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Determination and modelling of NO_X and particulate matter (PM) emissions from inland vessels at berth –

Results from the EU Life Project „Clean Inland Shipping“ (CLINSH)

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ist als Dezernent im FB 77 (Luftqualitätspläne) des LANUV u. a. verantwortlich für Konzeption und Koordination der Beiträge zum internationalen EU-Life-Projekt „Clean Inland Shipping (CLINSH)“.

The emissions from loading and berthing operations in the ports have so far been determined in NRW by estimations based on the cargo turnover. There was no applicable method for estimating emissions based on differentiated data on the number of moored ships. For this purpose, a methodology was developed and tested by the LANUV within the framework of CLINSH.
An important component is the analysis of the current generator stock on cargo vessels, tankers and river cruise ships and the mean emission factors per ship type and length class derived from this. In combination with the survey of the actual energy demand, the number of ships in port, the loading operations and the average berthing times, it was possible to carry out a more realistic estimate of the emissions. It turned out that the emissions determined are significantly lower than previously assumed.
For the year 2028, emission quantities of 15.5 t NO_X and 764 kg PM were determined for the Port of Duisburg. In the same year, 9.5 t NO_X and 588 kg PM were emitted by moored ships in the port of Neuss. The berths of river cruise ships "on tour" and the unloading berths of tankers emerged as potential locations for significant reductions in emissions through onshore power supply.

1. Introduction

Emissions from loading and berthing operations in ports in NRW have so far been determined by means of estimations based on the handling of goods. An applicable method for estimating emissions based on differentiated data on the number of berthing ships, the berthing times, the actual power demand and the emission behavior of the generators on the ships was missing. For this purpose, a methodology was developed and tested by the LANUV within the framework of CLINSH.

2. Determination of emissions from power generation of moored inland vessels

2.1 Required data

The following information is required for emission estimation:

1) Power demand of moored vessels/vessel types.
2) Type, size class, and number of vessels at berth (tankers, cargo vessels, cruise ships).
3) Average power of the "smallest" generators per ship class. (The power supply of moored cargo ships is provided by the smallest generator on board).
4) Diesel consumption (g/kWh) of these generators in low load range.
5) Composition of emission levels of the generator stock for each ship class to determine average emission performance.
6) Average emission factors for the different power classes of generators ("fleet generators"), differentiated by the different age classes, the respective applicable emission restrictions and, if applicable, operation in the low-load range
7) Average berthing times spend at the berths.
8) For further evaluations: Georeferencing of emissions and berths, e.g., characterization of emission sources as point or line sources.

2.2 Power demand of ships at berth

The power requirements of moored cargo and tanker vessels were determined through interviews and literature research [1; 2]. Berthing ships require electricity for on board electrical systems, e.g., lighting, galley (stove, refrigerator, etc.), living area and office (television, radio, computer, etc.). The demand of a cargo motor vessel is approximately equal to the consumption of a household with three to four persons and is about 1–2 kW. For modern double-hull tankers (length classes 85–130 m), the survey of shipping companies revealed a higher basic demand of about 8–9 kW, which is caused, for example, by the additional operation of aeration plants (explosion protection) and electric heating systems.

The power supply for ships at berth is provided by on board diesel generators. If several generators are available, always the smallest generator on board is used on cargo ships and tankers, which then operates in the low-load range. Therefore, an important basis for the emission calculations is the knowledge of the composition of the generator stock in the inland waterway fleet and their emission behavior.

The unloading of tankers requires a much higher power input in the order of about 90–110 kW, as it is usually done by on board pumps. These are supplied by large on board generators in the normal load range.

For river cruise ships, depending on the sailing situation (with/without passengers), there is a very large demand range of 2–200 kW, which is described in more detail in chap. 7.

2.3 Type and number of ships at the berths

The type and number of ships at berths can be determined by evaluating AIS signals. With a suitable evaluation program, the average duration of berths can also be determined. The collected data were compared with the information provided by the port operators.

The ships were classified according to the length classes of the CEMT (European Conference of Ministers of Transport, *Conférence Européenne des Ministres des Transports*) [3] in order to better characterize the generator fleet (Fig. 1).

3. Analysis of the generator inventory on cargo, tanker and cruise ships

Inland vessels are regularly inspected for safety. Ship owners can choose in which EU member state they have their vessels inspected. For CLINSH, data sets on generator inventory available in the German Ship Inspection Commission (ZBBD) database [4] were analyzed. Data from the Dutch and Belgian commissions were unfortunately not available.

In total, records of 923 tankers, cargo ships and river cruise ships also contained technical data on the generators on board. Most of these are German ships, but also about 100 Dutch and Belgian ships are included. The high number of ships is sufficient to develop a representative basis for the emission estimates.

3.1 Data situation

Power data (kW) on the "smallest" ship generators are available for 280 tankers, 609 cargo ships and 34 river cruise ships (cabin ships). For 370 cargo ships, 236 tankers and 34 cabin ships also the generators' year of construction is given. Entries on the respective emission level to be complied with (EU II, EU IIIa, EU V or CCNR I, CCNR II) of newer generators are available for 189 cargo ships (31 %), 177 tankers (63 %) and 22 (67 %) river cruise vessels. For 420 cargo ships, 103 tankers and 12 river cruise ships without information on the certification of the generators, their emission behavior was determined as an alternative.

a) Classification of generators based on their year of construction:

The year of construction of the generators is known for 184 cargo ships, 62 tankers and 12 cabin ships with no indication of emission level. The classification was based on the emission regulations applicable in the respective year of construction (Tab. 1). For years of construction before 2003, the emission factors were used in compliance with the classification according to TREMOD [5] (Tab. 6).

b) Classification of the generators based on the year of construction of the ships:

For 236 cargo ships and 41 tankers, data is only available on the power of the "smallest" generator. Here, the emission classification is based on the ship's year of construction. It is assumed that new generators were installed in each case. On the basis of the ship's year of construction, most of the generators are assigned to the oldest emission class according to TREMOD [5] with year of construction "before 1981"). Some of these generators have certainly already been replaced and are thus younger than 1981. Therefore, the emission estimate made in this way is to be classified as "conservative".

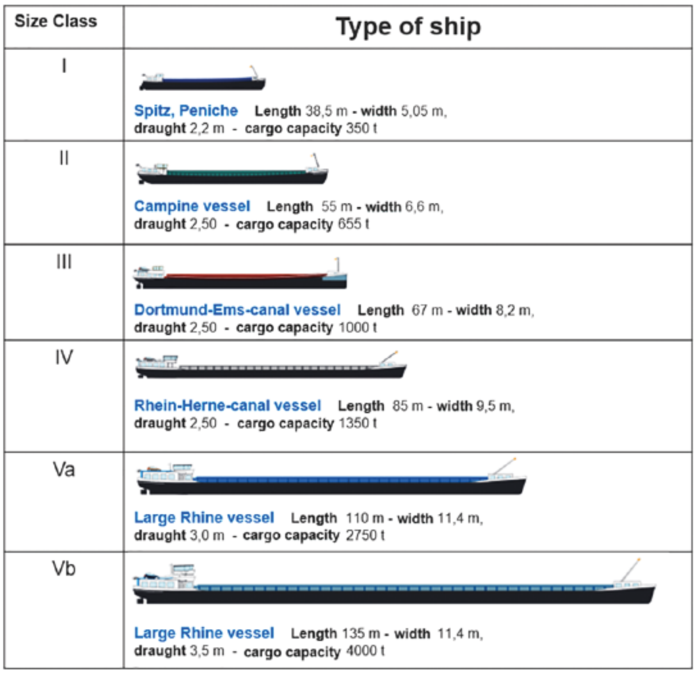

Fig. 1: Size classes of cargo and tanker vessels in this report, analogous to the CEMT-classification [3]
Ship Graphics: Buerau Voorlichting Binnenvaart

3.2 Summary of emission levels

To simplify the fleet emission estimates, a compromise must be found for a summary grouping of generators by EU stage, CCNR regulation, and TREMOD classification by year of manufacture. The EU has given different dates for the emission levels of the different generators' power classes coming into force. For the generators, only the year of manufacture (not the month) is available. Therefore, the beginning of each year was assumed as effective date. The years for the introduction of the emission levels are compiled in Tab. 1.

Furthermore, certifications according to CCNR I and EU Stage II as well as certifications according to CCNR II and EU Stage IIIa were combined. For construction years where emissions certification can be assumed, a uniform classification was made according to EU Stage II (construction year 2003–2006) or EU Stage IIIa (construction year 2007–2018).

Power class of generator	Entry into force of the respective emission limit values					
	EU 1	EU II	EU IIIa	EU V	CCNR I	CCNR II
18–37 kW		2001	2007	2019		
37–75 kW	1999	2004	2008	2019	2003	2007
130–560 kW	1999	2002	2006	2019		

Tab. 1: Entry into force of the respective emission limits

3.3 Cargo vessels

The analysis of the "smallest" generators on board in each case reveals two power classes: ships up to 110 m in length (Class I–Va) are equipped with the "smallest" generators in the average power range of about 20–30 kW, while the generators of the large ships (Class Vb 135 m) are around 55 kW. With only 10 ships, the power determination of this class remains uncertain.

