Study of ship emissions whilst at berth in the UK

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1 Introduction and Summary

This report has been prepared by Ricardo for Schneider Electric to estimate the 2016 emissions to air released from the operation of auxiliary engines on ships whilst at berth in UK ports. This is in the context of Schneider Electric considering the local benefits to be gained from the potential emissions to be avoided by supplying the ship with shoreside electricity that is generated from 100% renewable sources. The work has been carried out in March 2018.

This work estimates an annual total of emissions released by vessels' auxiliary engines at berth in ports around the UK. This report does not assess the resulting impacts on local air quality, i.e. the contribution to ambient concentrations of pollution after dispersal of the emitted pollutants, which would need to consider flue gas characteristics, meteorological conditions, and other local emission sources.

The vessels in scope of this assessment are all sea-going vessels, excluding military vessels and yachts, that report their positions with the Automatic Identification System (AIS). The vessel types assessed include cargo and passenger merchant vessels, fishing vessels, offshore industry vessels, service, tug and other miscellaneous vessels; military and inland waterway vessels are excluded. Emissions from main engines and auxiliary boilers are not included.

The pollutants under consideration are the greenhouse gas carbon dioxide (CO_2) and the air pollutants nitrogen oxides (NO_X), sulphur dioxide (SO_2) and airborne particulate matter of diameter less than 10 µm (PM_{10}). The air quality pollutants of NO_X, SO_2 and PM_{10} have significant health and environmental impacts – these are primarily local impacts, but also lead to impacts on a regional scale, for example through the formation of the sulphate component of particulate matter.

The geographic scope of this assessment is the UK, excluding crown dependencies. The work does not consider vessels at UK offshore platforms as 'at berth'. The periods at berth for all vessel movements are included, regardless of whether a vessel previously or subsequently travelled domestically or internationally.

The report sets out the methodology and assumptions in section 2 and the findings and their limitations in section 3. References are listed in section 4.

The key findings of the work are:

- Estimates of the emissions from ships' auxiliary engines at berth in UK ports in 2016 are presented as 'best estimates' within a range, where the range reflects the uncertainty in ship auxiliary engine operation at berth (further described in sections 3.1 and 3.5). The best estimates (and ranges) are:
    - CO_2: 0.83 Mt (0.37 to 0.93 Mt)
    - NO_X: 11.4 kt (5.0 to 12.5 kt)
    - PM_{10}: 0.27 kt (0.12 to 0.30 kt)
    - SO_2: 0.52 kt (0.23 to 0.58 kt)
- The best estimates of NO_X and PM_{10} emissions are equivalent to the exhaust emissions of approximately 1.1-1.2 million diesel cars and approximately 84,000 (NO_x) and 166,000 (PM) buses and coaches (further described in section 3.2).
- The value of the health and environmental impacts that could be avoided by eliminating all NO_X, SO_2 and PM_{10} emissions from ships' auxiliary engines at berth around the whole UK in 2016 would be up to £109 to £402 million/year (further described in section 3.3).
- Offshore supply vessels, fishing boats, roll-on-roll-off, bulk carriers and passenger ferries contribute the most to the estimates of these emissions (further described in section 3.6).
- The best estimate of NO_X emissions is equivalent to 2.6% of UK transport emissions and 1.3% of UK total emissions (this and other pollutants further described in section 3.7).

The methodology used to estimate the emissions from ship auxiliary engines at berth and their impacts is subject to several limitations which are described with their implications in section 3.4. The most important of these is that the valuation of the monetised health impacts is primarily based on road transport emissions, yet road transport emissions typically occur closer to sensitive receptors than emissions from vessels in ports.

2 Methodology and Assumptions

2.1 Summary

This study has taken pre-existing fuel consumption estimates for shipping for year 2014 from a Ricardo study for BEIS published in December 2017 (Ricardo, 2017) which fed in to the UK's National Atmospheric Emissions Inventory (NAEI), used for official international inventory reporting obligations. Ricardo (2017) reported the development of a new shipping emissions model using a year's worth of ship tracking data (2014 terrestrial Automatic Identification System (AIS) data) supplied by the Maritime and Coastguard Agency. The reported new model methodology meets and exceeds the requirements placed on official national inventories for shipping by calculating emissions specific to each vessel and for each point of the vessel's voyage that is tracked with AIS data. The model reported in Ricardo (2017) downsampled the AIS data to 5-minute granularity, and for ships at berth downsampled the AIS data to show the first and last AIS message at berth. The same designations from Ricardo (2017) concerning vessels being 'at berth' has been used.

The results from Ricardo (2017) specifically for auxiliary engine emissions at berth have been scrutinised in detail. The methodology used in the NAEI and reported on in Ricardo (2018), has been replicated to scale the fuel consumption from 2014 to represent the year 2016. This scaling accounts for: (i) changes in port activities per vessel type from statistical series published by the Department for Transport (DfT) used as proxies for changes in vessel activities; (ii) expected changes over time in emission factors due to turnover of the fleet; and (iii) expected efficiency improvements over time due to the IMO's energy efficiency design index (EEDI).

Emissions of the key pollutants to air released from ships – carbon dioxide (CO_2), nitrogen oxides (NO_X), particulate matter (PM_{10}) and sulphur dioxide (SO_2) – have been estimated using the emission factors from the NAEI applied to the fuel consumption estimates. Emissions results have also been converted to monetary values to represent the estimated health and environmental impacts of the NO_X, PM_{10} and SO_2 emissions, and for CO_2 the Government's value placed on mitigating carbon.

2.2 Fuel consumption in 2014 is estimated from a year of terrestrial AIS data

The full methodology used to estimate emissions from all sources on the ships is presented in Ricardo (2017). It is based on a dataset of terrestrially received Automatic Identification System (AIS) ship position updates provided by the Maritime and Coastguard Agency. The relevant part applicable to the estimation of emissions from auxiliary engines is reproduced here. No re-assessment of the AIS data has been carried out in this study. The fuel consumption in 2014 has been taken from the work in Ricardo (2017).

2.2.1 Classification of 'at berth'

In Ricardo (2017), each AIS message was classified as either at berth or at sea. The methodology is briefly summarised here.

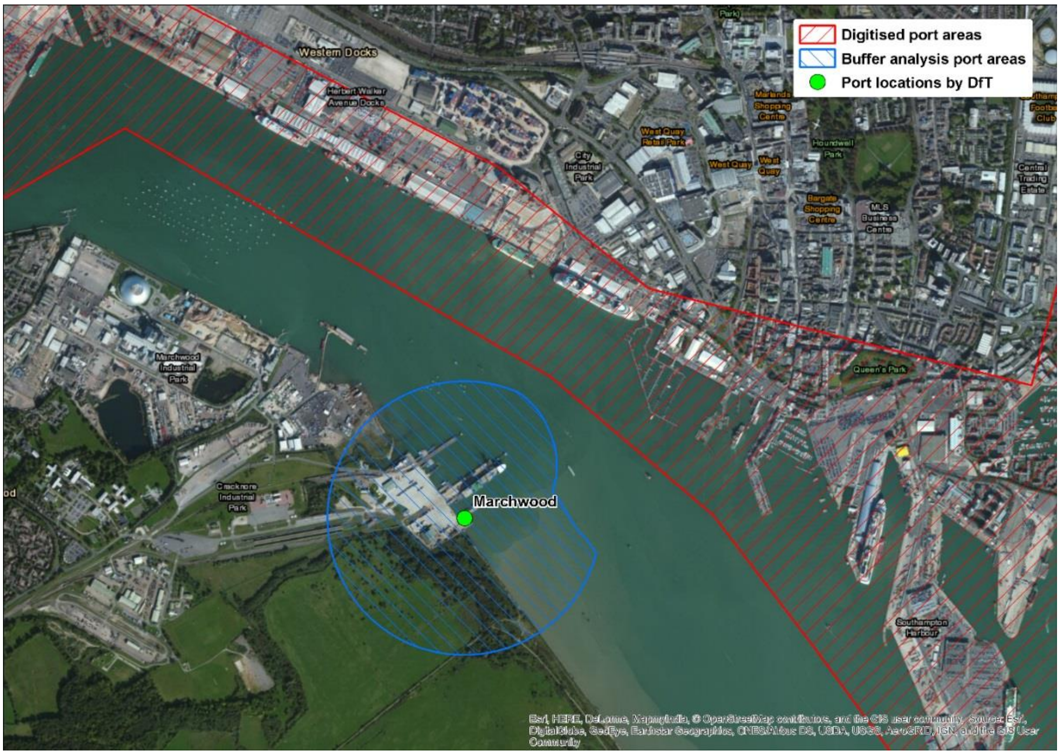
UK port locations were drawn from DfT's UK ports database (Pers. Comm., DfT). In this database, the port locations are defined as single points. The spatial extent of these ports, and thus where the vessels have been assumed to be at berth, were mapped. The resulting port boundaries have been created using a set of digitising and proximity analysis techniques:

- For the busiest UK ports, the location of the harbour and their extent were manually digitised (drawn as polygons) through reference to the areas of the port as visible with satellite imagery. This was completed for more than 35 ports, identified from DfT statistics on cargo tonnes loaded/unloaded at major UK ports, and from DfT statistics on the busiest passenger ports.
- For the smaller UK ports, the extent of the ports was determined using a combination proximity analysis:
    a. 500 metres from the location point as defined by DfT in the UK ports database,
    b. 300 metres from the coast as defined by Ordnance Survey Boundary Line^{TM}

Figure 1 indicates an example of the two techniques applied for UK ports.

An AIS message is designated as ‘at berth’ if the vessel is within the above-defined boundary of the port, and if the vessel’s AIS message reported a vessel speed of less than 1 knot. This speed-based assumption is aligned with IMO (2015).

Figure 1: Example of the assumed port boundaries used in part to define ‘at berth’. The example in red is a large port which has been manually mapped, and the example in blue uses assumed distances from the port latitude/longitude and the distance from shore.



Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community, Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

2.2.2 Selecting vessels at berth in the UK

The database underpinning Ricardo (2017) has been filtered geographically to only include those which are at berth in the UK. This has been implemented by applying a geographic mask of the UK 12 nautical mile territorial sea limit to the 1km grid that is used in the NAEI[1]. This excludes UK crown dependencies.

All vessel AIS messages at berth in the UK have been included – regardless of whether the preceding or subsequent voyages were domestic and international voyages. For the purpose of reporting emission inventories to international bodies such as the UNFCCC, UNECE and the EU, a distinction has to be made between a domestic and international voyage. In the absence of official inventory reporting guidelines, all ‘at berth’ vessel emissions were categorised in Ricardo (2017) as domestic.

2.2.3 Fuel consumption

Fuel consumption in grams (FC) is calculated for each AIS message (k) for each ship using

$$FC_{(k)} = scale\_factor_{(k)} * SFC * Load\_factor * Power_{(k)}$$

Where

> $scale\_factor$ (in hours) is the multiplier based on the time period between two consecutive AIS position messages which can define a period when a vessel is at berth, i.e. the calculation explicitly estimates emissions for the entire time period from one position message until the subsequent position message however long that time gap is. This can be capped at 24 hours or not (see section 2.2.7 for further discussion).

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[1] http://naei.beis.gov.uk/data/gis-mapping

SFC (in g/kWh) is the engine specific fuel consumption.

$Load\_factor$ is assumed for auxiliary engines to be 50%.

$Power$ (in kW) is the rated power of the engine, either specific for the vessel (if available) or with a default assumption.

The fuel consumption associated with each ship's AIS messages is summed.

2.2.4 Auxiliary engine power

The work uses the outputs from Ricardo (2017). In Ricardo (2017), data on auxiliary engine power were taken from a vessel characteristics database. Fewer than half of the vessels in the vessels characteristics database had information on auxiliary engines. Where auxiliary engine power ratings were available in the vessels characteristics database, this was used in Ricardo (2017) in the equation above. Where auxiliary engine power ratings were not available in the vessel characteristics database, their rated power outputs were estimated following a similar approach to that in IMO (2015) which is chosen to avoid extrapolation from a small and unreliable auxiliary engine dataset. Auxiliary unit power outputs were assumed to be related to the installed main engine power with the following relationships for both AIS Class A and Class B vessels:

- Main engine power >500kW – auxiliary engine power are based on assumptions in IMO (2015).
- Main engine power 150-500kW – auxiliary engine power is set to 5% of the main engine power.
- Main engine power <150kW – auxiliary engine power are set to zero (i.e. it is assumed that no auxiliary engines are on the vessel for such a small engined vessel).

The purpose of making these assumptions that deviate from IMO (2015) is due to the need to make appropriate assumptions for the smaller vessels that are mostly in the Class B AIS dataset. The resulting average auxiliary engine power (kW) per vessel type and size subcategory are shown for Class A and for Class B in Appendix 1.

2.2.5 Fuel type

The fuel type used in auxiliary engines at berth is assumed to be marine diesel oil (MDO), a distillate fuel. This is assumed in order to comply with the legislative limit on fuel sulphur content. EU Directive 2005/33/EC limits the amount of sulphur to 0.1% in all marine fuel used while at berth for more than two hours in EU ports. This analysis assumes that all fuel used at berth is 0.1% sulphur. This mean that the estimates of SO_2 (and consequently PM_{10}) emissions could be under-estimates of the real SO_2 (and PM_{10}) emissions if ships with at berth times less than 2 hours do not switch to the lower sulphur fuel.

2.2.6 Specific fuel consumption (SFC) rate

The specific fuel consumption assumed for auxiliary engines is 225g/kWh. This was not assumed to vary by load because the engine load of operational auxiliary engines is assumed to be adjusted by switching multiple engines on or off. The optimum working range of auxiliary engines is thus maintained by the crew and it is not expected to have large variability, in contrast to the main engine load (Ricardo, 2017).

2.2.7 Operational profile of auxiliary engines

The method used to estimate the emissions from auxiliary engines in the NAEI (Ricardo, 2017), on which this work is based, assumed that vessel auxiliary engines did not run for more than a maximum of 24 hours whilst at berth. This assumption, which was based on the understanding that the typical load/unload profile of cargo vessels at major ports is less than 24 hours, was implemented using the gap between consecutive AIS messages for a ship. An assumption was necessary due to the absence of formal guidance in the guidelines for developing emissions inventories (either the EEA guidebook (EMEP/EEA, 2016) or the IPCC (2006) guidelines). The IMO (2015) publication also does not provide further clarity on the matter, only summarising the assumed number of auxiliary engines per ship category and the number of auxiliary engines running on average, but not the number of engines running whilst at berth or the period of time operated.

A set of assumptions has been provided by Schneider Electric, based on their understanding of vessel operation, of the extent to which auxiliary engines are in operation on ships whilst at berth. These are the assumptions that have been applied in this study as a 'best estimate':

- Vessel types bulk carrier, passenger ferry, refrigerated bulk, offshore, fishing, service, tug and other are assumed to continue to operate auxiliary engines at berth until the vessel leaves the port, and that the engine load and the rate of fuel consumption of the auxiliary engines is constant throughout the period (and the same as assumed in Ricardo, 2017) whilst the vessel is at berth.
- Vessel types oil tanker, chemical tanker, liquefied gas tanker, container, general cargo, Ro-Ro and cruise vessels:
  - For periods at berth less than 24 hours, the assumptions for the engine load and fuel consumption rate of these vessels is as per Ricardo (2017)
  - For periods at berth more than 24 hours, the fuel consumption rate is assumed to drop by 50% compared to the fuel consumption rate in Ricardo (2017). This assumption is based on a hypothetical situation of a vessel with three auxiliary engines, which may operate two auxiliary engines during at berth periods of less than 24 hours, and is assumed to drop to operating one auxiliary engine for the longer periods at berth.

