finally, the Euro standards tailpipe emission limit value in g km^{-1} was then divided by this product, giving units of g kWh^{-1}.

Results are shown in Table 8.

Testing conversions

To test the validity of the conversion from g km^{-1} to g kWh^{-1}, the same method was used for large goods vehicles (LGVs) which are classed as HDDEs. Statistics for the fuel consumption of LGVs are subdivided by net weight and into rigid and articulated vehicles and are available up to 2016.[52]

Using a value of 25.6 l per 100 km (the average diesel fuel consumption for all rigid vehicles), alongside a measurement of NO_x pollution in grams per kilometre for a rigid vehicle (0.366 g km^{-1} (ref. 56)), with the same estimated value mechanical efficiency of 33%, a comparable value is achieved (0.43 g kWh^{-1}), compared to the regulatory standards (0.4 g kWh^{-1} under the steady state test cycle and 0.46 g kWh^{-1} under the transient).

$$\frac{0.366}{\frac{25.6}{100}\times 0.33\times 10.57}=$$

$$0.41\ \text{g kWh}^{-1}\ \text{approximately the regulated value}$$

To compare these values to the other regulatory standards on a power scale, the max power output (or midpoint of output range for buses and LGVs) of the most common type of vehicle in each category was taken (Table 9).

Table 9 The vehicle type, fuel, model and power used when collating the data for Fig. 5

Vehicle type	Fuel	Modal vehicle	Power (kW)
Car	Diesel	VW Golf[57]	85
Car	Petrol	VW Golf[57]	81
Motorcycle	Petrol	Yamaha NMAX 125 (ref. 58)	9
Van	Diesel	Ford Transit[59]	77–125
Bus	Diesel	Mercedes Tourismo[60]	112.5–260
LGV	Diesel	Mercedes Actros[61]	240–460

7. Aviation

Emission limits for the aviation sector are set by the International Civil Aviation Organisation (ICAO). The emission limits are specified based on the landing and take off cycle (LTO), regulating NO_x emissions up to 3000 feet. This testing cycle involves four stages: take-off, climb, approach and taxi.

NO_x emissions are measured in g kN^{-1} thrust and vary as a function of the overall pressure ratio of the engine. The lack of feasible exhaust aftertreatment options means that NO_x reduction is reliant on control of the combustion conditions. However, this poses a trade-off between fuel efficiency (and hence CO_2) and NO_x emissions; with higher combustion temperatures increasing the fuel performance but leading to increased NO_x emissions.[62,63]

Fleet wide emissions data is not publicly available. Therefore, to estimate the amount of NO_x produced by the aviation sector in comparison to the emission limits set out in ICAO CAEP-8 regulations,[64] the total annual NO_x emissions from the commercial aviation sector in 2018 (3 Mt)[65] was compared to the total fuel consumption (188 Mt). This gives an overall ratio of 16 g of NO_x per kg of fuel. Applying the energy density of kerosene (taken as 12 kWh per kg fuel),[66] a figure of 1300 mg kWh^{-1} is reached. However, this is a crude estimation, which does not consider differences in NO_x production that occurs under differing engine conditions, loads or flight routes.

Emission indices from laboratory testing are available for the four stages of the test cycle described above.[67] This emissions database was filtered to retain engines currently in operation, $n = 151$. An average of the emission indices for the four stages was then calculated. NO_x emissions were estimated from these values by applying the energy density of kerosene, as above. The values of 1300 mg kWh^{-1}, as calculated by taking an average across the entire civil fleet, fits within the figures for individual stages, see Table 10.