Tab. 2: Combination of the different approaches for determining the respective emission levels for the "smallest" generators of the freight vessels. The dark blue fields are not added up for "total"

Cargo vessels „smallest" generator					
Emission level according to TREMOD	Number	%	According to Emission level generator	According to year of construction generator	According to year of construction ship
before 1981	234	38,4	–	12	222
1981–1990	36	5,9	–	28	8
1991–2002	77	12,6	–	72	5
CCNR I	6	1,0	6	–	–
CCNR II	4	0,7	4	–	–
EG II (from 2003)	105	17,2	73	32	–
EG IIIa (from 2007)	146	24,0	105	40	1
EU V (from 2019)	1	0,2	1	–	–
∑ EU II + CCNR I	111	18,1	–	–	–
∑ EU IIIa + CCNR II	150	24,6	–	–	–
Total	**609**		**189**	**184**	**236**

The average age of the generators of cargo ships is between 13 (class Vb) and 22 years (class IV). The actual average age of the generators for ship classes I–IV is probably significantly higher, as 236 ships (39 %) with unknown year of the generators' construction are not included in the evaluation.

An evaluation of the data for the "smallest" generator to classify the emission potential was possible for 609 cargo ships.

The "smallest" generators on 43 % of the cargo ships already meet the requirements of one of the emission levels (Tab. 2, see Chap. 4.2). The 236 ships without information on the year of construction of the generators are predominantly classified in the highest emission level according to TREMOD [5] (year of construction before 1981) (Tab. 2). Therefore, the emissions are probably somewhat overestimated, as some of the generators may have already been renewed.

3.4 Tanker vessels

When estimating the emissions from tankers, a distinction must be made between berthing situations without the use of on board pumps (loading operations or waiting times, power requirement approx. 9 kW) and with the use of on board pumps (unloading operations, power requirement approx. 110 kW). A large on board generator is used for the supply of the pumps, so for tankers the "largest" generators were also analyzed.

For tankers (Class IV, Va, Vb; 85–135m), the classification was possible in 244 cases for the "smallest" generator and in 243 cases for the "largest" generator. If the database contains information on only one generator, it is listed as both "smallest" and "largest" generator (Tab. 3).

3.4.1 Loading processes and waiting times – emissions from the "smallest" generators.

With about 9 kW, the power requirement during loading is somewhat higher than for cargo ships and is needed, among other things, for the operation of ventilation systems (e.g. explosion protection). This demand is also covered by the smallest generators of the tankers.

The ships of the length classes I (< 40 m), IV (85 m), Va (110 m) and Vb (135 m) show a homogeneous picture for the "smallest" generators with an average power range of about 50–65 kW. For the medium classes II and III (ship lengths 40–56 m; 56–68 m), the average power of these generators is in the range of 35 kW. Since these classes are represented by only eight vessels, the determination remains uncertain.

The average age of the generators, depending on the class of vessel, is between 13 and 19 years. The generators of the tankers of length class I have the highest average age (19 years). For the larger ships (Class IV, Va, Vb), the average age is between 12 and 15 years. The actual average age of the generators for ship classes I–IV is probably somewhat higher, since the year of construction of the generators is unknown for 44 ships (16 %). These therefore mainly fall into the two highest TREMOD [5] emission levels (built before 1991).

Our interviews revealed that tanker traffic to the tank farms at Duisburg and Neuss is almost exclusively handled by vessels of the size classes IV, Va and Vb. Table 3 therefore only shows the results for these size classes. Even 75,8 % of the "smallest" generators on board tankers in the length classes IV, Va and Vb meet the requirements of one emission stage (EU II + CCNR I: 53,3 %; EU IIIa + CCNR II: 22,5 %) (Tab.3).

3.4.2 Unloading operations – emissions from the "largest" generators

During unloading operations, the "largest" generators on board are usually used to provide the electrical power needed for the pumps. For all tankers, information on the year of construction of the "largest" generator is available in 251 cases. For 192 (69 %) vessels, the emission level is also known.

The "largest" generators for ship classes I, II, and III have an average output of 66–74 kW. Ship classes IV and Va have significantly higher average generator outputs of 159–174 kW. In class Vb (135 m), the average power is even higher with 242 kW.

Depending on the ship class, the average age of the "largest" generators ranges from 11 to 19 years, with class I having the highest average age. For the larger class IV, Va and Vb ships (85–135 m), the average age is between 13 and 16 years. For tankers, the actual average age of the "largest"

Tanker vessels „smallest" generator (Ship classes IV, Va, Vb)					
Emission level according to TREMOD	**Number**	**%**	**According to Emission stage generator**	**According to year of construction generator**	**According to year of construction ship**
before 1981	**17**	**7,0**	–	2	15
1981–1990	**10**	**4,1**	–	4	6
1991–2002	**32**	**13,1**	–	29	3
CCNR I	28	11,5	28	–	–
CCNR II	10	41,8	10	–	–
EG II (from 2003)	102	41,8	92	9	1
EG IIIa (from 2007)	45	18,4	39	2	4
EU V (from 2019)	–	–	–	–	–
∑ EU II + CCNR I	**130**	**53,3**	–	–	–
∑ EU IIIa + CCNR II	**55**	**22,5**	–	–	–
Total	**244**		**169**	**46**	**29**
Tanker vessels „largest" generator (Ship classes IV, Va, Vb)					
Emission level according to TREMOD	**Number**	**%**	**According to Emission stage generator**	**According to year of construction generator**	**According to year of construction ship**
before 1981	**16**	**6,6**	–	**2**	**14**
1981–1990	**9**	**3,7**	–	**9**	–
1991–2002	**26**	**10,7**	–	**24**	**2**
CCNR I	44	18,1	44	–	–
CCNR II	18	7,4	**18**	–	–
EG II (from 2003)	59	24,3	**55**	**3**	**1**
EG IIIa (from 2007)	71	29,2	**65**	–	**6**
EU V (from 2019)	–	–	–	–	–
∑ EU II + CCNR I	**103**	**42,4**	–	–	–
∑ EU IIIa + CCNR II	**89**	**36,6**	–	–	–
Total	**243**		**182**	**38**	**23**

Tab. 3: Combination of the different approaches to determine the respective emission levels for the "smallest" and "largest" generators of the tankers of the size classes IV, Va and Vb. The dark blue fields are not added up for "total"

generators is also likely to be somewhat higher for ship classes I–IV, as the year of construction of the generators is unknown for 35 (13 %) ships.

For the emission calculations, 244, resp. 243 tankers of the size classes IV, Va and Vb were evaluated. 75.8 % of the "smallest" generators on board these tankers already meet the requirements of an emission level (Tab. 3).

79 % of the "largest" generators on board the tankers of these classes already meet the requirements of an emission stage. Of these, 103 ships (42.4 %) meet the requirements of the emission levels EU II or CCNR I and 89 ships (36.6 %) meet the requirements of the emission levels EU IIIa or CCNR II (Tab. 3).

3.5 River cruise ships

Data from 34 river cruise ships (cabin vessels) in the length classes IV, Va, and Vb were available for an analysis of the generator pool. Despite the relatively small number, the data could be used to estimate the composition of generators for vessels in the size classes Va (n = 19) and Vb (n = 11). The representativeness for the ship class around 85 m (n = 4) remains low. Cabin vessels have up to five generators on board. The year of construction is known for 80 of these generators with a power >130 kW. 56 (70 %) of these generators already meet the requirements of an emissions stage (Tab. 4). For the others, the classification of the emission behavior was based on their year of construction.

The average age of the generators on the 85 m class (IV) ships was 21 years, and the average output was 230 kW. 50 % of the generators in this class of ship already meet the EU IIIa or CCNR II emission levels (Tab. 4).

On the ships of the 110 m class (Va), the generators have an average age of 20 years. The "smallest" generators on board the 110 m ships have an average output of 150 kW, the "largest" have an output of 288 kW. Already 52.3 % of the "largest" generators of this ship class meet the requirements of an emission level. 27.3 % of the generators fall into the emission levels EU II or CCNR I and 25 % into the emission levels EU IIIa or CCNR II (Tab. 4).

The generators of the 135 m class (average 11 years) were younger than those of the smaller ships. The average outputs of the "smallest" (240 kW) and "largest" (461 kW) generators are significantly higher than for the 110 m vessels. All generators already meet EU II or CCNR I emission levels (26.7 %) or EU IIIa or CCNR II emission levels (73.3 %) (Tab. 4). Generators in the 130–299 kW power class are generally used to cover the power requirements of the moored river cruise vessels.