2.3 Fuel consumption in 2016 is estimated from the 2014 fuel consumption

To project the estimates of fuel consumption from 2014 to 2016, the approach taken in Ricardo (2017) and in the NAEI is followed. Further details are in Ricardo (2017). This accounts for the following changes between 2014 and 2016:

- Activity level changes between 2014 and 2016, represented at vessel category level using trends between 2014 and 2016 in DfT's published statistics on cargo and passenger ship activities, as well as other proxy statistical sources.
- Engine efficiency gains due to fleet turnover, driven by the IMO's EEDI.
- NOx emission factor reductions due to fleet turnover, as newer vessels meet tighter NO_X standards from the IMO's NO_X Technical Code from the MARPOL Annex VI.

2.4 Emissions in 2016 are estimated from the 2016 fuel consumption

Emissions are calculated from the fuel consumption as follows:

$$Pollutant_{(k)} = FC_{(k)} * EF$$

Where

EF is the emission factor for one of the pollutants expressed in grams of pollutant per gram of fuel and described in the following subsection.

The emission factors are taken from the NAEI, and are based on Ricardo (2017) which in turn uses many factors from IMO (2015). These emission factors represent the combined factors for auxiliary engines and boilers – factors specific to auxiliary engines but not auxiliary boilers are not available. The values have been used from the NAEI and represent the 2016 emission factors specifically for UK journeys and vessels at berth.

The CO_2 emission factor is 3,206 kg/t fuel, and applies to all vessel types.

The SO_2 emission factor is 2 kg/t fuel, and applies to all vessel types. This represents the 0.1% fuel sulphur limit value as applicable to vessels at berth in the UK since 2010.

The PM_{10} and NO_X emission factors vary by vessel category, and whether the vessel is in a Sulphur Emission Control Area (SECA). The PM_{10} emission factors vary from 0.5 to 1.8 kg/t fuel and the NO_X emission factors vary from 14 to 52 kg/t fuel.

2.5 Monetising the health and environmental impacts of emissions

The monetary equivalent value of the health and environmental impact of NO_X, PM_{10} and SO_2 emissions from auxiliary engines whilst at berth have been estimated using damage costs published by the UK Government for use in cost-benefit analyses (Defra, 2015).[2] By using these damage costs, it is assumed that the emissions estimated from auxiliary engines could be reduced to zero by displacing auxiliary engine operation with shoreside electricity that is generated from 100% renewable sources such as wind power. The damage costs that have been used are shown in Table 1, and for NOx and PM represent transport sector averages which are expected to be strongly weighted by road transport emissions which are released more typically closer to sensitive receptors than vessels at berth in ports. A key feature to note is the wide range between the low and high damage costs.

The damage costs account for the impacts of exposure to air pollution on health – both chronic mortality effects (which consider the loss of life years due to air pollution) and morbidity effects (which consider changes in the number of hospital admissions for respiratory or cardiovascular illness) – in addition to damage to buildings (through building soiling) and impacts on materials (Defra, 2011). Specifically, the impacts accounted for are:

- The NO_X damage cost includes acute morbidity effects on respiratory hospital admissions.
- The PM damage cost includes the health impacts of particulate matter (chronic effects on mortality in adults over 30, and acute morbidity effects on respiratory and cardiovascular hospital admissions) in addition to the impact of building soiling by particulate matter.
- The SO_2 damage cost includes the health impacts of secondary particulate matter (as the emission of SO2 causes the formation of sulphates, which are classed as particulate matter) but also includes the direct health impacts of SO2 as a gas. In addition the damage cost also includes the impact of SO2 on materials (e.g. through acid corrosion of stone and metals).

The valuation of the carbon emissions has used the carbon values in HM Treasury's Green Book (BEIS, 2017) which relate to the cost of mitigating CO_2 emissions rather than the social cost or shadow price of carbon. The CO_2 valuation is also shown in Table 1.

Table 1: Damage costs per tonne of pollutant reduced (2015 prices)

Pollutant	Damage cost (£/t)			Notes	Source
	Low	Central	High		
NOx	£8,417	£21,044	£33,670	• Transport sector average; • Valuation if PM also valued	Defra (2015)
PM	£45,510	£58,125	£66,052	• Transport sector average	Defra (2015)
SO_2	£1,581	£1,956	£2,224	• All sources/locations	Defra (2015)
CO_2	£33	£65	£98	• 2017 value, • For sectors not in EU Emissions Trading Scheme	BEIS (2017)

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[2] No pollution concentration modelling was carried out, and thus it wasn't possible to value changes in air quality using the impact pathway method described at https://www.gov.uk/government/publications/air-quality-impact-pathway-guidance. Instead, a damage cost approach [(Defra, 2015) has been taken which is derived from the full impact pathway method.

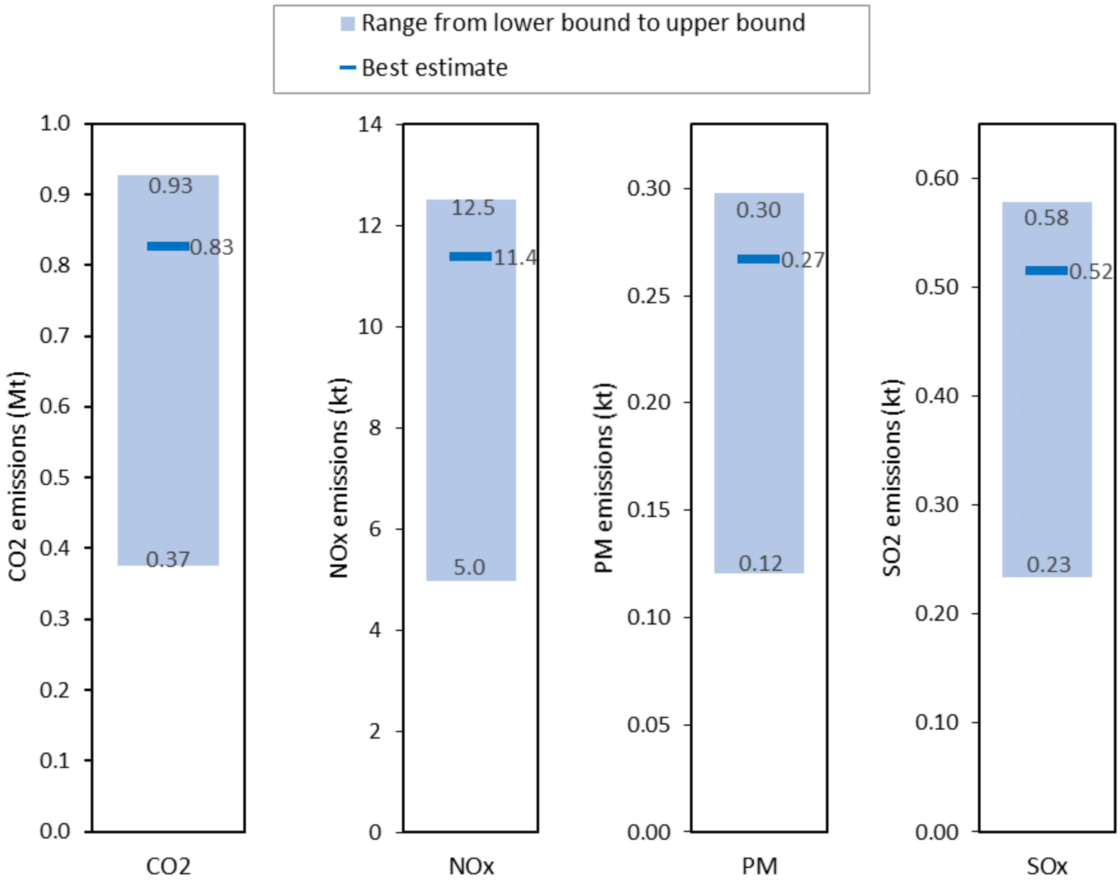
3 Key findings and their limitations

3.1 Best estimate of emissions from auxiliary engines at berth is towards the upper end of a wide range of uncertainty

There is considerable uncertainty and variability in the extent of auxiliary engine operation across different vessel categories whilst ships are at berth. This is apparent from the results shown in Figure 2, in which the wide range between lower and upper bounds reflects the uncertainty in how long, and at what load factor, vessels have auxiliary engine(s) running whilst at berth. A best estimate is presented in Figure 2, which applies the assumptions described in section 2.2.7. The range and best estimates in Figure 2 can be interpreted as:

- The lower bound of the range represents the operation of vessel auxiliary engines from all vessel types capped to a maximum of 24 hours whilst at berth.
- The best estimate, which assumes specific vessel types operate auxiliary engines without a cap, and other vessel types' auxiliary engines are assumed to drop their fuel consumption rate by 50% after 24 hours at berth.
- The upper bound of the range represents the operation of vessel auxiliary engines from all vessel types without a cap – i.e. assumed to continue to operate at the same fuel consumption rate until the AIS dataset shows the vessel next departing from berth.