To obtain a power rating of the aircraft to allow for intersectoral comparison, a simple approach was adopted. Working in one-dimensional space and taking the force as exactly the thrust, we can relate this to the power by:

$$P=\frac{\mathrm{d}W}{\mathrm{d}t}=T\frac{\mathrm{d}x}{\mathrm{d}t}$$

Table 10 Mean emission indices (grams NO_x per kg of fuel) for the four stages of the landing and take off cycle. These values have been converted to g kWh^{-1} by applying the energy density of kerosene

Stage	Mean emission indices (g kg^{-1})	NO_x emissions g kWh^{-1}
Take-off	30.1	2.51
Climb	22.1	1.84
Approach	10.5	0.875
Idle[a]	4.82	0.402
Overall	**16**	**1.30**

[a] Nomenclature in the ICAO engine database source uses the word 'Idle' as a stage in the LTO rather than taxi.

Assuming a constant speed, *e.g.* at cruise conditions, the above equation is reduced to:

$$P = Tv$$

where P is power (W), W is work done (Nm), x is distance (m), t is time (s), T is thrust (N) and v is velocity (ms^{-1}).

Taking a 900 km h^{-1} average speed at cruise and an average rated thrust from the aircraft database (assuming turbofan propulsion) of 170 kN, translates into a power of 43 MW. Rather than measuring the NO_x emissions for the aircraft, this represents emissions from just one of the engines.

From the values above in Table 10 we note that emissions at lower altitudes during the LTO cycle are not only higher in concentration than in cruise but are likely to have a greater effect on the population due to exposure and higher potential for the formation of particulate matter pollution.

8. International shipping

International shipping is regulated by the International Maritime Organisation (IMO). NO_x emissions are regulated based on the engine age, the rate speed and the waters that the ship is in, see Fig. 4 and Table 11.[32] To collate data for the combined plot, we have taken examples that we believe to be typical of a slow, medium and fast speed engine from the shipping industry. Large, low speed engines are used in cargo shipping and smaller, higher speed engines are typically be used in fishing vessels. Table 12 details the emission limits would be based on the engine parameters.

The tier system demonstrates the increasing stringency that has been placed on shipping emissions with additional restrictions for emission control areas (ECAs). However, ships with large engines running at low-rate speed (*e.g.* cargo ships) may still be emitting significant quantities of NO_x (up to 3.4 g kWh^{-1}).

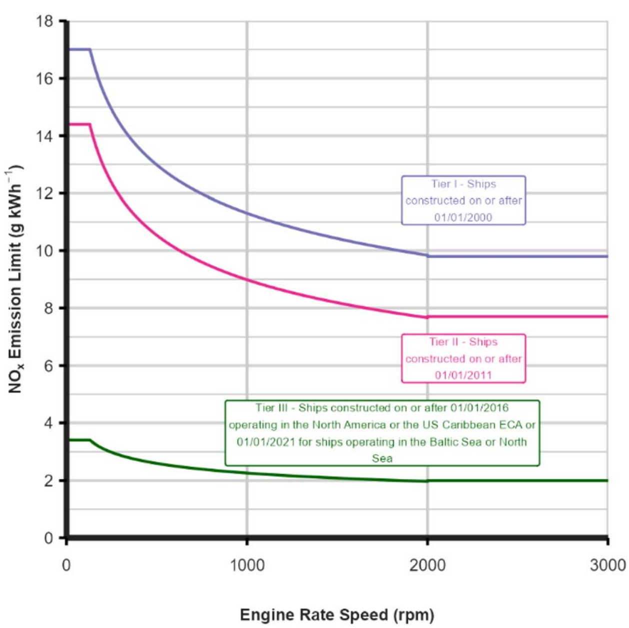

Fig. 4 NO_x emission limit (g kWh^{-1}) as a function of engine rate speed (rpm) for the three tiers.[32]

Table 11 The three tiers of NO_x emission regulation from the shipping sector.[32] n = engine rate speed (rpm)

Tier	Ship construction date on or after	NO_x (g kWh^{-1}) $n < 130$	$130 \le n < 2000$	$n \ge 2000$
I	01-Jan-00	17	$45n^{-0.2}$	9.8
II	01-Jan-11	14.4	$44n^{-0.23}$	7.7
III	1 Jan 2016 (North American and US Caribbean ECAs) or 1 Jan 2021 (Baltic and North Sea ECAs)	3.4	$9n^{-0.2}$	2

