Evaluating the variability and consistency of NO_x emission regulation between sectors - Supplementary Information

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Contents

Data Availability

This study was carried out using publicly available data that is fully referenced in the text. The collated dataset is included here in the supplementary information. All code used for the analysis is available in this github repository.

Table S1: Data from the on-the-market boilers used in the analysis

Name	Fuel	Power (kW)	NO_x emissions (mg kWh^{-1})	Usage
EVOMAX 2 30kW	NG	30	34.1	Commercial
EVOMAX 2 40kW	NG	40	33.2	Commercial
EVOMAX 2 60kW	NG	60	35.2	Commercial
EVOMAX 2 80kW	NG	80	34.9	Commercial
EVOMAX 2 100kW	NG	100	34.8	Commercial
EVOMAX 2 120kW	NG	120	33.9	Commercial
EVOMAX 2 150kW	NG	150	35.7	Commercial
EVOMAX 2 30kW	LPG	30	52.3	Commercial
EVOMAX 2 40kW	LPG	40	64.4	Commercial
EVOMAX 2 40kW	LPG	60	67.7	Commercial
EVOMAX 2 40kW	LPG	80	34.9	Commercial
EVOMAX 2 40kW	LPG	100	65.3	Commercial
EVOMAX 2 40kW	LPG	120	41.6	Commercial
Greenstar 8000 Life Regular	NG	35	25.0	Residential
Greenstar Ri 30	NG	30	32.0	Residential
Greenstar 8000 Style Combi	NG	30	23.0	Residential
Greenstar 8000 Life Combi	NG	30	23.0	Residential
Greenstar CDi Compact	NG	28	25.0	Residential
Greenstar 4000	NG	25	40.0	Residential
Greenstar 8000 Life Regular	NG	35	25	Residential
Greenstar Ri 30	NG	30	32	Residential
Greenstar Ri 12	NG	12	35	Residential
Greenstar CDi FS Regular	NG	41	57	Residential
Greenstar Danesmoor External	Oil	18	110	Residential
Greenstar Danesmoor Utility	Oil	18	110	Residential
Greenstar Utility Regular	Oil	50	94	Residential
Greenstar 8000 Style Combi	NG	30	23	Residential
Greenstar 8000 Style Combi	LPG	30	23	Residential
Greenstar 8000 Style Combi	NG	35	25	Residential
Greenstar 8000 Style Combi	LPG	35	25	Residential
Greenstar 8000 Style Combi	NG	40	25	Residential
Greenstar 8000 Style Combi	LPG	40	25	Residential
Greenstar 8000 Style Combi	NG	45	24	Residential
Greenstar 8000 Style Combi	LPG	45	24	Residential
Greenstar 8000 Style Combi	NG	50	24	Residential
Greenstar 8000 Style Combi	LPG	50	24	Residential
Greenstar 8000 Life Combi	NG	30	23	Residential
Greenstar 8000 Life Combi	LPG	30	23	Residential
Greenstar 8000 Life Combi	NG	35	25	Residential
Greenstar 8000 Life Combi	LPG	35	25	Residential
Greenstar 8000 Life Combi	NG	40	25	Residential
Greenstar 8000 Life Combi	LPG	40	25	Residential
Greenstar 8000 Life Combi	NG	45	24	Residential
Greenstar 8000 Life Combi	LPG	45	24	Residential
Greenstar 8000 Life Combi	NG	50	24	Residential
Greenstar 8000 Life Combi	LPG	50	24	Residential

Name	Fuel	Power (kW)	NO_x emissions (mg kWh^{-1})	Usage
Greenstar CDi Compact	NG	28	25	Residential
Greenstar CDi Compact	LPG	28	25	Residential
Greenstar CDi Compact	NG	32	25	Residential
Greenstar CDi Compact	LPG	32	25	Residential
Greenstar CDi Compact	NG	36	25	Residential
Greenstar CDi Compact	LPG	36	25	Residential
Greenstar 4000	NG	25	40	Residential
Greenstar 4000	NG	30	40	Residential
Greenstar CDi Highflow 440 CDI LPG	LPG	30	23	Residential
Greenstar CDi Highflow 440 CDI NG	NG	30	23	Residential
Greenstar CDi Highflow 550 CDI LPG	LPG	31	23	Residential
Greenstar CDi Highflow 550 CDI NG	NG	31	23	Residential
Greenstar Heatslave II 12/18	Oil	18	110	Residential
Greenstar Heatslave II EXT 25/32	Oil	32	109	Residential
Greenstar 1000	NG	24	43	Residential
Greenstar 1000	NG	30	41	Residential
Greenstar 8000 Style System	NG	30	23	Residential
Greenstar 8000 Style System	LPG	30	23	Residential
Greenstar 8000 Style System	NG	34	25	Residential
Greenstar 8000 Style System	LPG	34	25	Residential
Greenstar 8000 Life System	NG	30	23	Residential
Greenstar 8000 Life System	LPG	30	41	Residential
Greenstar 8000 Life System	NG	34	25	Residential
Greenstar 8000 Life System	LPG	34	25	Residential
Greenstar i System	NG	27	32	Residential
Greenstar i System	LPG	27	32	Residential
Greenstar i System	NG	30	32	Residential
Greenstar i System	LPG	30	32	Residential

Table S2: List of NRMM Products from the EMEP/EEA guidebook[1] with assigned NRE engine categories[2] and the corresponding emission limits