Figure 2: Range and best estimate of CO_2, NO_X, PM_{10} and SO_2 emissions in 2016 from auxiliary engines of ships at berth in the UK



3.2 The best estimate of NO_X and PM_{10} emissions from ships' auxiliary engines at berth in the UK in 2016 are equivalent to approximately 1.1-1.2 million diesel car exhausts

The best estimates of NO_X and PM emissions from ship auxiliary engines running at berth around the UK in 2016 are 11.4kt and 0.27kt respectively. This represents 9% and 10% respectively of the UK's NO_X and PM exhaust emissions from diesel cars (all Euro standards) in 2016 (Ricardo, 2018). The number of diesel cars (all Euro standards) in the UK fleet in 2016 was 12.1 million (DfT, 2017). Hence the best estimate of NO_X and PM emissions from ships' auxiliary engines at berth in the UK in 2016 is equivalent to the emissions of approximately 1.1 to 1.2 million diesel cars respectively. These figures represent the emissions equivalent of the average diesel car in the fleet in 2016.[3]

The best estimates of NO_X and PM emissions from ship auxiliary engines running at berth also represent 76% of all NO_x emissions and 150% of PM exhaust emissions from all diesel buses and coaches (all Euro standards) in 2016, i.e. the PM emissions from ship auxiliary engines exceed the total PM exhaust emissions from buses. There were approximately 110,000 buses and coaches in the UK fleet in 2016 by taxation class (DfT, 2017), so the NO_X and PM emissions from ships' auxiliary engines are equivalent to the emissions of approximately 84,000 (NOx) to 166,000 (PM) buses and coaches.[3]

This analysis assumes that the removal of these emissions – from both cars, buses and vessels – could hypothetically occur by switching diesel cars and buses to battery electric vehicles, and by supplying shoreside electricity to vessels, with the electricity for all cases generated from 100% renewable (non-combustion) sources. However, in terms of public exposure to the emissions, as the road transport emissions typically occur closer to sensitive receptors, there would be greater value in reducing 1 tonne of NO_X from a trafficked road near a sensitive receptor (e.g. a school) to reducing 1 tonne of NO_X from a vessel at berth in a port that is further from a sensitive receptor. Comparisons to SO_2 emissions are not made due to the very low level of sulphur content in road transport fuel.

3.3 The value of the health and environmental impacts that could be avoided by eliminating all NO_X, SO_2 and PM_{10} emissions from ships' auxiliary engines at berth around the whole UK in 2016 would be £109 to £402 million/year

As a maximum – considering vessel calling at all ports around the UK, and from all vessel categories – if all the emissions that have been estimated from the auxiliary engines at berth from these vessels were reduced to zero, e.g. by replacement with shoreside electricity generated from 100% renewable sources, then the value in reducing the best estimate emissions of CO_2, NO_X, PM_{10} and SO_2 would be between £136 million and £483 million. Of this, the component related to health and environmental impacts avoided from the reduction in NO_X, PM_{10} and SO_2 is between £109 million and £402 million (2015 prices). The wide range in this value is due to the large uncertainty in the valuation of health impacts associated with the pollutant emissions. The largest component of the total value (central estimate) is from reducing NO_X emissions (77%), followed by CO_2 (17%), PM_{10} (5%) and SO_2 (0.3%).

Table 2: Monetary value of best estimate of emissions from vessel auxiliary engines operated at berth around the UK in 2016 if the emissions from all vessels were reduced to zero

Pollutant	Value of best estimate of emissions reduced (£m/yr, 2015 prices)		
	Low	Central	High
CO_2	27	54	81
NO_X	96	240	384
PM_{10}	12	16	18
SO_2	0.8	1.0	1.1
TOTAL	**136**	**310**	**483**

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[3] These figures reflect the emissions equivalent of the average car/bus/coach in the fleet in 2016. These emissions are expected to decrease over time as the fleet turns over with newer vehicles emitting lower amounts of NO_x and PM.

3.4 There are several limitations of the methodology implying the results overestimate the true emissions that could be avoided by plugging vessels in to shoreside electricity

Table 3: The limitations in the methodology and their implications on the results are summarised here

Topic	Limitation	Implication
Classification of ‘at berth’	The method assumes that if a vessel was travelling at less than 1 knot and located in the area defined as the port, then it will be classed in the database as “at berth”, even if the vessel was not physically alongside the berth (e.g. it was still manoeuvring to the berth at less than 1 knot). The estimates presented in this paper of the auxiliary engine emissions whilst “at berth” are therefore likely to be overestimates of the potential emissions that could be avoided by supplying shore-power to the vessels using 100% renewably generated (non-combustion) electricity.	CO_2, NO_X, SO_2, and PM_{10} emissions results likely to be **small overestimates** of ‘at berth’ emissions.
Classification of ‘at berth’	The definition of at berth would also mean that if any anchorages are within the defined distances from the port and shore, then vessels at anchor would also be (erroneously) classified at berth. This means that the estimates of emissions labelled “at berth” are potentially overestimates of the releases from vessels actually at berth. For the busiest UK ports which have been manually digitised, it is considered unlikely that the defined port boundaries include any anchorages.	CO_2, NO_X, SO_2, and PM_{10} emissions results could be **small overestimates** of ‘at berth’ emissions.
Auxiliary engine power	Very limited data available on actual vessel auxiliary engine power. Assumptions on installed power made.	Unknown (may be positive or negative) impact)
Specific fuel consumption rate	The specific fuel consumption rate is assumed to be fixed for all auxiliary engines. Limited evidence has been identified that suggests engine load rates for certain engine types may be lower (i.e. lower kWh demand), and that the fuel consumption rate expressed in g/kWh would be higher at lower loads. The reduction in kWh demand is expected to more than outweigh the increase in fuel consumption rate in g/kWh.	CO_2, NO_X, SO_2, and PM_{10} emissions results could be **small overestimates**.
Fuel type	All auxiliary engines have been assumed to run in 2016 on marine diesel oil with sulphur content 0.1%. This is an upper limit required by legislation. In practice, vessel operators are likely to be using fuel with sulphur content a little below this value, in order to allow for a margin of error. The estimated SO_2 emissions and PM_{10} emissions are consequently likely to be small overestimates of the actual emissions.	SO_2 and PM_{10} emissions likely to be **small overestimates**.