Table 12 Three marine engines chosen to be used in the study with their accompanying NO_x emission limits (g kWh^{-1}) under all three tiers of regulation[32]

Engine	Power (kW)	Speed (rpm)	NO_x emission limit (g kWh^{-1}) Tier I	Tier II	Tier III
Yanmar 6AYEM common rail[68]	749	2000	9.8	7.7	2
Mitsubishi S8U-MPTK[69]	1790	1200	10.9	8.6	2.2
Wärtsilä-Sulzer RTA96-C[70]	80 080	120	17	14.4	3.4

9. Collated results

A summary of the emissions regulations, covering seven combustion sectors, is shown in Fig. 5. All emissions standards have been converted onto a common $g_{[NO_x]}$ kWh^{-1} basis compared to the rated power output. A full collation of the assumptions and estimations used to convert to the uniform scale can be found in the ESI, see Table S5.†

Once regulatory limits are normalised for power delivered, there is little consistency between sectors. Fig. 5 shows that some emissions sectors are subject to stricter regulation on a grams of NO_x per kWh basis. There are no obvious trends or inter-sectoral relationships within the data. An assumption that higher rated powered appliances might be regulated to a greater degree (having a notional economy of scale in aftertreatment) does not appear evident here. The following section describes and compares the key results from the main NO_x emitting sectors. Whilst an examination of the technical, historical and industry-specific reasons behind these differences is beyond the scope of this work, some speculative reasoning is provided.

We find that appliances covered by the Ecodesign directive and EURO-vehicle standards are regulated to a high degree on a per kWh basis (<0.5 g kWh^{-1}). This contrasts with the NRMM sector where many appliances have disproportionately high emission limits from a power output perspective. For example, comparing