Product	SNAP Code	Fuel	Power (kW)		Engine Category		NO_x ELV (g kWh^{-1})	
			Min	Max	Min	Max	Min	Max
Pilers	80700	Diesel	56.00	NA	NRE-5	NA	0.40	NA
Asphalt pavers/concrete pavers	80801	Diesel	15.00	160.0	NRE-2	NRE-5	6.73	0.40
Plate compactor/tampers/rammers	80802	4SG	1.00	3.0	NRE-1	NA	1.54	NA
Plate compactor/tampers/rammers	80802	Diesel	2.00	21.0	NRE-1	NRE-3	6.73	4.22
Plate compactor/tampers/rammers	80802	2SG	1.00	3.0	NRE-1	NA	0.02	NA
Rollers	80803	Diesel	2.00	390.0	NRE-1	NRE-6	6.73	0.40
Rollers (Modern)	80803	Diesel	2.00	55.0	NRE-1	NRE-4	6.73	4.30
Trenchers/mini excavators	80804	Diesel	10.00	40.0	NRE-2	NRE-4	6.73	4.30
Excavators (wheel /crawler type) - Medium	80805	Diesel	50.00	500.0	NRE-4	NRE-6	4.30	0.40
Excavators (wheel /crawler type) - Large	80805	Diesel	500.00	3000.0	NRE-6	NRE-7	0.40	3.50
Cement and mortar mixers - Small	80806	Electric	1.00	7.5	NRE-1	NA	NA	NA
Cement and mortar mixers - Large	80806	4SG	1.00	7.5	NRE-1	NA	1.54	NA
Cement and mortar mixers - Small	80806	Diesel	5.00	40.0	NRE-1	NRE-4	6.73	4.30
Cranes	80807	Generator	100.00	250.0	NRE-5	NRE-6	NA	NA
Graders	80808	Diesel	50.00	190.0	NRE-4	NRE-6	4.30	0.40
Scrapers	80808	Diesel	130.00	700.0	NRE-6	NRE-7	0.40	3.50
Off-highway trucks	80809	Diesel	300.00	500.0	NRE-6	NA	0.40	NA
Bulldozers	80810	Diesel	30.00	250.0	NRE-5	NRE-6	0.40	0.40
Mini Loader	80811	Diesel	15.00	40.0	NRE-2	NRE-4	6.73	4.30
Medium size Loader	80811	Diesel	40.00	120.0	NRE-4	NRE-5	4.30	0.40
Large Loaders	80811	Diesel	120.00	250.0	NRE-5	NRE-6	0.40	0.40
Backhoe Loader	80811	Diesel	10.00	130.0	NRE-2	NRE-5	6.73	0.40
Skid steer loader	80812	Diesel	15.00	60.0	NRE-2	NRE-5	6.73	0.40
Dumpers and tenders	80813	Diesel	5.00	50.0	NRE-1	NRE-4	6.73	4.30
Dumpers and tenders	80813	4SG	5.00	10.0	NRE-1	NRE-2	1.54	2.96
Aerial lifts	80814	Electric	0.00	2.0	NRE-1	NA	NA	NA
Aerial lifts	80814	2SG	3.00	10.0	NRE-1	NRE-2	0.02	0.02
Aerial lifts	80814	Diesel	5.00	25.0	NRE-1	NRE-3	6.73	4.22
Fork lifts	80815	Diesel	20.00	100.0	NRE-3	NRE-5	4.22	0.40
Small Generator	80816	Diesel	0.50	5.0	NRE-1	NA	6.73	NA
Medium Generator	80816	Diesel	5.00	100.0	NRE-1	NRE-5	6.73	0.40
Larger Generator	80816	Diesel	100.00	560.0	NRE-6	NRE-7	0.40	3.50
Generator ¿ 560kW	80816	Diesel	560.00	1000.0	NRG-1	NA	0.67	NA
Pumps	80817	Electric	0.50	70.0	NRE-1	NRE-5	NA	NA
Pumps	80817	2SG	0.50	10.0	NRE-1	NRE-2	0.02	NA
Pumps	80817	4SG	10.00	20.0	NRE-2	NRE-3	2.96	0.02
Pumps	80817	Diesel	20.00	70.0	NRE-3	NRE-5	4.22	1.62
Air/gas compressors	80818	Diesel	10.00	120.0	NRE-2	NRE-5	6.73	0.40
Welders	80191	4SG	0.00	10.0	NRE-1	NRE-2	1.54	0.40
Welders	80191	Diesel	10.00	120.0	NRE-2	NRE-5	6.73	2.96
Refrigerating units	80820	Diesel	10.00	20.0	NRE-2	NRE-3	6.73	0.40
Professional Chain Saw	80701	2SG	2.00	6.0	NRE-1	NA	0.02	4.22
Forest tractors/harvesters/skidders	80702	Diesel	25.00	75.0	NRE-3	NRE-5	4.22	NA
Trimmers/strimmers/edgers/brush cutters	80901	2SG	0.25	1.4	NRSh-1	NA	1.54	0.40
Lawn Mowers	80902	4SG	0.50	5.0	NRE-1	NA	1.54	NA
Lawn Mowers - Ride on	80902	Diesel	5.00	15.0	NRE-1	NRE-2	6.73	NA
Hobby chain saws	80903	2SG	1.00	2.0	NRE-1	NA	0.02	6.73

Table S3: NRMM engine categories as defined in Regulation 2016/1628.[2]

Engine	Equipment	Description
NRE	Other non-road mobile machinery	a) Engines for non-road mobile machinery b) Engines with a reference power < 560 kW used in place of engines of categories IWP, RLL or RLR intended and suited to move, or to be moved by road, and are not included in any other category
NRG	Generating sets	Engines > 560 kW exclusively used in generating sets
NRSh	Equipment with SI engines	SI engines < 19 kW exclusively used in hand-held machinery
NRS	Equipment with SI engines	SI engines < 56 kW and not included in category NRSh
IWP	Inland waterway vessels	Engines ≥ 19 kW exclusively used in inland waterway vessels, for their propulsion or intended for their propulsion
IWA	Inland waterway vessels	Engines ≥ 19 kW exclusively used in inland waterway vessels, for auxiliary purpose or intended for **auxiliary** purpose
RLL	Railway	Engines exclusively for use in locomotives, for their propulsion or intended for their propulsion.
RLR	Railway	Engines exclusively for use in railcars, for their propulsion or intended for their propulsion.
SMB	Snowmobiles	SI engines exclusively for use in snowmobiles, engines for snowmobiles other than SI engines are included in the category NRE.
ATS	All Terrain Vehicles and Side by Side vehicles	SI engines exclusively for use in ATVs and **SbSs**, engines for ATVs and **SbSs** other than SI engines are included in the category NRE.

Figure S1: Conversion between mg Nm^{-3} and g kWh^{-1} for installations covered by the MCP and the IED, separated by fuel type: Coal, Gas, Oil and Wood[3]