Cabin vessels : Emission relays of the generators on board with a power > 130 kW						
Emission level according to TREMOD	85 m (IV)		110 m (Va)		135 m (Va)	
	Quantity	%	Quantity	%	Quantity	%
Generators	6		44		30	
before 1981	1	16,7	2	4,5	–	–
1981–1991	–	–	6	13,6	–	–
1991–2002	2	33,3	13	29,5	–	–
EU II + CCNR I	–	–	12	27,3	8	26,7
EU IIIa + CCNR II	3	50	11	25	22	73,3

Tab. 4: Composition of the generators on cruise vessels according to different emission levels (TREMOD) [5]

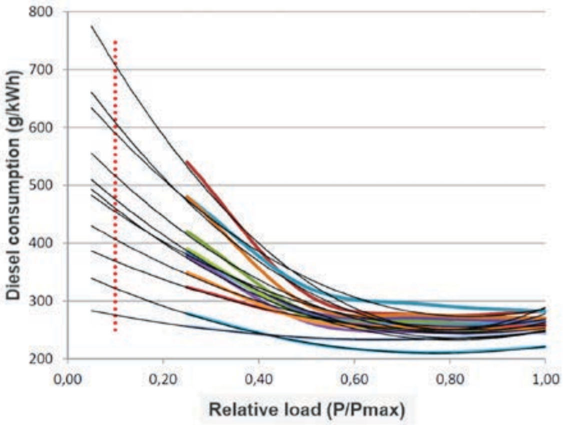

Fig. 2: Extrapolation of the specific fuel consumption (grams per electric kWh) of generator sets to the low-load range of 8 % utilization. Modified chart from the Walstroom study [1]

Generators with 28–36 kW power						
Emission level according to TREMOD	Diesel g/kWh		NO_x g/kWh		PM g/kWh	
	Tremod	low load	Tremod	low load	Tremod	low load
before 1981	300	525	18	31,5	2	3,5
1981–1990	281	525	18	33,6	1,4	2,6
1991–stage I	262	525	9,8	19,6	1,4	2,8
Stage I	262	525	7,7	15,4	1,4	2,8
Stage II	262	525	6,5	13,0	0,37	0,7
Stage IIIa	262	525	6,1	12,2	0,37	0,7
Stage IIIb	262	525	6,1	12,2	0,54	1,1
Stage IV	262	525	no data		no data	
Stage V	262	525	4,23	8,5	0,015	0,030

Generators with 37–74 kW power						
Emission level according to TREMOD	Diesel g/kWh		NO_x g/kWh		PM g/kWh	
	Tremod	low load	Tremod	low load	Tremod	low load
before 1981	290	430	7,7	11,4	1,8	2,7
1981–1990	275	430	8,6	13,4	1,2	1,9
1991–stage I	260	430	11,5	19,0	0,8	1,3
Stage I	260	430	7,7	12,7	0,35	0,6
Stage II	260	430	5,5	9,1	0,22	0,4
Stage IIIa	260	430	3,8	6,3	0,22	0,4
Stage IIIb	260	430	5,1	8,4	0,025	0,041
Stage IV	260	430	4,05	6,7	0,025	0,041
Stage V	260	430	2,1	3,5	0,015	0,025

Tab. 6: TREMOD [5] base emission factors for mobile diesel engines with adjustment for the low-load range (8 % load factor)

		Power	Diesel consumption at low load range
Manufacturer	TYP	kW max	g/kWh
Deutz	L2011	10	600
Deutz	M2011	10	590
Deutz	L2011	16	700
Deutz	M2011	16	610
Deutz	L2011	24	525
Deutz	M2011	24	460
J. Deere	3029	27	325
J. Deere	4039	31	410
Deutz	L2011	32	375
Deutz	M2011	32	380
Deutz	914	36	475
	Mean		**525**
Deutz	914	56	580
J. Deere	4045	79	280
	Mean		**430**

Tab. 5: Estimation of the diesel consumption of the “smallest” generators on freight and tanker vessels in the low-load range of about 8 % of capacity (“Walstroom study”) [1]

4. Diesel consumption and emission factors of generators on cargo ships and tankers

4.1 Diesel consumption of the “smallest” generators in the low-load range

Determining diesel consumption and emission factors of generators in the low load range of 2–9 kW is difficult. The performance curves of the manufacturers usually do not cover the power range below 25 %. The TU Delft extrapolated the typical power/consumption curves of various generators for inland vessels into the low load range [1].

In the TU Delft “Walstroom study” [1], these performance curves were extrapolated into the low-load range. From these curves (Fig. 2), the diesel consumptions for the low-load range compiled in Tab. 5 can be estimated (approx. 8 % load). For the power classes of the generators defined for TREMOD [5] (28–36 kW and 37–74 kW), an average diesel consumption per kWh in the low-load range can be derived from this.

4.2 Emission factors

The emission calculation model “TREMOD” (Transport Emission Model) [5], which is frequently used in Germany, maps motorized traffic in terms of mileage, its power consumption and the associated air pollutant emissions. Emissions from inland vessels and mobile power generators are also taken into account.

Using the higher diesel consumption derived from the “Walstroom study” [1], the TREMOD baseline factors [5] for mobile generators were adjusted to the low-load range. The expected ship emissions were calculated using the higher average diesel consumption per kWh at low load (Tab. 6).

The larger generators in Tab. 7 are used to supply the pumps when unloading (pumping empty) the tankers and for the energy supply of cruise vessels. Since they operate under normal load, no adjustment of the emission factors is required.

5. Model calculations for estimating emissions from the generator operation of moored ships

Using the data compiled in the Chapters 2–4, NO_x and particulate matter (PM) emissions from inland vessels at berth can be calculated. A power demand of 2 kW is assumed for cargo vessels and 9 kW for tankers, always covered by the “smallest” diesel generator on board. The calculations of NO_x and PM emissions are based on the diesel consumption at low load (see Tab. 6) and the base emission factors for diesel generators from TREMOD [5] adjusted to this.

In addition, the emission quantities at a model port are determined if an average of 50 ships are moored there for 8 hours each day. This figure is somewhat higher than the number of ships actually handled in Duisburg, Europe’s largest inland port.

5.1 Grouping of generators into TREMOD emission factors

Cargo vessels: For cargo ships at berth, all generator emissions are calculated using TREMOD [5] baseline emissions adjusted for “low load” for the 28–36 kW power class (see Tab. 6).

Tanker vessels: When estimating emissions from tankers at berth, the high power demand during unloading operations and the lower power demand during loading and waiting times must be taken into account.

Loading and waiting times: For tankers without shipboard loading operations, all generators are calculated with TREMOD baseline emissions of power class 37–74 kW, adjusted for “low load” (see Tab. 6).

Unloading: The calculation is done with the TREMOD base emissions of the power class 130–299 kW (Tab. 7). This is presented separately in chap. 6 using the real example of the “Oil Island” in Duisburg.

5.2 Model port: estimation of emissions from generators based on TREMOD emission levels

The expected emission quantities were calculated for the different emission levels (Tab. 8, 9).

Cargo vessels: In the “worst case” (all generators built before 1981), NO_x emissions in the model port (50 cargo ships/d; eight hours moored time; generators 28–36 kW) would reach about 9.2 t/a. If all generators already met Stage V, annual emissions would decrease by 73 % to 2.48 t/a (Table 8). The PM emissions from 50 cargo ships would be 1,022 kg/a in the “worst case”. If all generators meet the requirements of Stage V, PM emissions would drop by 99 % to only 7.3 kg/a (Tab.9).

Tanker vessels: For tankers at berth (generators in the power range of 37–74 kW, without unloading operations), the power requirement of 9 kW is higher than for cargo ships. In the “worst case scenario”, about 15 t/a NO_x would be emitted by 50 tankers (without pump operation). If all generators already meet the requirements of Stage V, NO_x emissions drop by 69 % to about 4.6 t/a (Tab. 7). PM emissions would be 3.6 t/a in the “worst case”. For Stage V generators, PM emissions drop by 99 % to 26 kg/a (Tab. 8).

Tab. 7: TREMOD [5] basic emission factors for mobile diesel engines of the power class 130–299 kW

Generators with power class 130–299 kW			
Emission level according to TREMOD	Diesel g/kWh TREMOD	NOX g/kWh TREMOD	PM g/kWh TREMOD
before 1981	270	17,8	0,9
1981–1990	260	12,4	0,8
1991–stage I	250	11,2	0,4
Stage I	250	7,6	0,2
Stage II	250	5,2	0,1
Stage IIIa	250	3,2	0,1
Stage IIIb	250	2,63	0,025
Stage IV	250	2,25	0,025
Stage V	250	0,4	0,015

6. Estimation of emissions from moored vessels based on emissions from average “fleet generators”

The inventory of generators in the active inland fleet has a wide range for years of construction and emission behavior. In practice, it is too costly to individually determine the data of the generators for each moored vessel.