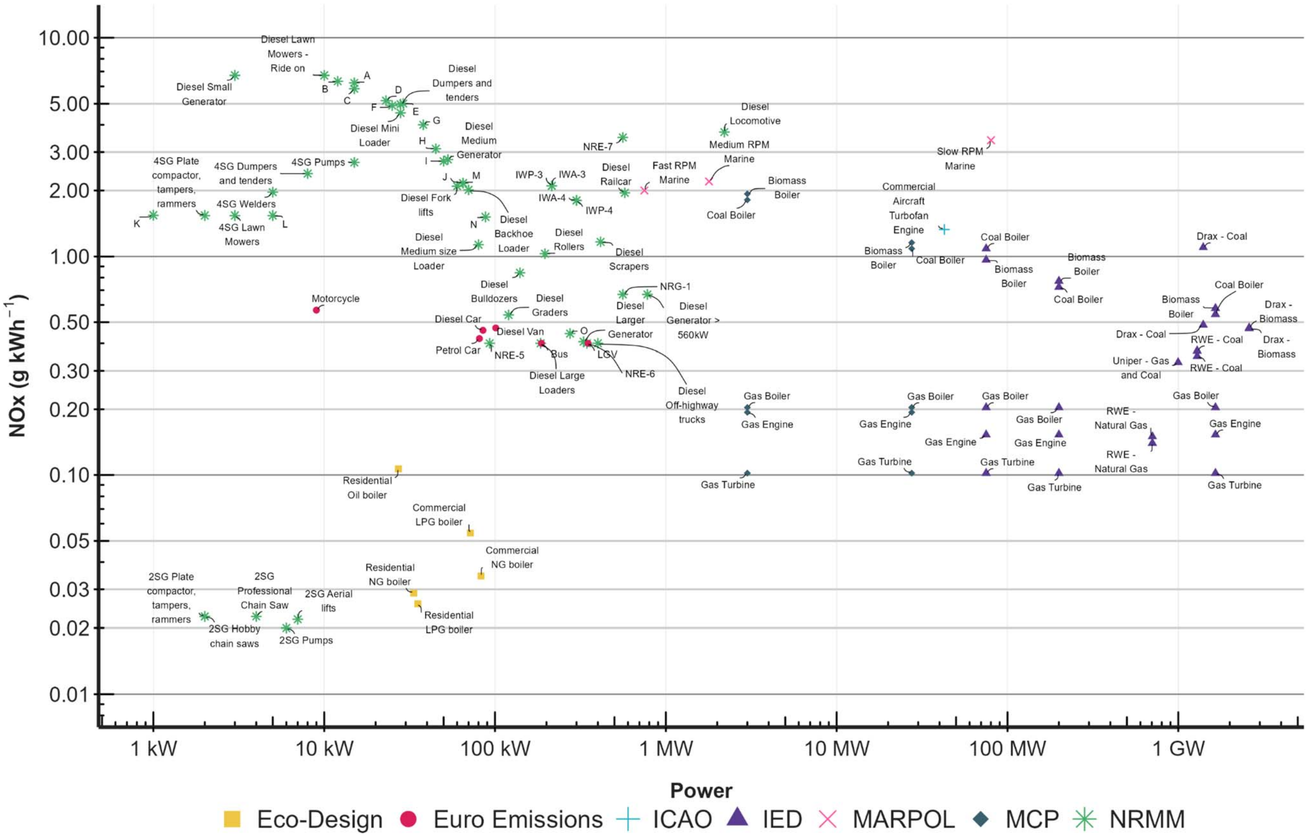

Fig. 5 NO_x emission limits as a function of power for appliances collated throughout this study. Note the log scale of x and y axes. An interactive version of this plot has been included as part of the ESI.† The data for the plot is available in the ESI tables, see Table S6.† To improve readability the following have been relabelled: (A) diesel refrigerating units, (B) diesel plate compactor/tampers/rammers, (C) diesel aerial lifts, (D) diesel cement and mortar mixers – small, (E) diesel rollers (modern), (F) diesel trenchers/mini excavators, (G) diesel skid steer loader, (H) diesel pumps, (I) diesel forest tractors/harvesters/skidders, (J) diesel air/gas compressors, (K) 2SG trimmers/strimmers/edgers/brush cutters, (L) 4SG cement and mortar mixers – large, (M) diesel welders, (N) diesel asphalt pavers/concrete pavers and (O) diesel excavators (wheel/crawler type) – medium.

a medium-sized 50 kW diesel generator to a 50 kW natural gas boiler, the former appliance has an estimated NO_x limit of 2.7 g kWh^{-1} compared to a regulated 0.056 g kWh^{-1} limit for the boiler. There is limited argument from a physical science perspective that would justify such a large (approximately 50 times) difference. More likely, divergent standards for similar sized combustion sources may be a consequence of emission policy being developed sector-by-sector, each with different trade body representation, and each sector potentially working with different government departments or arms-length bodies.

Aircraft emissions are high in relative terms (1.3 g kWh^{-1}), however, this might be considered understandable as there are very limited options for exhaust gas aftertreatment. Emission regulations for shipping, even under the strictest Tier III standards, appear lenient compared to other sectors. For example, smaller ship engines (covered under the category of fast RPM) have an emission limit of 2 g kWh^{-1}. Large electrical generators have similar power outputs (~500 kW) but the emission limits are approximately three times lower (0.67 g kWh^{-1}). Once again, the similarity in engine size (in some cases this may even involve the same engine such as the Cummins Diesel G-Drive model[71]) suggests that technological capability is not the limiting factor. Emission limits are more permissive for larger ships (3.4 g kWh^{-1}) yet one might anticipate these vessels to have greater potential for integrating larger or more sophisticated aftertreatment systems.

Large power stations appear less NO_x efficient than a small natural gas domestic boiler. For example, the Drax biomass power plant is 10 000 times larger than a domestic boiler. However, Drax emits 0.47 g kWh^{-1} of NO_x compared to 0.03 g kWh^{-1} for the boiler.