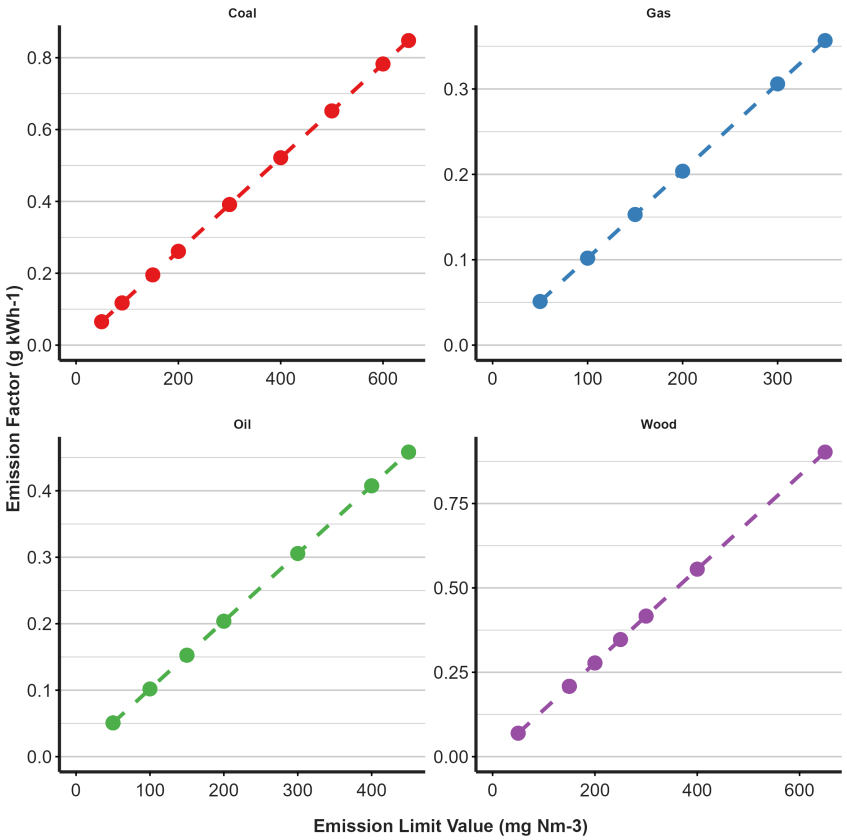

Table S4: Conversion factors and R^2 values for the calibration between emission limits in the units mg Nm^{-3} and g kWh^{-1}

Fuel	Conversion Factor	R^2
Coal	767	0.999
Wood (biomass)	720	0.999
Oil	982	0.999
Gas	981	0.999

Figure S2: Number of licensed vehicles on UK roads (millions)[4] compared to annual NO_x emissions (Tg) from the Road Transport sector[5]

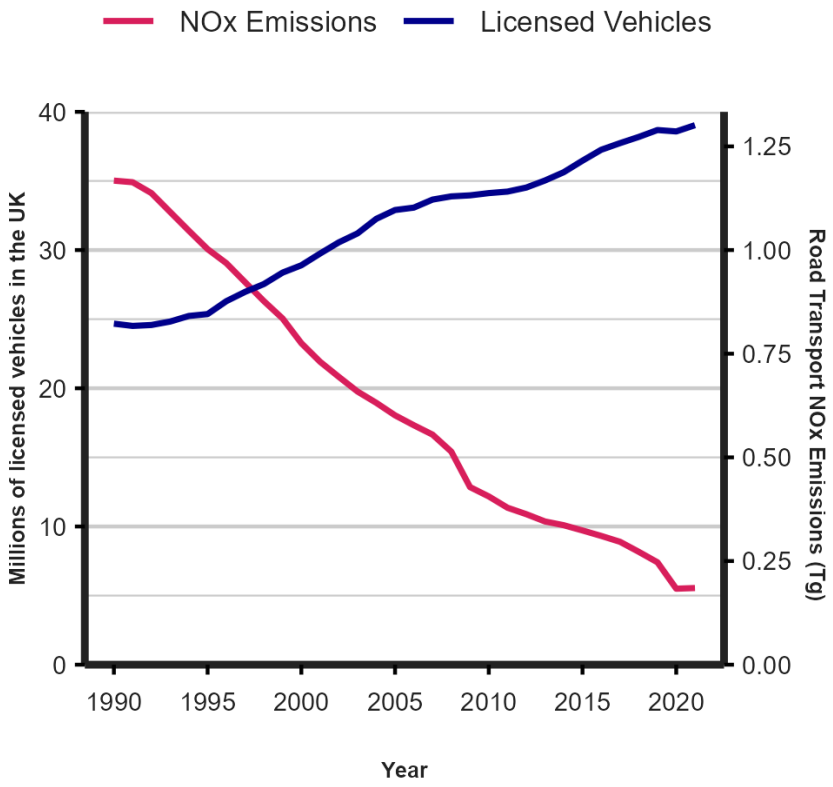

Table S6: Assumptions made when looking at trends in NO_x regulation and assigned uncertainty ratings.

Assumption Made	Details	Potential/Likely Impact	Uncertainty	Further Sources of Information
As **ecodesign** limits are specified in terms of mg/Nm^3, we cannot take values direct from legislation. However, for some appliances, ERG reports that are necessary as an additional part of this legislation quote the NO_x performance in terms of mg/kWh (i.e., the units desired). Therefore, we have approached the problem by using average power and NO_x values calculated by finding as many relevant ERG reports as possible. Errors in the power and NO_x values have also been calculated using standard error formulae ($\sigma/\sqrt{n}$). The Ecodesign directive specifies NO_x limits for six product categories: • Air Heating and Cooling Products • Water Heaters, Hot Water Storage Tanks and Packages of Water Heater and Solar Device • Space Heaters • Local Space Heaters • Solid Fuel Boilers • Solid Fuel Local Space Heaters				
Power rating and NO_x emission of domestic boilers	Data from 55 boilers marketed for residential use from ERG reports. Noted the power ratings and NO_x emissions (converting from NO_x class). Took an average and standard deviation. Additionally split into LPG (n = 21), NG (n = 29) and Oil (n=5).	Calculated error in value comes from the standard deviation/$\sqrt{n}$. Likely to be large as testing broad range from market rather than applying weighting on what the spread of boiler types within the population is.	Low	More data points would confirm confidence in value and reduce standard error.
Power rating and NO_x emission of commercial use boilers	Data from 13 boilers marketed for commercial use from ERG reports. Power ratings and emissions recorded. Also separated into LPG and NG. Mean values used for plot, with standard errors used for error bars	Reliant on only 13 data points and with no idea how representative the data sample is compared to population.	Medium	Additional data points
Errors in value from the standard error of the mean		Without understanding the markets, it is hard to know if the samples that have been collated accurately reflect the distribution. Additionally, as this is not weighted for what is likely to be the most actually used appliances, we are likely to see a higher error span than what may be anticipated. Thus, error likely to be large but high confidence true value is within interval.	Low	
NRMM limits are specified in the desired units of g/kWh. However, they are defined based upon usage, power, swept volume and operational speed and given unintelligible category names. To make this more tangible, a list of NRMM products was used that is defined in the EMEP/EEA – a guidebook that national inventories use to conduct emission estimates. An additional problem arises when considering appliances of lower power output. For engines categorised as 'NRE' with power ¡ 56kW, emissions standards are based upon a combined value of hydrocarbon and NO_x. As lots of engines fall into this category, it was important to gain an estimate of what the separated emission limit would be.				