Topic	Limitation	Implication
Fuel type	All vessels have been assumed to use 0.1% S fuel whilst at berth, regardless of whether they were at berth for less than 2 hours or not. The legislation allows vessel operators to use higher sulphur fuel if they are at berth for less than 2 hours. This means that the estimates of SO_2 (and PM_{10}) emissions could be underestimates of the real SO_2 (and PM_{10}) emissions if ships with at berth times less than 2 hours do not switch to the lower sulphur fuel.	SO_2 and PM_{10} emissions could be **small underestimates**.
Fuel type	All auxiliary engines have been assumed to run in 2016 on marine diesel oil. If any vessels instead use LNG as a fuel, then the estimates of all pollutants will be overestimates.	CO_2, NO_X, SO_2, and PM_{10} emissions results likely to be **small overestimates**.
Operational profile of auxiliary engines	An assumption for each vessel type has been applied as to the extent of continuous auxiliary engine operation whilst vessels are stationary. This was carried out due to an absence of information on the matter. The results are presented as a wide range between lower and upper bounds, with the best estimate close to the upper bound.	The ‘best estimate’ CO_2, NO_X, SO_2, and PM_{10} emissions results could be **significant overestimates or small underestimates**.
Time taken to connect to shore power	In addition to the limitations noted above, the results estimated will be upper estimates of the potential emissions that could be reduced by shore-powering these vessels to replace their auxiliary engine operation, because of the time necessary to connect and disconnect the electrical power and to start up the auxiliary engines prior to departure. Starcrest (2014) assume a 5% reduction to cover this time.	The ‘best estimate’ CO_2, NO_X, SO_2, and PM_{10} emissions results will be **overestimates** of the potential to be saved from shoreside electricity.
Projection from 2014 to 2016	There is uncertainty in how well the trend in statistical series of tonnes of cargo moved and numbers of passengers transported from 2014 to 2016 reflects the actual number of vessels operated.	Unknown (may be positive or negative) impact. Expected to be small.
Monetisation of emissions impacts	There is a large range of uncertainty in the damage costs assigned to each pollutant.	Unknown (may be positive or negative) impact). The full range of monetised impacts should be used.
Monetisation of emissions impacts	The damage costs for SO_2, NO_X and PM_{10} are based on average damage costs for transport, which are expected to be primarily based on road transport. However, as road transport emissions typically occur closer to sensitive receptors, there would be a lower value in reducing 1 tonne of e.g. NO_X from a vessel at berth in a port that is further from a sensitive receptor, than reducing the same quantity of NO_X from a trafficked road near a sensitive receptor (e.g. a school).	Monetised impacts of NO_X, SO_2, and PM_{10} emissions likely to be **overestimates**.
Monetisation of emissions impacts	The damage costs for SO_2, NO_X and PM_{10} do not take into account all possible health and environmental impacts that can arise from the pollutant emissions.	Monetised impacts of NO_X, SO_2, and PM_{10} emissions likely to be **underestimates**.

3.5 There is limited information in the literature on ship auxiliary engine operation at berth

Estimating the fuel consumption of auxiliary engines is also expressed as a major uncertainty in the literature (e.g. Jalkanen et al., 2016; TNO, 2016). There is also an absence of information on this topic in official emissions inventory guidelines (EMEP/EEA, 2016; IPCC, 2006). The limited information identified in literature on the subject is summarised below.

- AIS methods identify an increasing number of unidentified (not IMO-registered) vessels and a substantial fraction of these vessels are inactive at berth (Johansson et al., 2013). To estimate the fuel consumption of auxiliary engines from these vessels, Johansson et al (2013) assume the auxiliary engine fuel consumption rate decreases by 80% after 2 hours at berth until 8 hours at berth.
- AIS-based methodologies – such as this study – deliver more accurate but higher estimates of emissions for vessels at berth than non-AIS based methodologies (TNO, 2016).
- The use of auxiliary engines varies greatly between vessel types, and even for ships of the same type (Jalkanen et al., 2016).
    - The share of auxiliary engine fuel consumption from total consumption is very high for **service vessels** and **tugboats** (Jalkanen et al., 2016).
    - For **tankers** and **container** ships, the majority of fuel consumed at berth is by the boilers rather than the auxiliary engines (TNO, 2016).
    - A North Sea **offshore** supply vessel case study primarily had engines running whilst at berth (NHO, 2016). Specifically the vessel operated an engine at berth at very low (8%) load for 2,015 hours per year, and had all engines switched off (vessel was out of service) for 175 hours per year.
    - A Norwegian **passenger** vessel case study had a relatively even balance between engines on and off whilst at berth (NHO, 2016). Specifically, the vessel operated an engine at berth at low (28%) load for 2,312 hours per year, and had all engines switched off (vessel was out of service) for 1,825 hours per year.

Additional anecdotal views from Ricardo marine engine experts on ship auxiliary engine operation are:

- If **merchant vessels** are stationary at berth for more than 24 hours, then they are likely to be either undergoing some sort of maintenance for which auxiliary power on board would still be required, albeit possibly at reduce load/demand, or the vessels are in layup. The latter may be with the ship’s power systems on (again, at lower load), or off (and an on-deck generator may be used).
- **Bulk carriers** operating around the UK in 2014 – the year of AIS data underpinning the model – may have been stationary for longer at berth due to the volatile decline over this period in the market for coal consumed by UK power stations.
- Fuel consumption rates expressed in g/kWh increase at engine loads lower than 50%.

Further work is recommended to refine the estimate of emissions, for example through a stakeholder engagement exercise with vessel operators and port authorities in order to establish real world operational profiles of auxiliary engines used at berth.

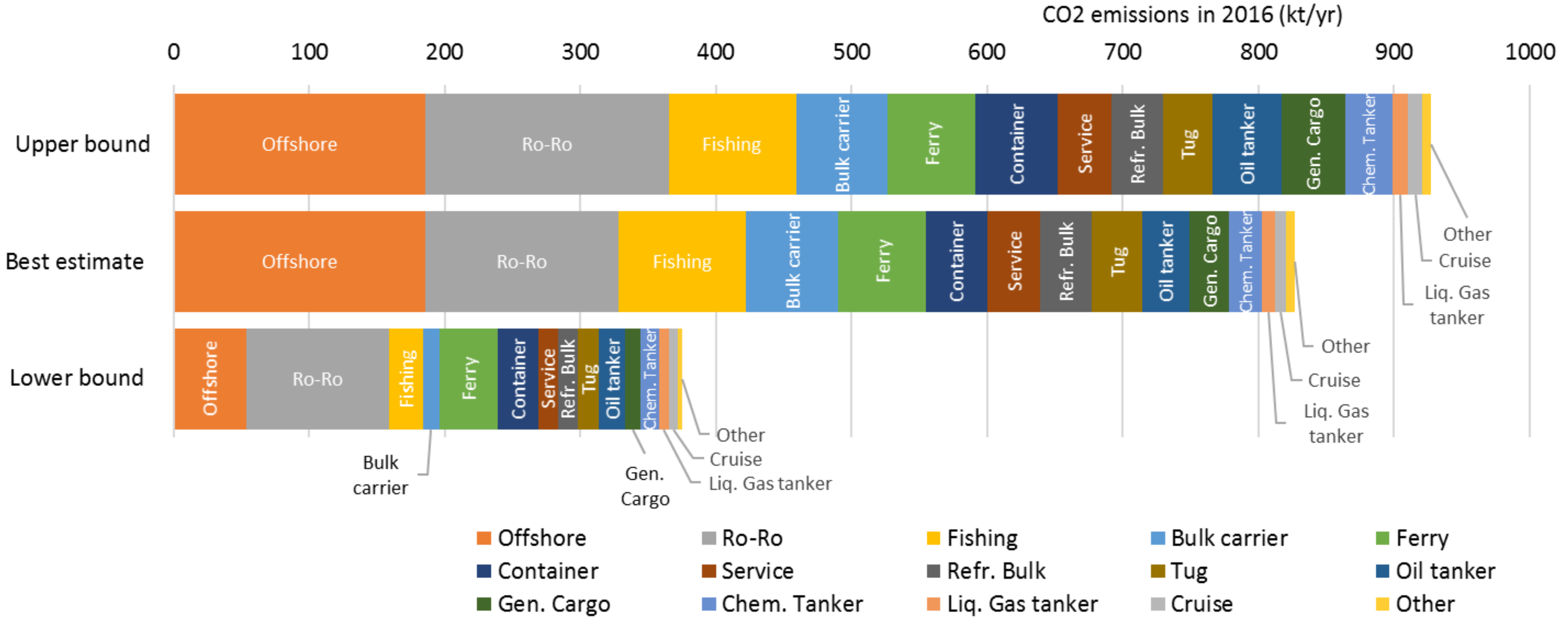
3.6 Offshore supply vessels, fishing boats, roll-on-roll-off, bulk carriers and passenger ferries contribute the most to the estimates of emissions from auxiliary engines at berth

The figures on the following pages (Figure 3 for CO_2, Figure 4 for NO_X, Figure 5 for PM_{10} and Figure 6 for SO_2) show the estimated emissions from auxiliary engines of ships at berth split by vessel category. The Figures show the lower bound, best estimate and upper bound of emissions.