We highlight that the 1–100 MW region of Fig. 5 is less well constrained than lower power sources due to the uncertain nature of MCP and IED emissions and the associated lack of transparency in regulatory limits imposed on individual installations. This appears to be something of a regulatory failing since some sectors work to transparent emissions standards and others do not, even accounting for commercial aspects of the permitting process. Without the publication of emissions on common scales, it is obscured from both experts and the public that a modern, large power station is, from a NO_x emissions perspective, an order of magnitude less efficient than a home domestic boiler. *E.g.*, Drax emits 0.47 g kWh^{-1} of NO_x compared to 0.03 g kWh^{-1} for a natural gas boiler. It would be reasonable to expect that significant investment and availability of abatement technologies should be applicable to large installations and therefore emission limits could be reduced.

Fig. 5 demonstrates that without a standardised scale, the effectiveness of Best Available Techniques (BAT) principles in promoting the adoption and implementation of emissions reduction methods across sectors is limited. The development of regulation in sectoral isolation has led to differences that cannot be explained by considering the technical feasibility alone.

10. Discussion

Fig. 5 does not show the relative contributions of different sectors to the overall NO_x budget of the UK or the location of these emissions. Although road transport and domestic boilers are legislated to a high degree, there are approximately 41 million licensed vehicles[14] and 23 million gas boilers[72] emitting NO_x across the UK, often in densely populated urban areas. Personal exposure to pollutants, as shaped by individual habits or occupations, can also influence the relative importance that an individual or governing body assigns to an emission source.

Annual NO_x emissions

To account for cumulative use, activity data from the National Atmospheric Emissions Inventory (NAEI) was compiled alongside the associated NO_x emissions for 2022 (the latest year available),[35] see Fig. 6. The level of detail that activity data is disseminated to available in the public domain is less granular