Assumption Made	Details	Potential/Likely Impact	Uncertainty	Further Sources of Information
List of appliances	As engine category are defined based upon 10 different categories, with 47 sub-categories, it is challenging to ensure have good coverage of appropriate engines. Have used the list from the EMEP/EEA. This covers NRE categories.	Categories in EMEP/EEA does not give many types of machinery for higher power uses. This is not an issue as is probable that most of the machinery used falls within these lower power categories. Leads to focus upon NRE and NRG categories where there are lots more. E.g. railways, snowmobiles, all-terrain vehicles	Low	Include further datapoints on railways. - Now added
Separated NOx and HC limits for engine categories where not specified	Several engine categories as defined by the regulation do not specify individual NOX limits, rather a combined HC + NOx value	Used the separated HC (CH4 + VOCs) and NOX emission factors. Took a ratio of this and applied to the combined limit for diesel, two-stroke and four-stroke engines. Assumed that total hydrocarbons were equal to the sum of the methane and VOCs.	Medium	Search literature for examples of HC and NOx emissions from a sample of engines to confirm whether the ratios of emission factors used seem sensible.
Assigned machinery from description in EMEP/EEA guidebook to NRMM regulatory category	Designation was based upon fuel, size and operation. Where power ranges were specified, the corresponding minimum and maximum NOx values were assigned. The 'final' NOx value was plotted as a weighted mean of the emission limit value (weighted for the power range). As for the power rating assignment, this was just given as the midpoint of the power range.	Midpoint may not represent what is actually on the market e.g. what values are actually like, or are we including outlier values that skew the midpoint? Weighting by the power banding ensures that this is at least taken into consideration (e.g. rather than taking a mean across all the power band emission limit values separately).	Medium	Could compare the midpoint values that are recorded to those that are most commonly sold. This is less of a problem over appliances that operate in a narrow power band but more of a concern for those with wide application and utility.
Assume no deterioration		As have specified that are looking at products currently to market, we have established that this is the 'best case scenario' approach. However, be explicit within text about this point mentioning that engine wear and deterioration likely means that NOx higher than reported.	Medium	No further action
Medium Combustion Plant directive specifies limits for NO_x production in units of mg/Nm3. This translation from an emission limit in concentration terms to per unit of useful energy (mg/kWh) is problematic. Unlike for the industrial emissions directive, data is not readily available. Therefore, lots of assumptions are required to investigate this relationship between NO_x concentrations and NO_x emissions.				

Assumption Made	Details	Potential/Likely Impact	Uncertainty	Further Sources of Information
Lack of Data	Could only find one source (gov CHP document) that gave details on the NOx produced per kWh. Could not find any other data to compare to.	Values are of the right order of magnitude (compared to IED emissions) but low confidence - do not use this data. Instead use the conversion provided by EPA Methodology.	High	Find alternative sources. Contact DEFRA to see if they maintain a list
	DEFRA cannot share any of their resources. Use the conversion factors that have derived for the IED sector.		Medium	
Industrial Emissions Directive also defines the emission limit value in mg/Nm3. Whilst this is problematic, unlike MCP there is more 'real world' emissions data supplied by companies that are big producers of NOx, e.g. power plants. However, most of this is through ESG reports.				
Power plants will be operating at, or near, the emission limit	Power stations sometimes produce individualised values for annual energy and NO_x generation over the year. Using these two values, we can then get at the grams of NOx produced per kWh.	These are the annual value produced by the company itself. No error supplied so use the resolution. As there is not much data available, heavily reliant on primarily one power plant (Drax) with no idea how representative this is compared to the whole sector.	Medium	Hard to see an alternative solution but values same order of magnitude between ESG reports and emission limits.
Power of the power plant	Total generation capacity taken to be the power of the power plant (for the x axis of the collated plot). Where this was not supplied (e.g. for RWE and Uniper), the power rating was approximated by using a list of major power stations in the UK at the end of May 2023 (DESNZ, 2023). This was filtered for the appropriate fuel type and the mean value of the installed capacity was taken as the power estimation.	Impact of power estimation likely to be low due to the fact that at this stage, we are operating in the region of the plot where, due to the log scale, changing the values has small impact of the position of the data point. Data seems to be on sensible scale but is hard to assign error bars to the power rating.	Medium	
Road Transport emission limits are given in units of g/km – except from for heavy duty diesel engines where emission limits are given as g/kWh. Therefore, required an approach to not only convert the emission limits to g/kWh, but also to produce sensible estimations of typical power of cars/vans that comply with the stage V emission standards				

Assumption Made	Details	Potential/Likely Impact	Uncertainty	Further Sources of Information
Take average fuel consumption (l/km) and the energy content of fuel (kWh/km)	Use average fuel consumption and energy content of the fuel to convert from km to kWh.	Average fuel consumption of vehicles is taken from stats from DfT. These values reflect laboratory conditions and therefore do not include real world driving. As shown by the VW scandal, machines can be optimised to perform well in these conditions. It is therefore likely that the real-world fuel consumption would be higher than the value taken here and therefore the NOx to be higher. However, this is looking across the entire market. We may expect more recently produced vehicles to have a lower fuel consumption than the mean taken across the entire fleet. Energy content of fuel has low uncertainty.	Medium	
Mechanical Efficiency assumption	Take 33% mechanical efficiency for diesel and 25% for petrol (reference in text)	Uncertain impact depending on whether these values are an under or overestimate. Lack of knowledge means that cannot be certain which. Would hope that these are underestimates of the mechanical uncertainty owing to improvements over time. This would therefore give a lower NOx rating in g/kWh useful energy. Apply bounds/boundaries on this estimate to obtain error bands.	Low	Make sure that is applicable to the cars that are under Stage V emission (as would hope that mechanical efficiencies have improved over time)
Typical power values	To compare these values to the other regulatory standards on a power scale, the max power output (or output range for buses and lorries) of the most common type of vehicle in each category was taken	Looking at one value rather than a range will lead to a distorted view.	Medium	Also, for the cars/vans it is worth looking across the market to get a range of power values (akin to the boilers in the ecodesign directive) this will allow errors to be calculated rather than just speculative one value.