The plots show that the vessel categories which contribute the most to the estimates of emissions are offshore supply vessels, fishing boats, roll-on-roll-off (Ro-Ro), bulk carriers and passenger ferries.

Full tabulated results are in Appendix 2.

Figure 3: Estimated CO_2 emissions in 2016 from auxiliary engines of ships at berth around the UK, split by vessel type (units: kilotonnes)



Lower bound	Operation of vessel auxiliary engines from all vessel types capped to a maximum of 24 hours whilst at berth.
Best estimate	Specific vessel types operate auxiliary engines without a cap, and other vessel types' auxiliary engines are assumed to drop their fuel consumption rate by 50% after 24 hours at berth.
Upper bound	Operation of vessel auxiliary engines from all vessel types without a cap – i.e. assumed to continue to operate at the same fuel consumption rate until the AIS dataset shows the vessel next departing from berth.

Figure 4: Estimated NOx emissions in 2016 from auxiliary engines of ships at berth around the UK, split by vessel type (units: kilotonnes)

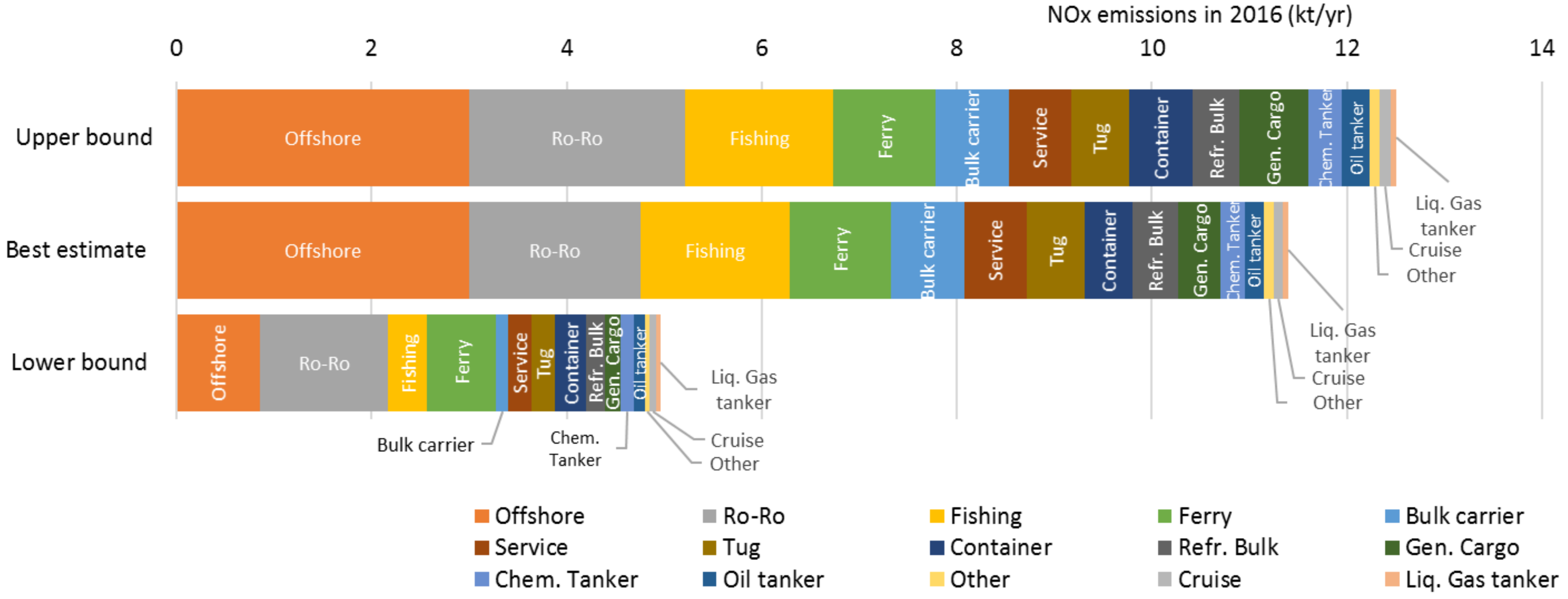


Figure 5: Estimated PM_{10} emissions in 2016 from auxiliary engines of ships at berth around the UK, split by vessel type (units: kilotonnes)

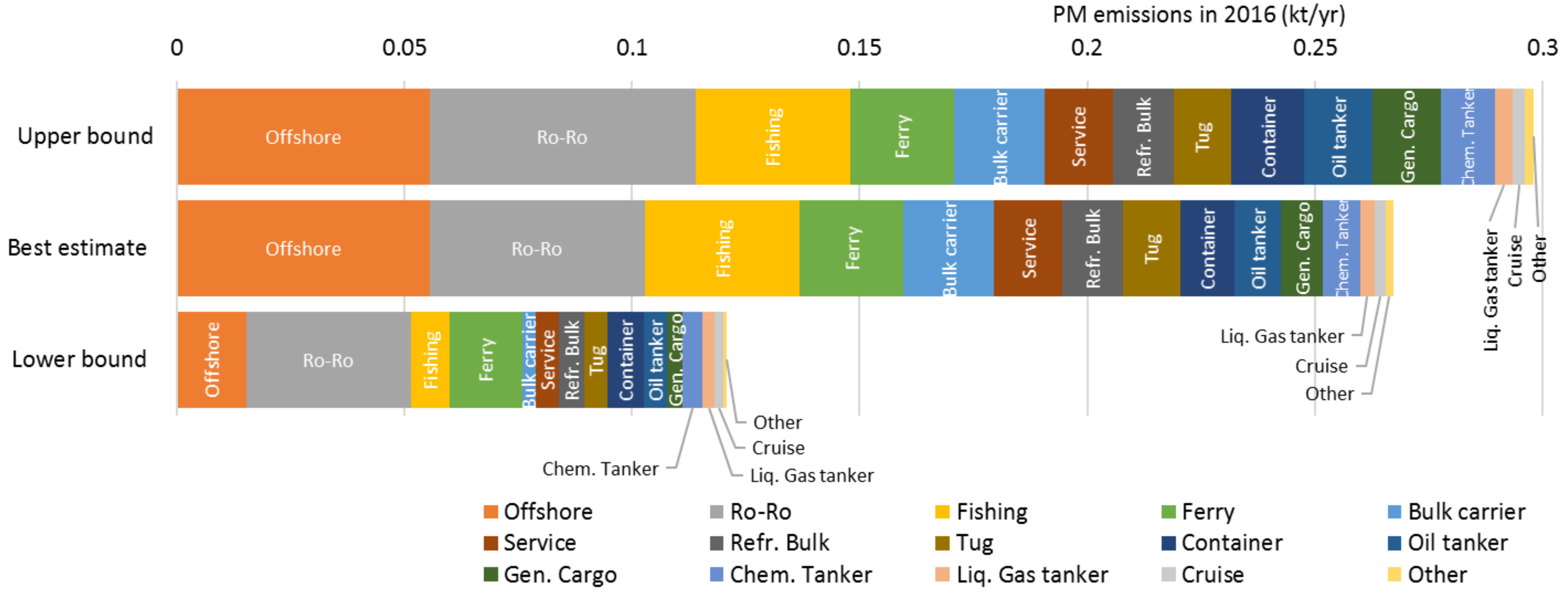
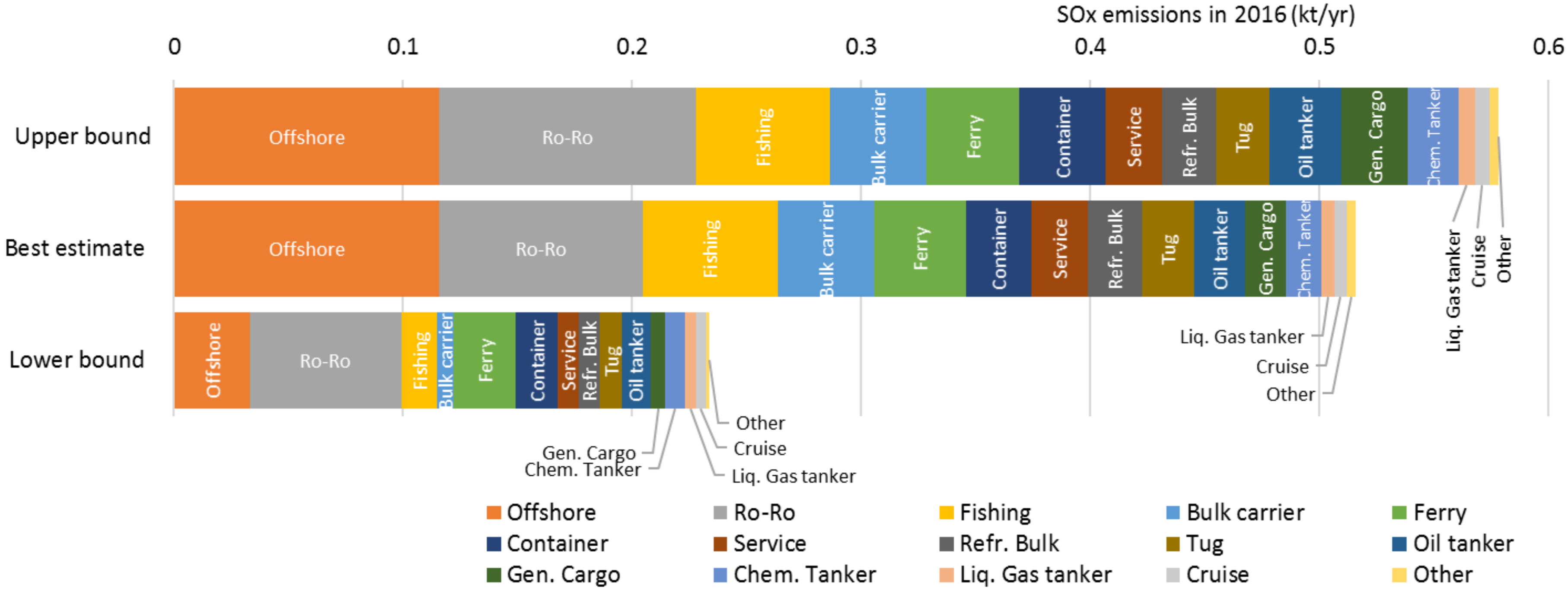