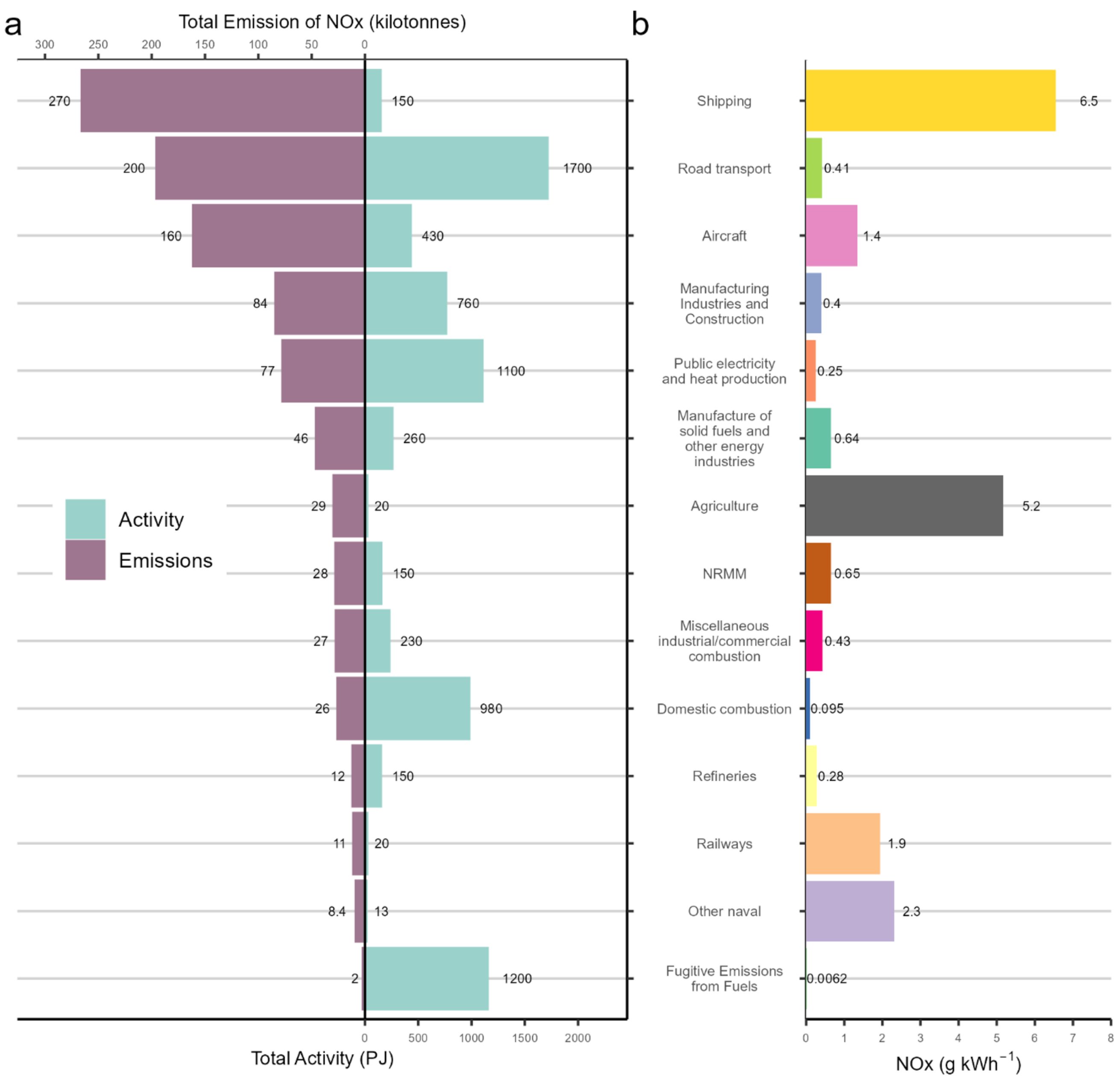

Fig. 6 (a) Annual data from 2022 NAEI[35] and includes all sources where the NO_x emissions (kilotonnes) and activity (petajoules) are specified, ordered based upon activity. (b) Shows the same dataset but reported as grams of NO_x per kilowatt hour of total (fuel-derived) energy input.

than compiled here and thus direct comparison is not possible. To aid comparison, groupings have been assigned to form 14 major categories displayed here. A list of these groupings, which is largely based on the nomenclature for reporting (NFR) code,[73] may be found in the ESI, see Table S7.†

This study so far has focused upon the most stringent, currently prevailing emission standards. However, the data in Fig. 6 is a collation of total annual activity and emissions, regardless of appliance age and therefore emission standard. What can be taken from this figure is the relative size of the sector, in terms of the overall NO_x emissions and the overall activity. Activity is typically estimated based upon the fuel consumption and is reported on an energy basis in joules; further details can be obtained from the NAEI methodology reports.[37] It should be noted that only NO_x sources that had both the activity and emissions specified were included in this figure. Fig. 6b calculates the ratio between these values to provide a 'NO_x efficiency' value. It is important to note that whilst Fig. 6b uses NO_x in grams per kilowatt hour, this is on an energy input basis, and thus is not directly equivalent to previous values reported in this analysis which were on a power output basis.

Road transport remains the sector with the highest activity. Making amendments to emission regulation for vehicles can therefore have a substantial bearing on the total national NO_x emissions. The introduction of EURO 7 standards (from July 1st 2025 for passenger vehicles and 2027 for heavy duty diesel engines),[74,75] increased sales of electric vehicles[76] and the aging out of older models means that NO_x emissions are likely to continue decreasing regardless of potential increases in activity.