Assumption Made	Details	Potential/Likely Impact	Uncertainty	Further Sources of Information
Aviation NO_x standards are given as g/kN (e.g. grams per kilonewton of thrust). To change this to g/kWh, a conversion of thrust to power must take place. Emissions are only regulated up to 3000 feet, with emission limits being specified for the following four sections of flight: • Take-Off • Climb • Approach • Taxi				
Average of NOx produced per kg of fuel	Taken the total NOx produced by the sector in 2018 (3Mt) and compare to the total fuel consumption (188Mt). This gives 16g of NOx per kg of fuel.	Crude estimation that does not consider different flight times, loads, amount of cruise etc.	Medium	Find other years' worth of data to constrain this ratio.
Thrust to Power conversion - Aeroplane at constant speed (e.g. cruise conditions) to convert from thrust to power.	Constant velocity assumed to make the calculation from thrust to power easier.	However, emissions are only regulated up to 3000 feet. Therefore, at cruise assumption not valid. At cruising altitude, the plane is likely travelling the fastest that it can during its flight. Therefore, the assumption of constant, but high velocity, is likely to lead to a power overestimation. Error on the power value should be specified.	High	Hard to see what could be done to alter this without bringing in complicated differential equations. Can constrain by using the fact that the largest aeroplane engine ever produced has a power of 64MW – Rolls Royce
Typical cruise speed	Taken as 900km/hr	Cruise speeds typically consistent. Only error propagation from this assumption is assuming the constant velocity in the first place.	Low	
Average rated thrust	To get what the 'average' plane looks like have looked at the rated thrust from the aircraft database.	Again, hard to know if the 'average' plane reflects what is most likely to be used or if by taking a crude mean we are incorporating small outlier values that do not contribute much to the overall NOx budget.	Medium	Try to find out the thrust of different plane types that are typically used. E.g. Boeing 737 etc
Energy density of kerosene (and assuming that all ran on kerosene rather than SAF)	Using the energy density of kerosene to convert the NOx g per kg of fuel to grams of NOx per kWh. This makes assumptions that all energy is converted to useful energy.	Assuming conversion to 100% useful energy is likely to increase the value of NOx in g/kWh. The energy density of kerosene is medium risk due to the fact combustion will occur at temperatures, pressures, humidities that are not the same when plane is grounded (or in the ¡ 3000 feet range) where emissions are regulated.	Low	Apply efficiency rating to the kerosene conversion

Assumption Made	Details	Potential/Likely Impact	Uncertainty	Further Sources of Information
International Shipping. MARPOL regulations are given as a function of engine rate speed. Tier II or Tier III is also dependent upon where the ship is operating. Tier II is much stricter and limits NOx to $2-3.5$ g/kWh (dependent upon the speed).				
Power rating of ship	Conversion from speed to power requires knowledge of the torque. Three examples of ship engines that cover the breadth of the emissions have been selected as reference points.	We are seeing the extremities of the emissions, with values lying in this range.	Low	Further data points

Table S7: Collated Data for Figure 5

Product	Power (kW)	NOx (mg/kWh)	Fuel	Directive
Fast RPM Marine	749	2000	Marine Fuel	MARPOL
Medium RPM Marine	1790	2200	Marine Fuel	MARPOL
Slow RPM Marine	80080	3400	Marine Fuel	MARPOL
Locomotive	2200	3707	Diesel	NRMM
Railcar	575	1951	Diesel	NRMM
Asphalt pavers/ concrete pavers	88	1517	Diesel	NRMM
Plate compactor/ tampers/ rammers	2	1539	4SG	NRMM
Plate compactor/ tampers/ rammers	12	6334	Diesel	NRMM
Plate compactor/ tampers/ rammers	2	23	2SG	NRMM
Rollers	196	1030	Diesel	NRMM
Rollers (Modern)	29	5009	Diesel	NRMM
Trenchers/ mini excavators	25	4903	Diesel	NRMM
Excavators (wheel /crawler type) - Medium	275	443	Diesel	NRMM
Cement and mortar mixers - Large	5	1539	4SG	NRMM
Cement and mortar mixers - Small	23	5164	Diesel	NRMM
Graders	120	539	Diesel	NRMM
Scrapers	415	1167	Diesel	NRMM
Off-highway trucks	400	400	Diesel	NRMM
Bulldozers	140	841	Diesel	NRMM
Mini Loader	28	4537	Diesel	NRMM
Medium size Loader	80	1132	Diesel	NRMM
Large Loaders	185	400	Diesel	NRMM
Backhoe Loader	70	2014	Diesel	NRMM
Skid steer loader	38	4000	Diesel	NRMM
Dumpers and tenders	28	4973	Diesel	NRMM
Dumpers and tenders	8	2389	4SG	NRMM
Aerial lifts	7	22	2SG	NRMM
Aerial lifts	15	5852	Diesel	NRMM
Fork lifts	60	2092	Diesel	NRMM
Small Generator	3	6730	Diesel	NRMM
Medium Generator	53	2771	Diesel	NRMM
Larger Generator	330	407	Diesel	NRMM
Generator > 560kW	780	670	Diesel	NRMM
Pumps	6	20	2SG	NRMM
Pumps	15	2688	4SG	NRMM
Pumps	45	3107	Diesel	NRMM
Air/gas compressors	65	2160	Diesel	NRMM
Welders	5	1964	4SG	NRMM
Welders	65	2160	Diesel	NRMM
Refrigerating units	15	6228	Diesel	NRMM

Product	Power (kW)	NOx (mg/kWh)	Fuel	Directive
Professional Chain Saw	4	23	2SG	NRMM
Forest tractors/ harvesters/ skidders	50	2725	Diesel	NRMM
Trimmers/ strimmers/ edgers/ brush cutters	1	1544	2SG	NRMM
Lawn Mowers	3	1539	4SG	NRMM
Lawn Mowers - Ride on	10	6730	Diesel	NRMM
Hobby chain saws	2	23	2SG	NRMM
NRE-v-5	93	400	NA	NRMM
NRE-c-5	93	400	NA	NRMM
NRE-v-6	345	400	NA	NRMM
NRE-c-6	345	400	NA	NRMM
NRE-v-7	560	3500	NA	NRMM
NRE-c-7	560	3500	NA	NRMM
NRG-v-1	560	670	NA	NRMM
NRG-c-1	560	670	NA	NRMM
IWP-v-3	215	2100	NA	NRMM
IWP-c-3	215	2100	NA	NRMM
IWP-v-4	300	1800	NA	NRMM
IWP-c-4	300	1800	NA	NRMM
IWA-v-3	215	2100	NA	NRMM
IWA-c-3	215	2100	NA	NRMM
IWA-v-4	300	1800	NA	NRMM
IWA-c-4	300	1800	NA	NRMM
Drax	2600000	471	Biomass	IED
Drax	1400000	1100	Coal	IED
Drax	2600000	468	Biomass	IED
Drax	1400000	485	Coal	IED
Uniper Europe	997500	328	Gas and Coal	IED
RWE Total	1290000	350	Coal	IED
RWE Total	704978	140	Natural Gas	IED
RWE Total	1290000	370	Coal	IED
RWE Total	704978	150	Natural Gas	IED
Gas Turbine	3000	102	Gas	MCP
Gas Engine	3000	194	Gas	MCP
Gas Boiler	3000	204	Gas	MCP
Biomass Boiler	3000	1929	Biomass	MCP
Coal Boiler	3000	1811	Coal	MCP
Gas Turbine	27500	102	Gas	MCP
Gas Engine	27500	194	Gas	MCP
Gas Boiler	27500	204	Gas	MCP
Biomass Boiler	27500	1157	Biomass	MCP
Coal Boiler	27500	1086	Coal	MCP
Gas Turbine	75000	102	Gas	IED
Gas Engine	75000	153	Gas	IED
Gas Boiler	75000	204	Gas	IED
Biomass Boiler	75000	965	Biomass	IED
Coal Boiler	75000	1086	Coal	IED
Gas Turbine	200000	102	Gas	IED
Gas Engine	200000	153	Gas	IED
Gas Boiler	200000	204	Gas	IED