From the analysis of the ZBDD database on power, age and the percentage distribution to the individual emission levels of the generators on board, emission factors were deter-

Tab. 8: Basic table for NO_x emission quantities of cargo and tanker vessels at berth from diesel generators in the low-load range

Cargo vessels: „smallest“ generator with 28–36 kW; demand 2 kW						
Emission level according to TREMOD	NO_x g/kWh	1 Ship/h g	1 Ship/8h g	1 Ship/a kg	50 Ships/8h kg/a	50 Ships/a t/a
before1981	31,5	63	504	184	25,2	9,2
1981–1990	33,6	67,2	537,6	196,2	26,88	9,81
1991–EU Stage I	19,6	39,2	313,6	114,5	15,68	5,72
EU I	15,4	30,8	246,4	89,9	12,32	4,5
EU II	13	26	208	75,9	10,4	3,8
EU IIIa	12,2	24,4	195,2	71,2	9,76	3,56
EU IIIb	12,2	24,4	195,2	71,2	9,76	3,56
EU IV	no data					
EU V	8,5	17	136	49,6	6,8	2,48
Tanker vessels: 85–130 m, no shipside unloading, “smallest” Generators with 37–74 kW power; demand 9 kW						
Emission level according to TREMOD	NO_x g/kWh	1 Ship/h g	1 Ship/8h g	1 Ship/a kg	50 Ships/8h kg/a	50 Ships/a t/a
before 1981	11,4	102,6	820,8	299,6	41	14,98
1981–1990	13,4	120,6	964,8	352,2	48,2	17,61
1991–EU Stage I	19	171	1368	499,3	68,4	24,97
EU I	12,7	114,3	914,4	333,8	45,7	16,69
EU II	9,1	81,9	655,2	239,1	32,8	11,96
EU IIIa	6,3	56,7	453,6	165,6	22,7	8,28
EU IIIb	8,4	75,6	604,8	220,8	30,2	11,04
EU IV	no data					
EU V	3,5	31,5	252	92	12,6	4,6

Cargo vessels: „smallest" generator with 28–36 kW; demand 2 kW						
Emission level according to TREMOD	**PM g/kWh**	**1 Ship/h g**	**1 Ship/8h g**	**1 Ship/a kg**	**50 Ships/8h kg/a**	**50 Ships/a kg/a**
before 1981	3,5	7	56	20,4	2,8	1022
1981–1990	2,6	5,2	41,6	15,2	2,08	759,2
1991–Stage I	2,8	5,6	44,8	16,4	2,24	817,6
EU I	2,8	5,6	44,8	16,4	2,24	817,6
EU II	0,7	1,4	11,2	4,1	0,56	204,4
EU IIIa	0,7	1,4	11,2	4,1	0,56	204,4
EU IIIb	1,1	2,2	17,6	6,4	0,88	321,2
EU IV	no data					
EU V	0,03	0,06	0,48	0,2	0,02	7,3
Tanker vessels: 85–130 m, no shipside unloading, „smallest" generators with 37–74 kW power; demand 9 kW						
Emission level according to TREMOD	**PM g/kWh**	**1 Ship/h g**	**1 Ship/8h g**	**1 Ship/a kg**	**50 Ships/8h kg/a**	**50 Ships/a kg/a**
before 1981	2,7	24,3	194,4	70,96	9,72	3.548
1981–1990	1,9	17,1	136,8	49,93	6,84	2.497
1991–EU I	1,3	11,7	93,6	34,16	4,68	1.708
EU I	0,6	5,4	43,2	15,77	2,16	788
EU II	0,4	3,6	28,8	10,51	1,44	526
EU IIIa	0,4	3,6	28,8	10,51	1,44	526
EU IIIb	0,04	0,36	2,88	1,05	0,14	53
EU IV	no data					
EU V	0,02	0,18	1,44	0,53	0,07	26

Tab. 9: Basic table for PM emission quantities of freight and tanker vessels at berth from diesel generators in the low-load range

mined in each case for an average generator ("fleet generator") of the ship group under consideration. This then represents the average emission behavior of the generator stock under consideration (e.g., "smallest fleet generator" of cargo vessels). Based on the average emissions per kWh, the number of ships and the average berthing time, the expected emission quantity of the moored ships is estimated.

6.1 Emissions from moored cargo and tanker vessels without ship-side loading activity

The evaluation of the ZBBD data set for the "smallest" generators on board of the different ship classes with regard to the average power showed a homogeneous picture in each case for both tankers and cargo ships. A summary of the length classes of the ships is possible. The derivation of the emission factors of the "fleet generators" for tankers and cargo ships was summarized in Tab. 10 and 11.

Based on the "smallest fleet generators", a model calculation was also made for 50 moored ships per day. For 50 cargo ships of the current fleet, a daily emission quantity of 17.5 kg NO_x would be expected, resulting in an annual emission of 6.4 t/a (Tab. 10). For PM, this results in 1.7 kg per day and an annual amount of 627.6 kg, which consists almost exclusively of soot (Tab. 11). With 50 tankers at berth (without pumping), a daily NO_x quantity of 36.4 kg and an annual emission quantity of 13.3 t can be expected. For PM, this results in 2.7 kg/d and an annual quantity of 973 kg (Tab. 11).

The assumption of a "model port" with 50 cargo ships or tankers each exceeds the actual port activity in Duisburg,

Cargo vessels: „smallest" generator 28–36 kW, 2 kW/h							
NO_x	**Share of fleet**	**Basic data per stage**	**Generator per 2 kWh**	**Share of emissions to „Fleetgenerator"**	**1 ship**	**50 Ships**	
Emission level according to TREMOD	**%**	**g/kWh**	**g/ 2kWh**	**g/kWh**	**g/8h**	**kg/8h**	**t/a**
before 1981	**38,4**	31,5	63	12,1	193,5	9,7	3,5
1981–1990	**5,9**	33,6	67,2	2,0	31,7	1,6	0,6
1991–2002	**12,6**	19,6	39,2	2,5	39,5	2	0,7
∑ EU II + ZKR I	**18,1**	13	26	2,4	37,6	1,9	0,7
∑ EU IIIa + ZKR II	**24,6**	12,2	24,4	3,0	48,0	2,4	0,9
EG V since 2018	**0,2**	8,5	17	0,02	0,272	0,01	0,01
Basic data for calculation		**Emissions „Fleet generator"**		**g/kWh**	**g/8h**	**kg/8h**	**t/a**
				21,9	**350,7**	**17,5**	**6,4**
Tanker vessels: „smallest" generator 37–74 kW; (Ship classes IV, Va, Vb = 85–135 m), 9 kW/h							
NO_x	**Share of fleet**	**Basic data per stage**	**Generator per 9 kWh**	**Share of emissions to „Fleetgenerator"**	**1 ship**	**50 Ships**	
Emission level according to TREMOD	**%**	**g/kWh**	**g/ 9kWh**	**g/kWh**	**g/8h**	**kg/8h**	**t/a**
before 1981	**7,0**	11,4	102,6	0,8	57,5	2,9	1,0
1981–1990	**4,1**	13,4	120,6	0,5	39,6	2,0	0,7
1991–2002	**13,1**	19	171	2,5	179,2	9,0	3,3
∑ EU II + ZKR I	**53,3**	9,1	81,9	4,9	349,2	17,5	6,4
∑ EU IIIa + ZKR II	**22,5**	6,3	56,7	1,4	102,1	5,1	1,9
EG V since 2018	**–**	3,5	–	–	–	–	–
Basic data for calculation		**Emissions „Fleet generator"**		**g/kWh**	**g/8h**	**kg/8h**	**t/a**
				10,1	**727,5**	**36,4**	**13,3**

Tab. 10: Estimation of NO_x emissions from the power generators of cargo ships and tankers at berth without shipboard loading activity, taking into account the composition of the emission levels of the "smallest" generators

Cargo vessels: „smallest" generator 28–36 kW, 2 kW/h							
PM	**Share of fleet**	**Basic data per stage**	**Generator per 2 kWh**	**Share of emissions to „Fleetgenerator"**	**1 ship**	**50 Ships**	
Emission level according to TREMOD	**%**	**g/kWh**	**g/ 2kWh**	**g/kWh**	**g/8h**	**g/8h**	**kg/a**
before 1981	**38,4**	3,5	7	1,3	21,5	1075,2	392,5
1981–1990	**5,9**	2,6	5,2	0,2	2,5	122,7	44,8
1991–2002	**12,6**	2,8	5,6	0,4	5,6	282,2	103
∑ EU II + ZKR I	**18,1**	0,7	1,4	0,1	2,0	101,4	37
∑ EU IIIa + ZKR II	**24,6**	0,7	1,4	0,2	2,8	137,8	50,3
EG V since 2018	**0,2**	0,03	0,06	0,00	0,001	0,05	0,018
Basic data for calculation		**Emissions „Fleet generator"**		**g/kWh**	**g/8h**	**kg/8h**	**kg/a**
				2,1	**34,4**	**1,7**	**627,6**
Tanker vessels: „smallest" generator 37–74 kW; (Ship classes IV, Va, Vb = 85–135 m), 9 kW/h							
PM	**Share of fleet**	**Basic data per stage**	**Generator per 9kWh**	**Share of emissions to „Fleetgenerator"**	**1 ship**	**50 Ships**	
Emission level according to TREMOD	**%**	**g/kWh**	**g/ 9kWh**	**g/kWh**	**g/8h**	**g/8h**	**kg/a**
before 1981	**7,0**	2,7	24,3	0,2	13,6	680,4	248,3
1981–1990	**4,1**	1,9	17,1	0,1	5,6	280,4	102,4
1991–2002	**13,1**	1,3	11,7	0,2	12,3	613,1	223,8
∑ EU II + ZKR I	**53,3**	0,4	3,6	0,2	15,4	767,5	280,1
∑ EU IIIa + ZKR II	**22,5**	0,4	3,6	0,1	6,5	324,0	118,3
EG V since 2018	**–**	0,02	–	–	–	–	–
Basic data for calculation		**Emissions „Fleet generator"**		**g/kWh**	**g/8h**	**kg/8h**	**kg/a**
				0,7	**53,3**	**2,7**	**972,9**

Tab. 11: Estimation of PM (particulate matter) emissions from the power generators of moored vessels and tankers without shipside loading activity, taking into account the composition of the emission levels of the "smallest" generators

Central Europe's largest inland port. However, it clearly illustrates the order of magnitude of the currently expected emissions for NO_x in the single or low double-digit ton range and for PM in the triple-digit kg range. Thus, the power supply of the moored ships results in lower emission quantities than originally assumed.