The sectors where we have identified the lowest per kWh NO_x stringency in the current regulation, tend to be the sectors emitting more than their pro rata share of emissions, such as shipping and aviation. In 2022, shipping represented the largest per kilowatt hour contribution to NO_x emissions (6.5 g kWh^{-1}) with an energy consumption activity that was an order of magnitude smaller than road transport, but with total greater NO_x emissions. The long operational lifespan of ships (the current mean merchant ship age is 21.9 years[77]) means that many of the fleet comply to emission standards introduced several years ago, rather than to Tier III standards, and thus contribute to the high NO_x emission estimate.

Aviation emissions are also a significant contributor compared to relative energy input and activity. This results in an overall ratio of 1.4 g kWh^{-1} – close to the estimated value of 1.3 g kWh^{-1} (albeit a slightly different measure in terms of the measure of energy as the former value is the value in grams per kilowatt hour total energy *versus* the grams per kilowatt hour useful energy). This reflects that emission standards have not substantially evolved or been redefined over the course of fleet lifespan.

Agricultural machines, such as tractors and combine harvesters, fall under the remit of the non-road mobile machinery regulatory framework for emissions,[20] but they are considered separately under an 'agriculture' category within the EMEP guidance are therefore presented separately in Fig. 6. Total NO_x emissions from the agricultural sector are relatively high in comparison to the activity, suggesting limited abatement technologies are being applied, however, it should be recognised that agricultural emissions do tend to occur outside of population density hotspots, and the exposure effect may be lower.

Similarly, railways have also been separated from NRMM in Fig. 6. The relatively high emissions reported is due in part to the old age of many UK trains; if the railway network was further electrified and older diesel rolling stock are replaced by Stage V compliant trains, this source would be anticipated to fall substantially over time.

Domestic combustion stands out positively in terms of NO_x efficiency, with reported per kilowatt hour emissions close to what would be inferred as regulated under the Ecodesign directive ($\sim$0.1 g kWh^{-1}). The data from the NAEI also indicates that public electricity and heat production performs worse than domestic combustion on a per kWh basis, matching the regulatory assessment in Fig. 5.

Location

Whilst climate change may be mitigated simply by reducing the production of greenhouse gases, improving air quality offers an additional lever of control through consideration of where those emissions occur. For example, several cities have implemented 'Clean Air' or 'Low Emission' zones applying extra NO_x reduction strategies to the road transport sector. These schemes seek to reduce emissions in densely populated areas through applying charges to cars that are larger polluters, incentivising use of public transport or switching to low pollution vehicles.

A similar program has been implemented by the Greater London Authority (GLA) whereby they have designated a clean air zone that regulates NRMM used on construction sites within the ultra-low emission zone (ULEZ). All engines with a power rating between 37 and 560 kW must be registered, and must, as of the 1st of January 2025, comply with at least Stage IV regulation or Stage V limits for generators. The GLA have set an additional target for 100% zero carbon NRMM by 2040.

In January 2020, the City of London Corporation proposed a parliamentary private members' bill titled "Emissions Reduction (Local Authorities in London) Bill".[78] The aim of this bill was to allow local authorities to place tighter NO_x and particulate matter emission limits for London boroughs for boilers, NRMM, stationary generators, solid fuel boilers and combined heat and power (CHP) plants. This bill did not obtain royal assent, but it does demonstrate the capacity for local authorities to go beyond national NO_x limits and standards where it may locally improve air quality. Planning regulation provides a further lever for local authorities to impose tighter emission limit NO_x on specific activities, where the density of population would justify further intervention.

Relevance to net zero pathways

Decarbonising the UK economy, as for many countries, will likely lead to the elimination of some sectoral emissions as appliances transition to electric powertrains and battery energy storage. Speculating on the changes likely to occur as the UK moves towards net zero greenhouse gas emissions is more straightforward for some sectors than others.[79] For cars, the trajectory towards electrification seems inevitable. For domestic heating the use of heat pumps in place of gas boilers now seems likely to be central to decarbonising homes. It is also probable that larger fossil gas power stations will be decommissioned without like-for-like replacement as more renewable energy sources are connected to the grid. Medium sized dispatchable combustion plants seem likely to be retained for some time as a means of supporting fluctuations in renewable energy supply, with the Department for Energy Security and Net Zero forecasting there to be 35 GW of unabated gas dispatchable power in 2030 under the 'Clean Power Capacity Range' model (a reduction of only 0.6 GW when compared to current capacity).[80] The decarbonisation of aviation is proposed through switching to sustainable aviation fuels (SAF) rather than altering the powertrain itself. Decisions on adoption of low carbon fuels for international maritime are less clear but involve retention of combustion (*e.g.* with hydrogen, ammonia, methanol or biofuels).