Product	Power (kW)	NOx (mg/kWh)	Fuel	Directive
Biomass Boiler	200000	772	Biomass	IED
Coal Boiler	200000	724	Coal	IED
Gas Turbine	1650000	102	Gas	IED
Gas Engine	1650000	153	Gas	IED
Gas Boiler	1650000	204	Gas	IED
Biomass Boiler	1650000	579	Biomass	IED
Coal Boiler	1650000	543	Coal	IED
Commercial Aircraft Turbofan Engine	42693	1330	Kerosene	ICAO
Diesel Car	85	459	Diesel	Euro Emissions
Petrol Car	81	420	Petrol	Euro Emissions
Motorcycle	9	568	Petrol	Euro Emissions
Diesel Van	101	470	Diesel	Euro Emissions
Bus	187	400	Diesel	Euro Emissions
LGV	350	400	Diesel	Euro Emissions
Commercial LPG boiler	72	54	LPG	Eco-Design
Residential LPG boiler	35	26	LPG	Eco-Design
Commercial NG boiler	83	35	NG	Eco-Design
Residential NG boiler	33	29	NG	Eco-Design
Residential Oil boiler	27	107	Oil	Eco-Design

Table S8: NFR Groupings

Source category represents the granularity of the NAEI, minor group is the assigned subgroup with also assigned into one of 15 major groups for presentation in Figure 6.

Source	Minor Group	Major Group
Miscellaneous industrial/ commercial combustion	Miscellaneous industrial/ commercial combustion	Miscellaneous industrial/ commercial combustion
Power stations	Power stations	Public electricity and heat production
Heat supply	Heat supply	Public electricity and heat production
Refineries - combustion	Refineries	Refineries
Coke production	Coke production	Manufacture of solid fuels and other energy industries
Collieries - combustion	Collieries	Manufacture of solid fuels and other energy industries
Gas production	Gas production	Manufacture of solid fuels and other energy industries
Nuclear fuel production	Nuclear fuel production	Manufacture of solid fuels and other energy industries
Upstream Oil Production - fuel combustion	Upstream Oil Production	Manufacture of solid fuels and other energy industries
Oil terminal: fuel combustion	Oil terminal	Manufacture of solid fuels and other energy industries
Gas terminal: fuel combustion	Gas terminal	Manufacture of solid fuels and other energy industries
Upstream Gas Production - fuel combustion	Upstream Gas Production	Manufacture of solid fuels and other energy industries
Blast furnaces	Blast furnaces	Manufacturing Industries and Construction
Sinter production	Sinter production	Manufacturing Industries and Construction
Iron and steel - combustion plant	Iron and steel	Manufacturing Industries and Construction
Autogenerators	Autogenerators	Manufacturing Industries and Construction
Autogeneration - exported to grid	Autogenerators	Manufacturing Industries and Construction
Non-Ferrous Metal (combustion)	Non-Ferrous Metal	Manufacturing Industries and Construction
Ammonia production - combustion	Ammonia production	Manufacturing Industries and Construction
Chemicals (combustion)	Chemicals	Manufacturing Industries and Construction
Methanol production - combustion	Methanol production	Manufacturing Industries and Construction
"Pulp, Paper and Print (combustion)"	"Pulp, Paper and Print"	Manufacturing Industries and Construction
"Food and drink, tobacco (combustion)"	"Food and drink, tobacco"	Manufacturing Industries and Construction
Lime production - non decarbonising	Lime production	Manufacturing Industries and Construction
Cement - non-decarbonising	Cement	Manufacturing Industries and Construction
Mineral products (other): combustion	Mineral products (other)	Manufacturing Industries and Construction
NRMM: Construction	NRMM	NRMM
NRMM: Generators	NRMM	NRMM
NRMM: Mining and Quarrying	NRMM	NRMM

Source	Minor Group	Major Group
NRMM: Other Industry	NRMM	NRMM
NRMM: Waste	NRMM	NRMM
Other industrial combustion	Other industrial combustion	Manufacturing Industries and Construction
Mechanical Engineering (combustion)	Mechanical Engineering	Manufacturing Industries and Construction
Aircraft - international take off and landing	Aircraft	Aircraft
Aircraft between UK and CDs - TOL	Aircraft	Aircraft
Aircraft between UK and Gibraltar - TOL	Aircraft	Aircraft
Aircraft between UK and other OTs (excl Gib. and Bermuda) - TOL	Aircraft	Aircraft
Aircraft between UK and Bermuda - TOL	Aircraft	Aircraft
Aircraft - domestic take off and landing	Aircraft	Aircraft
Road transport - cars - rural driving	Road transport - cars	Road transport
Road transport - cars - urban driving	Road transport - cars	Road transport
Road transport - cars - motorway driving	Road transport - cars	Road transport
Road transport - cars - cold start	Road transport - cars	Road transport
Road transport - all vehicles LPG use	Road transport - all vehicles LPG use	Road transport
Road transport - LGVs - rural driving	Road transport - LGVs	Road transport
Road transport - LGVs - urban driving	Road transport - LGVs	Road transport
Road transport - LGVs - motorway driving	Road transport - LGVs	Road transport
Road transport - LGVs - cold start	Road transport - LGVs	Road transport
Road transport - buses and coaches - rural driving	Road transport - buses and coaches	Road transport
Road transport - HGV articulated - rural driving	Road transport - HGV	Road transport
Road transport - HGV rigid - rural driving	Road transport - HGV	Road transport
Road transport - buses and coaches - urban driving	Road transport - buses and coaches	Road transport
Road transport - HGV articulated - urban driving	Road transport - HGV	Road transport
Road transport - HGV rigid - urban driving	Road transport - HGV	Road transport
Road transport - buses and coaches - motorway driving	Road transport - buses and coaches	Road transport
Road transport - HGV articulated - motorway driving	Road transport - HGV	Road transport
Road transport - HGV rigid - motorway driving	Road transport - HGV	Road transport
Road transport - buses and coaches - cold start	Road transport - buses and coaches	Road transport
Road transport - HGV articulated - cold start	Road transport - HGV	Road transport
Road transport - HGV rigid - cold start	Road transport - HGV	Road transport
Road transport - general	Road transport - general	Road transport
Road transport - motorcycle (¿50cc 4st) - rural driving	Road transport - motorcycle	Road transport