For real port operations in Duisburg, the calculation carried out with this method resulted in an emission quantity of 3.88 t NO_x and 380 kg PM for the moored cargo ships in 2018.

6.2 Real calculation: Emissions from tankers with and without shipside loading activity using the example of the Port of Duisburg: Port Basin A in 2018

6.2.1 Transport routes and expected loading operations

Emissions from tankers at berth are more difficult to determine than for cargo ships. Therefore, it is important to know some basic information about tanker shipping.

The transport of petroleum products on the Rhine (gasoline, diesel, crude oil) takes mainly place from the coast to the inland. The ships are loaded in seaports and sail upstream to their destination ports. Sometimes the ships lighten in intermediate ports. In this case, a fully loaded large tanker vessel can use the deeper shipping channel of the Lower Rhine to Duisburg, where it is partially unloaded. After lightering, the ship has a lower draft and can thus easily reach the ports on the Upper Rhine.

For mineral oil products, there is usually no return cargo, so that the tankers return empty to the coastal ports. For petroleum products and crude oil, therefore, inland ports are mainly used for unloading operations, which are carried out on the ship's side via on board pumps.

In the case of industrial chemicals and petrochemical products, downstream transports are more frequent. This involves transportation between seaports and industrial sites as well as between industrial sites. In some cases, there is transshipment from rail tank cars to tankers or vice versa. Industrial chemicals and finished products also generally involve either unloading or loading operations. Depending on the liquid cargo, either unloading or loading operations predominate at the individual tank farms.

For a realistic estimate of the emissions emitted by moored tankers, it is therefore important to also take into account the relationships between unloading and loading operations in the respective ports. This relation can only be found out by direct questioning of the operators of the shore facilities.

6.2.2 Loading capacities of tanker types on the Rhine in NRW

Freight traffic with liquid products on the Lower Rhine is predominantly handled by tankers of the 85 m, 110 m and 135 m length classes. The technical data of the respective ship classes are compiled in Tab. 12.

6.2.3 Loading and unloading operations for tankers:

The time required for loading and unloading depends on the size of the vessel, the pumping and receiving capacities of the vessel and the shore facilities. Two different berthing situations arise for tankers:

Ship class	Length (m)	Width (m)	Draugth (m)	Number of tanks	Load capacity (m³)
IV	85	9,5	2,5	5	1.800
Va	110	11,4	3	8-0ct	3.300
Vb	135	11,4	3,5	14	4.050

Tab. 12: Technical data of tankers of the length classes IV, Va and Vb

6.2.3.1 Loading procedures and waiting times

Loading of tankers is usually done with the pumps of the shore plant. During the loading process, the ship only requires the power for ventilation, living quarters, engine room and wheelhouse. According to the Harms shipping company (personal communication), there is a power requirement of about 9 kW on modern tankers at berth, which is generated by the smallest generator on board. The higher power requirement compared to cargo ships results from the higher safety requirements for ventilation (e.g. engine room, living quarters, etc.) and possibly also from the use of electrically operated heating systems. Emissions are calculated in the same way as for cargo ships.

6.2.3.2 Unloading operations

Additional information requirements:
Unloading operations are carried out on the ship-side with the pumps on board, which have a much higher power demand. In order to estimate the emissions caused by these operations, additional information for unloading operations is required in addition to chapter 2:

1) Power demand of the pumps on board (kW).
2) Capacity of the (submersible) pumps on board (m³/h).
3) Intake capacity of the shore plant (m³/h).
4) Determination of the required discharge times (from the data of 2 and 3).
5) Composition of the emission levels of the “largest” generator pool on the ships to determine the average emission behavior.
6) Medium power class of the “largest” generators per ship class.
7) Diesel consumption (g/kWh) of these generators in normal load range.
8) Determination of the average emission factors for the power classes of the “largest” generators, differentiated by the different age classes and the respective applicable emission restrictions.
9) For further evaluations: Georeferencing of the moorings to characterize the emission sources as point sources.

Technical equipment and sequence of unloading operations
On modern tankers, each tank is equipped with a submersible pump. About 75 % of the tankers in the Rhine area are equipped with pumps with delivery rates of up to 90 m³/h (Shipping company Deymann, personal communication). The time required for unloading depends both on the ship-side parameters such as cargo volume and pumping capacity available on board and on the shore-side intake capacity (m³/h) of the system. The facilities on the “Oil Island” in the port of Duisburg, for example, each have an intake capacity of 400 m³/h.

When unloading a tanker, a maximum of 4–5 tanks can be emptied at the same time using the on board pumps. The unloading process is initially “slow-started”, i.e. starting with about half the required flow and slowly increasing to full power. These pumps have an estimated power requirement of 20–30 kW each. If the pumps of 4–5 tanks are used in case of an intake capacity of the shore unit of 400 m³/h, the power requirement is about 100 kW. (Communications from the shipping companies Harms, Jägers and Deymann).

With an intake capacity of the shore facility of 400 m³/h, the active “pumping times” for the unloading processes compiled in Tab. 13 result for the respective ship sizes. In addition to the pure “pumping times”, 1–2 hours are required for connecting the ship to the shore facility, for disconnecting the connections after unloading and for clearing the ship in and out at the facility.

Tab. 13: Average loading times of tankers in the length classes IV, Va and Vb

Average unloading or loading times for tankers				
Capacity of the shore facility 400 m³/h				
Ship class	Length	Capacity	Loading times	Clearing in/out
IV	85 m	1800 m³	about 5–6 h	1h
Va	110 m	3300 m³	about 8–9 h	1h
Vb	135 m	4050 m³	about 10–12 h	1h

Length class of the ships						
Class	I	II	III	IV	Va	Vb
Length	< 40 m	40–56 m	56–68 m	68–86 m	86–110 m	> 110 m
Number	27	8		113	127	5
Mean „smallest“ generator (kW)	49	35		54	66	50
Mean „largest“ generator (kW)	66	74		159	174	242

Tab. 14: Power structures (average power) of the “smallest” and largest generators on tankers. Overview of the analyzed data on tanker vessels (German ZBBD database, 2019)

6.3 Capacity of the “largest” generators on tankers

For a total of 280 tankers, data on the power of the ship generators (kW) are available and in some cases also on their year of construction and on the emission level (Tab. 3).

6.4 Emission behaviour of the “largest” generators on tankers

Emissions from tankers without unloading activity are calculated using TREMOD [5] baseline factors for the 27–74 kW power class, adjusted for low load (Tab. 6).

Table 15 summarizes the baseline emissions (TREMOD) for estimating NO_x and PM emissions from the “largest” fleet generators (130–299 kW power class) of tankers of the length classes IV, Va and Vb. Analogously to the procedure for the “smallest” generators, the emission values were also determined for the average “largest fleet generator” on tankers per hour of unloading activity with a power requirement of 110 kW (Tab. 15).

6.5 Calculation of emissions from real tanker traffic on the "Oil Island" in the Port of Duisburg for the year 2018

Mineral oil products and industrial chemicals are handled on the so-called "Oil Island" in the Port of Duisburg (Fig. 3). The seven facilities for handling tankers are all located in port basin A. The facilities have a reception capacity of 400 m³/h each. The tankers are unloaded with the ship's own pumps. Loading is done with pumps from the shore facility.

In 2018, a total of 1,864 tankers visited the Oil Island tank farm. About 40 % of the vessels belonged to size class IV (85 m) and 60 % to size class Va (110 m). Smaller tankers cannot be handled at the facility. Class Vb (135 m) vessels call at the facilities only 1–2 times per month. Therefore, additional five unloading and twelve loading operations were included in the estimate. In 715 cases the ships were unloaded, in 1149 cases the ships were loaded (Tab. 16).

The calculation of loading emissions is analogous to the procedure for cargo vessels using the number of berthing vessels, the average berthing time, a power requirement of 9 kW, and the emission factors for the assumed average "smallest fleet generator" (TREMOD [5] baseline emissions, low load, power 37–74 kW) of the tankers (Tab. 10 & 11).

Emissions from tankers with shipboard unloading activities are calculated using the number of loading operations per ship class, a power requirement of 110 kW, the number of average unloading times per ship class, and emission factors for the average "largest fleet generator" (130–299 kW) (Tab. 15).

Since the unloading requires an additional berthing time of about 1 h for clearing in and out, an additional "emission surcharge" of 1 h was considered for each unloading process and runtime "smallest generator". For the loading operations, this time has already been considered in the time at berth. The calculation results were compiled in Table 17. In total, the 1,864 tankers, that were handled at the "Oil Island" in port basin A in 2018, emitted an emission quantity of 4.06 t NO_x and 145 kg PM.