It is notable therefore that the sectors that are most likely to electrify are those with already stringent NO_x emission regulation. Conversely, potential combustion-retaining sectors such as NRMM, shipping and aviation have more permissive NO_x emission regulations on a $g_{[NO_x]}$ kWh^{-1} basis than those being electrified. The NRMM, aviation and maritime sectors may well continue to rely on the combustion of fossil or non-fossil fuels (*e.g.* biofuels, SAF, hydrogen and ammonia) and hence retain their NO_x emissions. In the absence of new regulation, NO_x emissions from a system combusting non-fossil fuels would need only to conform with the existing sectoral regulations identified here. Any potential increases in activity within these sectors would therefore lead to an increase in NO_x emissions.

International shipping activity is forecasted to increase from 125 to 265 trillion tonne kilometres over the period 2022 to 2050.[81] Without non-fuel burning engines at a sufficiently high technology readiness level, it is likely that this sector will retain combustion and the associated NO_x emissions for the foreseeable future. Similarly, globally the aviation sector is forecast to see an increase in activity from 6.0 to 16.5 trillion revenue passenger-kilometres over the period 2022 to 2050.[81] Without any additional regulatory imposition (and it should be noted that emissions from these sectors are set internationally *via* the IMO and the ICAO), the adoption of sustainable low-carbon fuels may lead to an increase in NO_x emissions from aviation and shipping as activity increases.

11. Conclusions

The collation of emission regulation onto a standardised scale has allowed for direct comparison of regulatory stringency. We found inconsistencies between sectoral NO_x regulation when placed onto a common energy-based scale. The latest standards for road transport and domestic boilers mean that emissions from these appliances are low on a grams of NO_x per kWh output basis. This contrasts with non-road mobile machinery where NO_x emissions can be as great as 7.5 g kWh^{-1}, a factor of 50 higher for the same nominal maximum power output.

Additionally, we found that sectors with more lenient regulation, such as solid fuel medium combustion plants, maritime and aviation, are expected to continue using combustion systems and thus will continue to produce NO_x regardless of any future adoption of lower-carbon fuels.

Study limitations and areas for future research

It proved difficult to translate the emission limit values for industrial scale combustion, covered by the MCP and IED directives, into the common framework used here. This represents a fundamental legislative flaw, limiting the potential for public scrutiny of these emissions.

This analysis relied on assumptions of emissions test cycle behaviour and adherence to emission standards without accounting for what 'real-world' emissions may look like. Future research should focus on increased measurements of the real-world emission profile of various engines and their applications. By considering only the most recent and most stringent standards, we have inadvertently produced the 'best case scenario'.

Recommendations

Following this analysis, we recommend that:

- Emission regulation development seeks more inter-sectoral insights and considers reporting emission limit values using common units for transparency.
- NO_x emission standards should be updated with ambitious limits for alternative lower carbon fuels to ensure that the air quality co-benefits of net zero are realised.
- For sectors where combustion is likely to be retained long-term, such as aviation and maritime industries, emission regulation should be reviewed to ensure NO_x emissions continue to decline. This is of particular importance where total activity levels are forecast to increase.

Data availability

This study was carried out using publicly available data that is fully referenced in the text. The collated dataset is included in the ESI.† All code used for the analysis is available in the GitHub repository linked in the ESI.†

Conflicts of interest

There are no conflicts to declare.

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