Source	Minor Group	Major Group
Road transport - mopeds (¡50cc 2st) - urban driving	Road transport - mopeds	Road transport
Road transport - motorcycle (¿50cc 2st) - urban driving	Road transport - motorcycle	Road transport
Road transport - motorcycle (¿50cc 4st) - urban driving	Road transport - motorcycle	Road transport
Road transport - motorcycle (¿50cc 4st) - motorway driving	Road transport - motorcycle	Road transport
Railways - intercity	Railways	Railways
Railways - regional	Railways	Railways
Railways - freight	Railways	Railways
Rail - coal	Railways	Railways
Shipping - coastal	Shipping	Shipping
Sailing boats with auxiliary engines	Sailing boats with auxiliary engines	Other naval
Motorboats / workboats (e.g. canal boats, dredgers, service boats, tourist boats, river boats)	Motorboats / workboats (e.g. canal boats, dredgers, service boats, tourist boats, river boats)	Other naval
Personal watercraft e.g. jet ski	Personal watercraft e.g. jet ski	Other naval
Inland goods-carrying vessels	Inland goods-carrying vessels	Shipping
Shipping between UK and Gibraltar	Shipping	Shipping
Shipping between UK and OTs (excl. Gib and Bermuda)	Shipping	Shipping
Shipping between UK and Bermuda	Shipping	Shipping
Shipping between UK and CDs	Shipping	Shipping
NRMM: Airport	NRMM	NRMM
NRMM: Refrigerated Transport	NRMM	NRMM
NRMM: Sea Ports	NRMM	NRMM
Public sector combustion	Public sector combustion	Public electricity and heat production
Railways - stationary combustion	Railways	Railways
NRMM: Forklifts	NRMM	NRMM
Domestic Fireplace - Standard	Domestic combustion	Domestic combustion
Domestic Closed Stove - Basic	Domestic combustion	Domestic combustion
Domestic Boiler	Domestic combustion	Domestic combustion
Domestic Outdoor	Domestic combustion	Domestic combustion
Domestic Space Heater	Domestic combustion	Domestic combustion
Domestic Water Heater	Domestic combustion	Domestic combustion
Domestic Cooking and Other	Domestic combustion	Domestic combustion
Domestic combustion	Domestic combustion	Domestic combustion
Domestic Closed Stove - Upgraded	Domestic combustion	Domestic combustion
Domestic Closed Stove - EcoDesign	Domestic combustion	Domestic combustion
House and garden machinery	House and garden machinery	NRMM
Agriculture - stationary combustion	Agriculture	Agriculture
Forestry Machinery	NRMM	NRMM
NRMM: Agriculture	NRMM	NRMM
Fishing vessels	Fishing vessels	Shipping
Aircraft - military	Aircraft	Aircraft
Shipping - naval	Shipping	Shipping
Solid smokeless fuel production	Solid smokeless fuel production	Fugitive Emissions from Fuels
Iron and steel - flaring	Iron and steel	Fugitive Emissions from Fuels
Charcoal production	Charcoal production	Fugitive Emissions from Fuels
Upstream Oil Production - Offshore Well Testing	Upstream Oil Production	Fugitive Emissions from Fuels
Upstream Oil Production: direct process emissions	Upstream Oil Production	Fugitive Emissions from Fuels
Upstream Gas Production - Offshore Well Testing	Upstream Gas Production	Fugitive Emissions from Fuels
Gas Terminal: Other Fugitives	Gas Terminal	Fugitive Emissions from Fuels
Upstream Gas Production: direct process emissions	Upstream Gas Production	Fugitive Emissions from Fuels

Source	Minor Group	Major Group
Upstream Oil Production - flaring	Upstream Gas Production	Fugitive Emissions from Fuels
Oil Terminal: Gas Flaring	Oil Terminal	Fugitive Emissions from Fuels
Gas Terminal: Gas Flaring	Gas Terminal	Fugitive Emissions from Fuels
Onshore oil production: gas flaring	Onshore oil production	Fugitive Emissions from Fuels
Upstream Gas Production - flaring	Upstream Gas Production	Fugitive Emissions from Fuels
Upstream Oil Production - venting	Upstream Gas Production	Fugitive Emissions from Fuels
Upstream Gas Production - venting	Upstream Gas Production	Fugitive Emissions from Fuels
Gas Terminal: Venting	Gas Terminal	Fugitive Emissions from Fuels
Chemical industry - nitric acid use	Chemical industry	Chemical industry
Nitric acid production	Nitric acid production	Chemical industry
Adipic acid production	Adipic acid production	Chemical industry
Electric arc furnaces	Electric arc furnaces	Metal production
Basic oxygen furnaces	Basic oxygen furnaces	Metal production
Primary aluminium production - general	Primary aluminium production	Metal production
Primary aluminium production - anode baking	Primary aluminium production	Metal production
Non-ferrous metal processes	Non-ferrous metal processes	Metal production
Cigarette smoking	Cigarette smoking	Cigarette smoking
Fireworks	Fireworks	Fireworks
Paper production	Paper production	Paper production
Dairy - Dairy Cows	Dairy	Agriculture
Other cattle - Beef females for slaughter	Other cattle	Agriculture
Other cattle - Bulls for breeding	Other cattle	Agriculture
Other cattle - Cereal fed bull	Other cattle	Agriculture
Other cattle - Cows	Other cattle	Agriculture
Other cattle - Dairy Calves Female	Other cattle	Agriculture
Other cattle - Dairy Replacements Female	Other cattle	Agriculture
Other cattle - Dairy In Calf Heifers	Other cattle	Agriculture
Other cattle - Heifers for breeding	Other cattle	Agriculture
Other cattle - Steers	Other cattle	Agriculture
Sheep - Ewe	Sheep	Agriculture
Sheep - Lamb	Sheep	Agriculture
Sheep - Ram	Sheep	Agriculture
Pig - Boar	Pig	Agriculture
Pig - Fattening Pig 20 to 80 kg	Pig	Agriculture
Pig - Fattening Pig ¡ 20 kg	Pig	Agriculture
Pig - Fattening Pig ¿ 80 kg	Pig	Agriculture
Pig - Gilt	Pig	Agriculture
Pig - Sow	Pig	Agriculture
Goats	Goats	Agriculture
Agricultural Horses	Agricultural Horses	Agriculture
Poultry - Laying Hens	Poultry	Agriculture
Poultry - Broilers	Poultry	Agriculture
Poultry - Turkeys	Poultry	Agriculture
Poultry - Breeding Flock	Poultry	Agriculture
Poultry - Ducks	Poultry	Agriculture
Poultry - Geese	Poultry	Agriculture
Poultry - Growing Pullets	Poultry	Agriculture
Poultry - Other	Poultry	Agriculture
Deer	Deer	Agriculture
Arable	Arable	Agriculture
Grass	Grass	Agriculture
Sewage Sludge Cake - Total N	Sewage Sludge Cake	Agriculture
Sewage Sludge Liquid - Total N	Sewage Sludge Liquid	Agriculture
Other cattle - Beef females for slaughter - Digestate	Other cattle	Agriculture
Poultry - Broilers - Digestate	Poultry	Agriculture