Tanker vessels: „largest" generator 130–299 kW; (Ship classes IV, Va, Vb = 85–135 m), 110 kW/h				
NO_x	Share of fleet	Basic data per stage	Share of emissions to „Fleetgenerator"	
Emission level according to TREMOD	%	g/kWh	g/kWh	g/110 kWh
before 1981	**6,6**	17,8	1,2	129,2
1981–1990	**3,7**	12,4	0,5	50,5
1991–2002	**10,7**	11,2	1,2	131,8
∑ EU II + ZKR I	**42,4**	5,2	2,2	242,5
∑ EU IIIa + ZKR II	**36,6**	3,2	1,2	128,8
EG V ab 2018	–	–	–	–
Basic data for calculation		Emissions „Fleet generator"	g/kWh	g/110kWh
			6,2	682,9

Tanker vessels: „largest" generator 130–299 kW; (Ship classes IV, Va, Vb = 85–135 m), 110 kW/h				
PM	Share of fleet	Basic data per stage	Share of emissions to „Fleetgenerator"	
Emission level according to TREMOD	%	g/kWh	g/kWh	g/110 kWh
before 1981	**6,6**	0,90	0,06	6,5
1981–1990	**3,7**	0,80	0,03	3,3
1991–2002	**10,7**	0,40	0,04	4,7
∑ EU II + ZKR I	**42,4**	0,10	0,04	4,7
∑ EU IIIa + ZKR II	**36,6**	0,10	0,04	4,0
EG V ab 2018	–	–	–	–
Basic data for calculation		Emissions „Fleet generator"	g/kWh	g/110kWh
			0,21	23,2

Tab. 15: Estimation of NO_X and PM (particulate matter) emissions from the power generators of moored tankers with shipboard loading activity, taking into account the composition of the emission levels of the "largest" generators

„Oil Island"	Loading activities		Ship class		
2018	Number	% share	IV	Va	Vb
		%	85 m (40 %)	110 m (60 %)	135 m
Unloadings	715	38,4	286	424	5
Loadings	1149	61,6	460	678	12
Total	1864				

Tab. 16: Unloading and loading operations in 2018 at the "Oil Island" in the Port of Duisburg

Fig. 3: Four tanker vessels at the "Oil Island" in the port of Duisburg

Unloading operations with ship facilities Total: 715	Ship class	IV	Va	Vb
		85 m	110 m	135 m
	Unloading time	6 h	9 h	12 h
Emissions per unloading	NO_x (kg)	4,10	6,15	8,20
	PM (g)	139,2	208,8	278,4
Unloading operations	Quantity	286	429	5
Emissions 2018	NO_x (kg)	1.172,0	2.637,1	41,0
	PM (kg)	39,8	89,6	1,4
Surcharge clearing (in/out)	NO_x(kg)		14,5	
1h „smallest“ generator	PM (kg)		1,0	
Unloading	Ship's emissions Duisburg 2018			
	Tanker unloading operations in port basin A			
		NO_x (t)	3,86	
		PM (kg)	131,8	
Loading activities with shore facilities Total: 1.149	Ship class	IV	Va	Vb
		85 m	110 m	135 m
	Loading time	7 h	10 h	13 h
Emissions per loading	NO_x (g)	141,4	181,8	242,4
	PM (g)	9,8	12,6	16,8
Loading operations	Quantity	460	678	12
Emissions 2018	NO_x (kg)	65,04	125,26	2,91
	PM (kg)	4,5	8,7	0,2
Surcharge for clearing (in and out)	Already included in loading times			
Loading	Ship's emissions Duisburg 2018			
	Tanker loading operations in port basin A			
		NO_x (t)	0,19	
		PM (kg)	13,4	
2018	Ship's emissions Duisburg 2018			
	Tanker vessels at berth in the port basin A "Oil Island"			
		NO_x (t)	4,06	
		PM (kg)	145,2	

Tab. 17: Estimation of the NO_x and PM emissions generated by the tanker vessels, loading or unloading at the tank farm on "Oil Island" in port basin A in Duisburg for the year 2018

Shore power facilities at Nijmegen	Number of ships in 2019/2020	Average moored time
Name of facility	n	h
Grote Straat	233	14
Labyrinth	90	15
Oude Haven	195	12
Vikingsteiger*	1	16
Other facility	11	154
Total	530	16

Tab. 18: Frequency of use and average duration of use of various shore power installations at Nijmegen *The Vikingsteiger was out of order in 2019/20

7. Estimation of emissions from passenger ships (river cruises)

During a river cruise, there are berths at inner-city areas where ships moor for extended periods (sightseeing, night rest). These berths often lead to complaints from residents about noise and air pollution. Therefore, the pollutant and noise emissions associated with these berths are particularly relevant to clean air planning in cities such as Cologne and Düsseldorf, which are located on major waterways.

7.1 Power demand of river cruise ships

As a rule, river cruise ships arrive at their daily destination in the early afternoon and continue their journey the next morning. The mooring times are about 14–19 hours. The ships' power requirements generally increase in proportion to the number of passengers on board. Surveys of German shipping companies showed a wide range between 30 and 230 kW for the power requirements of moored river cruise ships. One shipping company provided more precise information on power requirements: average length of stay in Düsseldorf 8 h, average power requirement:

- 85 m ship: 130 kW;
- 110 m ship: 180 kW;
- 135 m ship: 230 kW.

The power requirement fluctuates over the course of the berthing time. It is highest when all passengers are active and restaurant operations are running at meal times. If an empty ship is waiting for new passengers at the end of the voyage, the power demand can be significantly lower. During the rest periods in winter, the power requirement can drop to 1–2 kW.

Real measured data on the actual power demand of cruise ships can be obtained from the power consumption at existing onshore power supply (OPS) facilities. As part of CLINSH, data from 530 ships at four berths equipped with OPS on the Waal Quay in Nijmegen (Netherlands) were analyzed (Tab. 18).

In 332 cases (61 %), information on ship lengths was available in addition to the power consumption, so that the power demand can be classified by ship length. For each length class, average values for the expected power demand (with passengers) could be derived. From the 332 consumption datasets, the following orders of magnitude can be derived for estimating the average power demand of a river cruise ship with passengers (Tab. 19).

Power consumptions below 30 kW were not included in the evaluation, as these ships were presumably docked there without passengers, e.g. at the beginning or end of the voyage (example: 110 m ship, arrival 04.05.2019, 7:27 a.m., departure 12:30 p.m., average power consumption 22.4 kW).

Shore power Nijmegen	Size class		
	85 m	110 m	135 m
Quantity	28	131	154
Mean (kW)	70,3	95,7	113,7
Min (kW)	31,3	30,4	30
Max (kW)	126,8	179,5	203,5

Tab. 19: Power demand (kW) of river cruise vessels with passengers at berth. Evaluation of real power consumption data at shore power facilities in Nijmegen (2019–2020). Ships from 105 m were assigned to the 110 m class and ships from 130 m were assigned to the 135 m class

Four different load ranges emerge from the analysis of the data:

a) Power consumption below 30 kW — Ship is in idle mode without passengers and on board operation.

b) Power consumption 30–80 kW — Ships in the length class 85 m (IV), or the ship was at the beginning or end of the voyage temporarily without passengers.

c) Power consumption 80–105 kW — Ships in the length class 110 m (Va).

d) Power consumption > 115 kW — Ships in the length class 135 m (Vb).

The data compiled in Table 20 can serve as a basis for calculating the expected emission quantities at the berths without shore power facilities.

Ships length	Size class	Passengers	Crew	Persons on board	Power demand
85–104 m	IV	70–100	25–30	95–130	70 kW
105–129 m	Va	110–150	30–40	140–190	95 kW
< 130 m	Vb	140–190	45–50	195–250	115 kW

Tab. 20: Average number of passengers and crewmembers for the individual ship sizes and associated average power demand (kW) for berthing phases during a cruise.

7.2 Composition of the current generator pool on the cruise ships

Data from 34 river cruise ships of the length classes IV (85 m), Va (110 m) and Vb (135 m) were available for the analysis of the generator pool [4] (Chap. 3.5). Analogous to the approach taken for cargo ships and tankers, "average fleet generators" were also determined for the cabin ships. On average, the generators of the 110 m vessels were about 20 years old, with only 52 % of the generators already complying with specified emission regulations. Most of the 135 m ships in the cruise fleet were built after 2010, so all generators here already meet emission standards. The average age was 11 years. This also explains the lower emissions per berth hour compared to the 110 m ships (Tab. 21 & 23).

Emissions were estimated using emission factors according to TREMOD [5] (power class 130–299 kW; Tab. 7) and taking into account the actual composition of the generator pool. Based on these datasets, emission factors were determined for the average "mean fleet generators" per ship size class, which can be used to calculate the average NO_x and particulate matter emissions per berthing time (Tab. 22a & b).

The lowest average emission levels were achieved by the 135 m vessels equipped exclusively with EU Stage II (or CCNR I) and EU Stage IIIa (or CCNR II) generators. They were 429 g/h NO_x and 11.5 g/h PM. The generators of the 110 m class ships achieved significantly higher average emissions of 761 g/h NO_x and 30.4 g/h PM. In the 85 m class, the emission values for both pollutants were still somewhat lower.

Based on the average power demand expected for the ship size, the frequency of visits, and the emission quantity/kWh, the expected emissions at berth can be estimated.