Figure 6: Estimated SO_2 emissions in 2016 from auxiliary engines of ships at berth around the UK, split by vessel type (units: kilotonnes)



3.7 Emissions from auxiliary engines at berth compared to other sources

This section compares the emissions from auxiliary engines at berth to other sources in the NAEI. NAEI emissions are the national totals for the UK territory only, as reported in Ricardo (2018) for NO_x, SO_2, and PM_{10}, and to be published in spring 2018 for CO_2.

3.7.1 Best estimates of NO_X from vessels' auxiliary engines at berth in 2016 are equivalent to 2.6% of UK transport emissions and 1.3% of UK total emissions

Similarly, the best estimates of PM_{10} and SO_2 from vessels' auxiliary engines at berth in 2016 are equivalent to 1.1% and 3.6% of UK transport emissions and 0.16% and 0.29% of UK total emissions respectively. Table 4 shows the emissions estimates for vessel auxiliary engines at berth compared against the transport sector[4] and national totals from the NAEI for the calendar year 2016. The transport sector includes aviation, road traffic, diesel train and domestic shipping and inland waterway emissions. Emissions sources presented in section 3.7.2 are disaggregated by the sector categories (sources) used for national inventory reporting.

The pollutant with the largest emissions relative to the NAEI UK transport total for 2016 is SO_2 (3.6%), whereas the pollutant with the largest emissions relative to the NAEI UK national total for 2016 is NO_x (1.3%). This difference is because the transport sector makes a larger contribution to the national total for NO_x relative to SO_2.

Table 4: Best estimate of total UK emissions from vessel auxiliary engines at berth compared against the transport and national totals from the NAEI (units: CO_2 emissions in megatonnes; kilotonnes for other pollutants).

	CO_2 (Mt)	NO_x (kt)	PM_{10} (kt)	SO_2 (kt)
Best estimate (BE) of total UK emissions from auxiliary engines at berth	0.83	11.4	0.27	0.52
UK Transport sector total emissions	**122**	**437**	**24**	**14**
BE as % of Transport total	*0.68%*	*2.6%*	*1.1%*	*3.6%*
UK National total emissions	**379**	**892**	**170**	**179**
BE as % of National total	*0.22%*	*1.3%*	*0.16%*	*0.29%*

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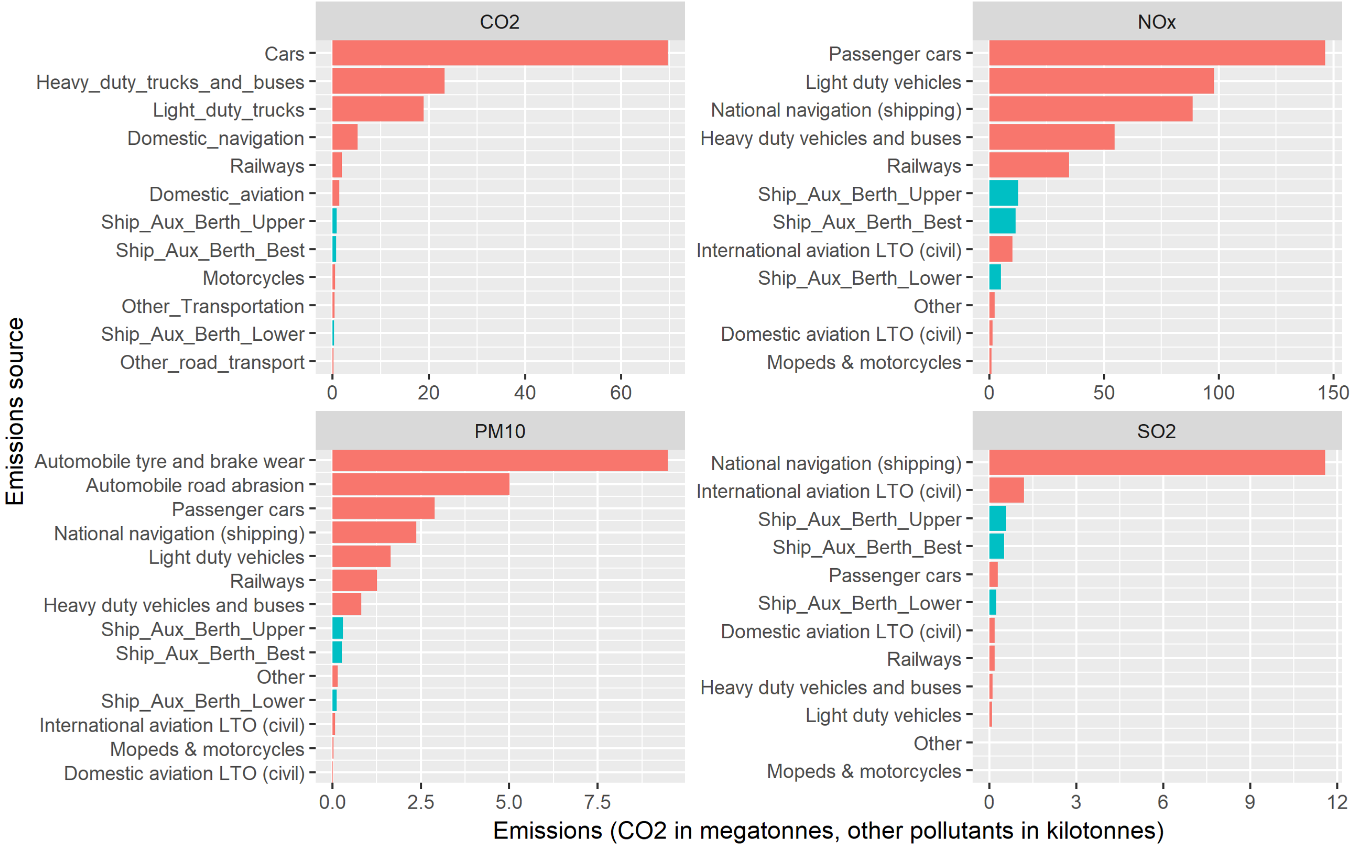
[4] The transport total for CO_2 is the sum of the emissions from the inventory Intergovernmental Panel on Climate Change code "1A3" (Transport), and for the other pollutants, it is the sum of the emissions from the inventory Nomenclature for Reporting code "1A3" (Transport). In the case of aviation, the reporting of CO_2 emissions under IPCC Guidelines covers only domestic take-off and landing and cruise movements; all parts of international aviation are excluded. In the case of reporting air pollutant emissions to UNECE and NECD, aviation emissions cover only take-off and landing emissions, but include both domestic and international flights.