Source	Minor Group	Major Group
Other cattle - Bulls for breeding - Digestate	Other cattle	Agriculture
Other cattle - Cereal fed bull - Digestate	Other cattle	Agriculture
Other cattle - Cows - Digestate	Other cattle	Agriculture
Other cattle - Dairy Calves Female - Digestate	Other cattle	Agriculture
Other cattle - Dairy Replacements Female - Digestate	Other cattle	Agriculture
Other cattle - Dairy In Calf Heifers - Digestate	Other cattle	Agriculture
Dairy - Dairy Cows - Digestate	Dairy	Agriculture
Crop Digestates - Total N	Crop Digestates	Agriculture
Other cattle - Heifers for breeding - Digestate	Other cattle	Agriculture
Poultry - Laying Hens - Digestate	Poultry	Agriculture
Poultry - Other - Digestate	Poultry	Agriculture
Other cattle - Steers - Digestate	Other cattle	Agriculture
Poultry - Turkeys - Digestate	Poultry	Agriculture
Poultry - Breeding Flock - Digestate	Poultry	Agriculture
Poultry - Growing Pullets - Digestate	Poultry	Agriculture
Other organic residue Digestates - Total N	Other organic residue Digestates	Agriculture
Poultry - Ducks - Digestate	Poultry	Agriculture
Poultry - Geese - Digestate	Poultry	Agriculture
Food Digestates - Total N	Food Digestates	Agriculture
Pig - Boar - Digestate	Pig	Agriculture
Pig - Fattening Pig 20 to 80 kg - Digestate	Pig	Agriculture
Pig - Fattening Pig ¡ 20 kg - Digestate	Pig	Agriculture
Pig - Fattening Pig ¿ 80 kg - Digestate	Pig	Agriculture
Pig - Gilt - Digestate	Pig	Agriculture
Pig - Sow - Digestate	Pig	Agriculture
Arable - Direct	Arable	Agriculture
Grass - Direct	Grass	Agriculture
Field burning	Field burning	Agriculture
Incineration	Incineration	Waste Incineration
Incineration - chemical waste	Incineration	Waste Incineration
Incineration - clinical waste	Incineration	Waste Incineration
Incineration - sewage sludge	Incineration	Waste Incineration
Crematoria	Crematoria	Waste Incineration
Incineration - animal carcases	Incineration	Waste Incineration
Foot and mouth pyres	Incineration	Waste Incineration
Small-scale waste burning	Incineration	Waste Incineration
Accidental fires - vehicles	Accidental fires	Accidental fires
Accidental fires - dwellings	Accidental fires	Accidental fires
Accidental fires - other buildings	Accidental fires	Accidental fires
Professional horses	Horses	Agriculture
Domestic Horses	Horses	Agriculture
Other LULUCF	Other LULUCF	Other LULUCF
Other LULUCF - Cropland remaining Cropland - Biomass Burning - Wildfires	Other LULUCF	Other LULUCF Forestry - Forest Land converted to Cropland - Biomass Burning - Controlled Burning
Forestry	Biomass Burning - wildfires and controlled	

Source	Minor Group	Major Group
Other LULUCF - Grassland remaining Grassland - Biomass Burning - Wildfires	Other LULUCF	Biomass Burning - wildfires and controlled
Forestry - Forest Land converted to Grassland - Biomass Burning - Controlled Burning	Forestry	Biomass Burning - wildfires and controlled
Forestry - Forest Land converted to Settlements - Biomass Burning - Controlled Burning	Forestry	Biomass Burning - wildfires and controlled
Forestry - Forest Land converted to Other Wetlands - Biomass Burning - Controlled Burning	Forestry	Biomass Burning - wildfires and controlled
Accidental fires - forests	Accidental fires	Accidental fires
Accidental fires - vegetation	Accidental fires	Accidental fires
Accidental fires - straw	Accidental fires	Accidental fires
Aircraft - international cruise	Aircraft	Aircraft
Aircraft between UK and CDs - Cruise	Aircraft	Aircraft
Aircraft between UK and Gibraltar - Cruise	Aircraft	Aircraft
Aircraft between UK and other OTs (excl Gib. and Bermuda) - Cruise	Aircraft	Aircraft
Aircraft between UK and Bermuda - Cruise	Aircraft	Aircraft
Aircraft - domestic cruise	Aircraft	Aircraft
Shipping - international IPCC definition	Shipping	Shipping
Exports	Exports	Exports
Industrial engines	Other industrial combustion	Other industrial combustion
Aircraft engines	Aircraft	Aircraft
Road transport - all vehicles biofuels use	Road transport - all vehicles biofuels use	Road transport
Marine engines	Shipping	Shipping
Agricultural engines	Agriculture	Agriculture
Gas leakage	Fugitive Emissions from Fuels	Fugitive Emissions from Fuels
Chemical industry - methanol	Methanol production	Chemical industry
Road vehicle engines	Road transport - general	Road transport

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