Cabin vessels : Emission relays of the generators on board with a power > 130 kW

Emission level according to TREMOD	up to 85 m (IV)		up to 110 m (Va)		up to 135 m (Vb)	
	Quantity	%	Quantity	%	Quantity	%
Total	6		44		30	
before 1981	1	16,7	2	4,5	–	–
1981–1991	–	–	6	13,6	–	–
1991–2002	2	33,3	13	29,5	–	–
EU II + ZKR I			12	27,3	8	26,7
EU IIIa + ZKR II	3	50	11	25	22	73,3

Tab. 21: Composition of the generators on cruise vessels according to different emission levels (TREMOD) [5]

Cabin ship, 85 m, generator class 130–299 kW, power requirement 70 kW/h

NO_x	Share of fleet	Basic data per stage	Emissions of „Fleetgenerator"		
			Share of Emissions	1 ship 1h	1 ship 18 h
Emissionsstufe nach TREMOD2	%	g/kWh	g/kWh	g/h	g/18h
before 1981	**16,7**	17,8	2,97	208,1	3745,5
1981–1990	**–**	12,4		–	–
1991–2002	**33,3**	11,2	3,73	261,1	4699,3
∑ EU II + ZKR I	**–**	5,2		–	–
∑ EU IIIa + ZKR II	**50**	3,2	1,60	112,0	2016,0
EG V ab 2018	**–**	0,4		–	–
Basic data for calculation	Emissions „Fleet generator"		g/kWh	g/70 kWh	kg/18h
			8,30	581	10,5

Cabin ship, 110 m, generator class 130–299 kW, power requirement 95 kW/h

NO_x	Share of fleet	Basic data per stage	Emissions of „Fleetgenerator"		
			Share of Emissions	1 ship 1h	1 ship 18 h
Emission level according to TREMOD5	%	g/kWh	g/kWh	g/h	g/18h
before 1981	**4,5**	17,8	0,81	76,9	1383,5
1981–1990	**13,6**	12,4	1,69	160,6	2891,5
1991–2002	**29,5**	11,2	3,31	314,4	5658,5
∑ EU II + ZKR I	**27,3**	5,2	1,42	134,7	2425,1
∑ EU IIIa + ZKR II	**25,0**	3,2	0,80	76,0	1368,0
EG V ab 2018	**–**	0,4	–	–	–
Basic data for calculation	Emissions „Fleet generator"		g/kWh	g/95 kWh	kg/18h
			8,03	763	13,7

Cabin ship, 135 m, generator class 130–299 kW, 115 kW/h

NO_x	Share of fleet	Basic data per stage	Emissions of „Fleetgenerator"		
			Share of Emissions	1 ship 1h	1 ship 18 h
Emission level according to TREMOD5	%	g/kWh	g/kWh	g/h	g/18h
before 1981	**–**	17,8	–	–	–
1981–1990	**–**	12,4	–	–	–
1991–2002	**–**	11,2	–	–	–
∑ EU II + ZKR I	**26,7**	5,2	1,39	159,7	2874,0
∑ EU IIIa + ZKR II	**73,3**	3,2	2,35	269,7	4855,4
EG V ab 2018	**–**	0,4	–	–	–
Basic data for calculation	Emissions „Fleet generator"		g/kWh	g/110 kWh	kg/18h
			3,73	429	7,7

Tab. 22a: Estimation of average emissions of NO_x from moored cruise vessels with crew and passengers "Fleetgenerators"

Cabin ship, 85 m, generator class 130–299 kW, power requirement 70 kW/h					
PM	Share of fleet	Basic data per stage	Emissions of „Fleetgenerator"		
			Share of Emissions	1 ship 1h	1 ship 18 h
Emission level according to TREMOD	%	g/kWh	g/kWh	g/h	g/18h
before 1981	16,7	0,9	0,15	10,5	189,4
1981–1990	–	0,8		–	–
1991–2002	33,3	0,4	0,13	9,3	167,8
∑ EU II + ZKR I	–	0,1		–	–
∑ EU IIIa + ZKR II	50	0,1	0,05	3,5	63,0
EG V ab 2018	–	0,015		–	–
Basic data for calculation	Emissions „Fleet generator"		g/kWh	g/70 kWh	g/18h
			0,33	23,3	420
Cabin ship, 110 m, generator class 130–299 kW, power requirement 95 kW/h					
PM	Share of fleet	Basic data per stage	Emissions of „Fleetgenerator"		
			Share of Emissions	1 ship 1h	1 ship 18 h
Emission level according to TREMOD	%	g/kWh	g/kWh	g/h	g/18h
before 1981	4,5	0,9	0,04	3,9	70,0
1981–1990	13,6	0,8	0,11	10,4	186,5
1991–2002	29,5	0,4	0,12	11,2	202,1
∑ EU II + ZKR I	27,3	0,1	0,03	2,6	46,6
∑ EU IIIa + ZKR II	25,0	0,1	0,03	2,4	42,8
EG V ab 2018	–	0,015	–	–	–
Basic data for calculation	Emissions „Fleet generator"		g/kWh	g/95 kWh	g/18h
			0,32	30,4	548
Cabin ship, 135 m, generator class 130–299 kW, power requirement 115 kW/h					
PM	Share of fleet	Basic data per stage	Emissions of „Fleetgenerator"		
			Share of Emissions	1 ship 1h	1 ship 18 h
Emission level according to TREMOD	%	g/kWh	g/kWh	g/h	g/18h
before 1981	–	0,9	–	–	–
1981–1990	–	0,8	–	–	–
1991–2002	–	0,4	–	–	–
∑ EU II + ZKR I	26,7	0,1	0,03	3,1	55,3
∑ EU IIIa + ZKR II	73,3	0,1	0,07	8,4	151,7
EG V ab 2018	–	0,015	–	–	–
Basic data for calculation	Emissions „Fleet generator"		g/kWh	g/110 kWh	g/18h
			0,10	11,5	207

Tab. 22b: Estimation of average emissions of PM from moored cruise vessels with crew and passengers

7.3 Estimation of the emission quantities to be expected from river cruise ships at berths close to the city center

Based on the derived emission factors of the "fleet generators", an estimation of the emissions from berthing cabin vessels was made. The average emission amounts caused by a modern, 135 m cabin vessel during a berthing time of 18 h are about 7.7 kg NO_x and about 207 g PM. A 110 m cabin vessel emits approx. 13.7 kg for NO_x and 548 g PM during the same mooring time. For the 85 m length class, no reliable emission data can be derived based on generator composition due to the low number of vessels. The expected emissions for the 85 m class are probably somewhat lower than those of the 110 m ships (Tab. 23).

Frequently used berths near the city center may be visited by cruise ships up to 280 times per year. If only 110 m class ships are involved, NO_x emissions of about 3.8 t/a and PM emissions of about 153 kg/a would be expected. If used exclusively by 135 m class vessels, annual emissions would be in the order of 2.16 t NO_x and 58 kg PM. If the two length classes were equally distributed, annual emissions would be in the order of about 3.0 t/a NO_x and 100 kg/a PM.

The extent to which these ships' emissions contribute to air pollution in the neighboring settlements depends on the distance between the berth and the settlement, the prevailing wind directions and the morphology of the shore and settlement.

Pollutant emissions from moored cabin vessels per hour			
Size class of ship	85 m*	110 m	135 m
Emitted substance	g/h	g/h	g/h
NO_x	581	761	429
PM	23,3	30,4	11,5
Pollutant emissions from moored cabin vessels per 18 h mooring time			
Emitted substance	kg/18 h	kg/18 h	kg/18 h
NO_x	10,5	13,7	7,7
PM	0,419	0,547	0,207
Pollutant emissions from moored cabin vessels per year with 280 uses/a			
Emitted substance	kg/a	kg/a	kg/a
NO_x	2.929	3.835	2.164
PM	117	153	58

Tab. 23: Pollutant emissions from moored river cruise ships with passengers (*only Data of 4 ships)

7.4 More accurate estimates of the amounts of pollutants emitted by cruise ships based on real-world recording of power consumption at onshore power supply (OPS) facilities

Data from the OPS facilities in Nijmegen allow more precise estimates of expected emission quantities. The OPS plants located directly in front of the old town on the left bank of the Waal River are mainly visited by cruise ships. In 2019, the OPS facilities were visited by a total of 530 ships (Tab. 24). The three frequently used facilities were each visited by ships on average about 173 times. This resulted in a total of 8592.5 hours of berthing time in 2019, during which ships used a total of 467,499 kWh (Tab. 25).

7.4.1 Classification of vessels in the OPS facilities in Nijmegen

332 vessels could be assigned to the respective size classes by means of their length. 198 ships without length information were assigned to the respective size classes based on their power consumption (kW) (Tab. 24). This assignment remains uncertain due to the wide range of power consumption of the ships, but is necessary for the calculation of emissions.

Size class ship	2019	Power demand
	Quantity	kW
unknown	44	< 30
IV 85 m	112	30–80
Va 110 m	166	80–105
Vb 135 m	208	> 105

Tab. 24: Classification of visiting cruise vessels at the OPS facilities in Nijmegen

7.4.2 Estimation of the emissions saved by the onshore power supply (OPS) installations in Nijmegen

Also for cabin vessels, the individual determination of the generator equipment for each vessel is too time-consuming. Therefore, the emission factors of the "average fleet generators" are used here as well, which reflect the composition of the generators on the ships of the respective length classes.