3.7.2 Comparison against other transport sources

Figure 7 shows the emissions estimates for auxiliary engine operation at berth compared against NAEI transport emissions by IPCC and NFR[5] source categories as defined for international inventory reporting for the calendar year 2016. The blue bars are emission estimates from this project for ship auxiliary engines at berth, and the red bars are emissions from the NAEI.

Figure 7 shows that for CO_2, NO_x, and PM_{10}, emissions are dominated by road transport sources. For SO_2, emissions are dominated by shipping (national navigation), as the sulphur limit within road transport fuels is much lower than the fuels used for shipping. This shows that the best estimate of emissions from this project are relatively small when considered against all other NAEI transport sources.

Figure 7: Emissions estimates of vessel auxiliary engines at berth (blue bars) compared against UK transport emission sources (red bars) (units: CO_2 emissions in megatonnes; kilotonnes for other pollutants).



Notes: The sector ‘Domestic_navigation’ in the CO_2 plot refers to domestic shipping. ‘LTO’ stands for landing and take-off. SO_2 emissions from combustion of engine lubricants are excluded.

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[5] NFR stands for Nomenclature For Reporting and is the nomenclature used for air quality emissions inventory reporting to United Nations Economic Commission for Europe's (UNECE) and European Monitoring and Evaluation Programme (EMEP).

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Appendices

Appendix 1: Auxiliary engine power assumptions

Appendix 2: Tables of results for estimated emissions from ship auxiliary engines at berth, per vessel category

Appendix 1: Auxiliary engine power assumptions

AIS Class	Vessel type and size subcategory	Auxiliary engine power (kW) at berth
Class A	**1 Bulk carrier (average)**	**317**
	1	201
	2	280
	3	370
	4	600
	5	600
	6	600
	3 Chemical tanker (average)	**459**
	1	149
	2	490
	3	490
	4	1,170
	4 Container (average)	**746**
	1	252
	2	600
	3	700
	4	940
	5	970
	6	1,000
	7	1,200
	8	1,320
	5 General cargo (average)	**339**
	1	117
	2	328
	3	970
	6 Liquefied gas tanker (average)	**789**
	1	240
	2	1,710
	3	1,710
	7 Oil tanker (average)	**861**
	1	213
	2	375
	3	625
	4	750
	5	750
	6	1,000
	7	1,250
	8	1,500
	9 Ferry-pax only (average)	**113**
	1	105
	2	524
	10 Cruise (average)	**789**
	1	450
	2	450
	3	3,500
	12 Refrigerated bulk	**1,072**
	13 Ro-Ro (average)	**1,141**
	1	702
	2	1,200
	16 Service – tug	**41**
	17 Miscellaneous - fishing	**180**
	18 Offshore	**266**
	19 Service - other	**182**
	20 Miscellaneous - other	**84**

AIS Class	Vessel type and size subcategory	Auxiliary engine power (kW) at berth
Class B	**1 Bulk carrier (average)**	**18**
	1	14
	2	280
	3 Chemical tanker (size bin 1 only)	**0**
	4 Container (average)	**770**
	2	600
	4	940
	5 General cargo (size bin 1)	**50**
	7 Oil tanker (size bin 1)	**173**
	9 Ferry-pax only (size bin 1)	**11**
	12 Refrigerated bulk	**550**
	13 Ro-Ro (size bin 1)	**600**
	16 Service - tug	**10**
	17 Miscellaneous - fishing	**18**
	18 Offshore	**77**
	19 Service - other	**72**
	20 Miscellaneous - other	**22**

Appendix 2: Tables of results for estimated emissions from ship auxiliary engines at berth, per vessel category

Pollutant	Vessel type	Units	Emissions Lower bound	Emissions Best estimate	Emissions Upper bound
CO_2	Offshore	kt	53	190	190
	Ro-Ro	kt	110	140	180
	Fishing	kt	25	94	94
	Bulk carrier	kt	12	68	68
	Ferry	kt	43	65	65
	Container	kt	30	45	61
	Service	kt	14	40	40
	Refr. Bulk	kt	15	38	38
	Tug	kt	15	37	37
	Oil tanker	kt	20	35	50
	Gen. Cargo	kt	11	29	47
	Chem. Tanker	kt	14	25	35
	Liq. Gas tanker	kt	7.2	9.4	12
	Cruise	kt	7.0	8.5	10
	Other	kt	2.7	6.2	6.2
NOx	Offshore	kt	0.86	3.0	3.0
	Ro-Ro	kt	1.3	1.8	2.2
	Fishing	kt	0.40	1.5	1.5
	Ferry	kt	0.70	1.0	1.0
	Bulk carrier	kt	0.13	0.75	0.75
	Service	kt	0.23	0.64	0.64
	Tug	kt	0.25	0.60	0.60
	Container	kt	0.32	0.49	0.65
	Refr. Bulk	kt	0.19	0.47	0.47
	Gen. Cargo	kt	0.16	0.43	0.71
	Chem. Tanker	kt	0.14	0.24	0.35
	Oil tanker	kt	0.11	0.20	0.29
	Other	kt	0.04	0.10	0.10
	Cruise	kt	0.08	0.09	0.11
	Liq. Gas tanker	kt	0.04	0.05	0.06

Pollutant	Vessel type	Units	Emissions Lower bound	Emissions Best estimate	Emissions Upper bound
PM_{10}	Offshore	kt	0.015	0.056	0.056
	Ro-Ro	kt	0.036	0.047	0.058
	Fishing	kt	0.009	0.034	0.034
	Ferry	kt	0.016	0.023	0.023
	Bulk carrier	kt	0.003	0.020	0.020
	Service	kt	0.005	0.015	0.015
	Refr. Bulk	kt	0.005	0.013	0.013
	Tug	kt	0.005	0.013	0.013
	Container	kt	0.008	0.012	0.016
	Oil tanker	kt	0.005	0.010	0.015
	Gen. Cargo	kt	0.003	0.009	0.015
	Chem. Tanker	kt	0.004	0.008	0.012
	Liq. Gas tanker	kt	0.003	0.003	0.004
	Cruise	kt	0.002	0.002	0.003
	Other	kt	0.001	0.002	0.002
SO_2	Offshore	kt	0.033	0.12	0.12
	Ro-Ro	kt	0.066	0.089	0.11
	Fishing	kt	0.015	0.059	0.059
	Bulk carrier	kt	0.007	0.042	0.042
	Ferry	kt	0.027	0.040	0.040
	Container	kt	0.019	0.028	0.038
	Service	kt	0.009	0.025	0.025
	Refr. Bulk	kt	0.009	0.024	0.024
	Tug	kt	0.010	0.023	0.023
	Oil tanker	kt	0.012	0.022	0.031
	Gen. Cargo	kt	0.007	0.018	0.029
	Chem. Tanker	kt	0.009	0.015	0.022
	Liq. Gas tanker	kt	0.004	0.006	0.007
	Cruise	kt	0.004	0.005	0.006
	Other	kt	0.002	0.004	0.004

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