If both the ship class and the power consumption are known for the individual berthing periods, it is possible to calculate for each individual data set according to the formula:

Power consumption (kWh) * ship class-related emission factor (g/kWh) (= "fleet generator")

The calculation is made for each individual ship by multiplying the kWh consumed by the emission factors for NO_X or PM belonging to the size class of the ship (see Tab. 7 & 8). The sum of the individual results of all ships gives the annual emission amount of the pollutants. Without onshore power facilities, river cruise ships would have emitted about 2.6 t NO_X and about 93 kg PM in Nijmegen in 2019 (Tab. 25).

Ships	Berthing time	Energy consumption	NO_X	PM
Quantity	h	kWh	t	kg
530	8.593	467.499	2,6	93

Tab. 25: Estimation of the emission quantities saved in 2019 by the four OPS systems in Nijmegen

For the 44 ships with a power consumption of less than 30 kW, whose type and length class remain "unknown", the calculation was carried out with the emission factors of the "average fleet generator" of class IV (85 m). These are either cruise ships without passengers, cargo ships or private yachts. Due to the small number of ships and the low power consumption, the share in the total emissions and the error rate remain insignificant with this method.

8. Emissions from ships at berth due to ship heating

Inland vessels are often heated with oil-fired heating systems. As a rule, normal burners are installed on inland vessels, such as those used to heat houses. On many modern tankers, space heating is provided by electric convectors or by air conditioning.

The heating systems on ships usually have a capacity in the range of 20–40 kW. An estimate of emissions from ship heating systems can therefore be derived analogously to the procedure for small and medium-sized combustion systems. The bases for such a derivation [6] are maintained nationwide by the State Institute for the Environment, Baden-Württemberg (Landesanstalt für Umwelt, Baden-Württemberg; LUBW) (Tab. 26).

Emitted pollutant	Unit	Heating oil EL
Calorific value	**MJ/kg**	**42,7**
NO_X ($NO+NO_2$ als NO_2)	***kg/TJ***	***42***
Particulate matter	**kg/TJ**	**0,89**
PM 10	kg/TJ	0,85
PM 2,5	kg/TJ	0,85

Tab. 26: Average emission factors for small and medium-sized KuMFA combustion plants (according to 1st BImSchV of 26.01.2010) without flue gas cleaning, as of 5 February 2018 for the report 2016 (LUBW, Landesanstalt für Umwelt, Baden-Württemberg) [6]

Calculation example for a heating system with nominal heat output 37 kW (on the LANUV laboratory vessel Max Prüss), EL fuel oil:

Based on these data, the following calculation for the emissions of the heating system on the LANUV laboratory ship "Max Prüss" (37 kW) can be carried out as an example:

a) Calculation of TJ/h (terajoules/h) = 37 000 J/s = 0,0001332 TJ/h.

b) Emissions per hour of full load:
NO_X: 42 (kg/TJ) * 0,0001332 = 5,6 g/h
PM_{10}: 0,9 (kg/TJ) * 0,0001332 = 0,12 g/h

It is assumed that these heating systems are operated at full load for 980 hours per year. This results in an annual average operating time of about 11,2 % of the annual hours, which corresponds to a running time of about 6.5 minutes/hour. This results in the average hourly emissions (order of magnitude) for the heating emissions of a plant (and thus of a ship at berth) on an annual average:

NO_X: 5,6 g/h * 0,11 = 0,62 g/h
PM_{10}: 0,12 g/h * 0,11 = 0,013 g/h

Based on these values, an estimate for emissions from ship heating can be made for a model port with 50 ships moored daily (average mooring time of 8 h). This results in NO_X emissions of about 90 kg and PM emissions of about 2 kg per year. Compared to the much higher emissions from diesel generators, these emission quantities can be neglected (Tab. 27). In case of modern tankers with electric heating, the power required and the resulting emissions are already included in the power requirement of 9 kW.

Emissions from ship heating systems				
	1 Ship		50 Ships	
	g/h	g/8h	g/8h	kg/a
NO_X	0,62	4,96	248	90,52
PM10	0,013	0,104	5,2	1,9

Tab. 27: Estimation of emissions from the heating systems of moored ships

Tab. 28: Emission volumes of ships at berth in the ports of Neuss and Duisburg in 2018

Study area Duisburg		
2018	NO_x (t)	PM (kg)
Cargo vessels	3,9	380
Tanker vessels	11,6	384
Total	15,5	764
Study area Neuss/Düsseldorf		
2018	NO_x (t)	PM (kg)
Cargo vessels	4,1	390
Tanker vessels	5,4	198
Total	9,5	588

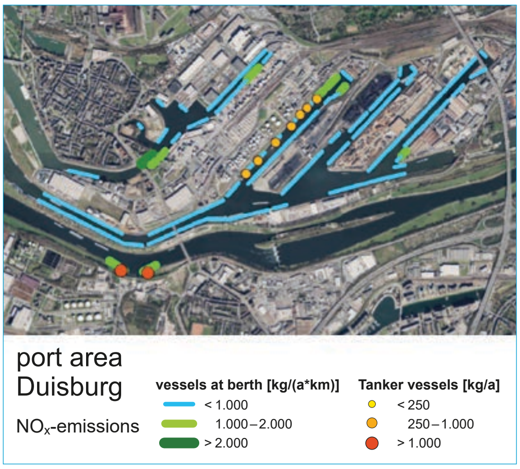

Fig 4: Geo-referenced representation of the NO_x emissions of the moored ships in some port basins in Duisburg in 2018

9. Outlook

With the presented method, a more realistic estimation of the NO_x and PM quantities emitted by moored ships has become possible. The described methods were used within the framework of CLINSH to estimate more realistic emission quantities from ships at berth in the inland ports of Duisburg and Neuss/Düsseldorf. This was based on real ship numbers and berthing times derived from AIS data and/or information provided by port operators on real ship traffic in the reference year under consideration.

In 2018, a total of 15.5 t NO_x and 764 kg PM were emitted by ships at berth in the Duisburg study area. For the study area Neuss, the calculations resulted in an amount of 9.46 t NO_x and 588 kg PM (Tab. 28). An example of a geo-referenced representation of the NO_x emissions of the moored ships is shown in Fig. 4 for some port basins in Duisburg. The results show that the dimensions of emissions from moored inland cargo vessels, tanker vessels and cruise ships are significantly lower than previously assumed.

Within the framework of CLINSH, extensive studies were carried out on air pollution in the ports of Duisburg and Neuss. The results have already been documented in a CLINSH report and are partly published [7; 8]. Further results will be published as part of CLINSH:

CLINSH delivery of the LANUV to Action B.4 Modelling, evaluating and scenario building:

"Harbour monitoring Part C: Emission inventories for the ports of Duisburg and Neuss/Düsseldorf"

"Harbour monitoring Part E: Onshore measurements: Identification of passing inland vessels based on AIS signals and determination of the associated emission factors for NO_x based on onshore measurements"

"Harbour monitoring Part F: Causal analyses on the respective shares of different emission sources in the air pollution measured in Neuss/Düsseldorf and Duisburg".

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Literature and Sources

[1] Walstroom versus Generatorstroom, Een studie naar de kosten, P. de Vos & R. van Gils, TU Delft, 2011, unpublished
[2] Eigene Erhebungen aus Befragungen von Binnenschiffern und Reedereien
[3] Bureau Voorlichting Binnenvaart (BVB); /www.bureauvoorlichtingbinnenvaart.nl, Types of vessels, Internet 15.03.2021
[4] German ZBBD database (German Ship Inspection Commission) on the engines and generators on the ships inspected by the Commission. (Database extract requested for CLINSH 2020)
[5] TREMOD (Transport Emission Model of the German Federal Environment Agency, UBA), UBA-Texte 117: Aktualisierung der Modelle TREMOD/TREMOD-MM für die Emissionsberichterstattung 2020, (Berichtsperiode 1990–2018), Berichtsteil "TREMOD-MM", C. Heidt, H. Helms, C. Kämper, J. Kräck, Institut für Energie und Umweltforschung (ifeu), Heidelberg, 2020, Auftrag des Umweltbundesamtes, Projektnummer 123 135
[6] C. Tebert; S. Volz; K. Töfge (2016): Ermittlung und Aktualisierung von Emissionsfaktoren für das nationale Emissionsinventar bezüglich kleiner und mittlerer Feuerungsanlagen der Haushalte und Kleinverbraucher. Az 50 121-2/22, Ufoplan 3712 42 313-2, im Auftrag des Umweltbundesamtes, Hamburg, Februar 2016
[7] D. Busch; A. Bergen, K. Krause, W. Wosniok (2021): Harbour Monitoring Part A: Air quality on the Rhine and in the inland ports of Duisburg and Neuss/Düsseldorf. Immission-side effect of emissions from shipping and port operations on nitrogen oxide pollution. CLINSH delivery of the LANUV to Action B.4 Modelling, evaluating and scenario building https://www.lanuv.nrw.de/umwelt/luft/eu-life-projekt-clean-inland-shipping
[8] D. Busch, K. Krause (2021): Air quality on the Rhine and in the inland ports of Duisburg and Neuss – Immission-side effect of emissions from shipping and port operations on nitrogen oxide pollution – Results from the EU Life Project "Clean Inland Shipping" CLINSH), Immissionsschutz 2/2021, pp. 78–85

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