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SUSTAINABLE WATERWAY TRANSPORT, CLEAN AIR

Action B.4: Modelling, evaluating and scenario building

Harbour monitoring, Part B: Determination of NO_X and particulate matter emissions from inland vessels at berth

CLEAN INLAND SHIPPING

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Action B.4: Modelling, evaluating and scenario building

Harbour monitoring Part B:

Determination of NO_X and particulate matter emissions from inland vessels at berth

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1. Introduction

Up to now, emissions from loading and berthing operations in ports in NRW have been determined by means of estimates based on the volume of goods handled. Currently there was no reliable, differentiated data basis for the direct estimation of emissions caused by inland cargo, tanker and cruise ships at berth.

Within the framework of CLINSH, the LANUV has developed a methodology to arrive at a more realistic estimate of the emissions from ships moored in the port due to power generation and heating. The emission sources "electricity generation by on-board generators" and "heating by means of commercial oil burners" are examined.

2. Data required to determine emissions from power generation

2.1 Cargo and tanker vessels at berth without own loading activities

A moored ship requires electricity for the on-board electrical system, e.g. for lighting, kitchen (cooker, refrigerator, etc.), living area and office (television, radio, computer, etc.). The energy demand of a normal **cargo ship** corresponds approximately to the demand of a household with three to four persons. It can thus be assumed, that an inland vessel requires an average power of 1-2 kW during berthing times, if the energy supply for the loading and unloading processes is provided on shore. This amount of energy is derived from our own surveys of inland navigation operators and from the study “Walstroom versus Generatorstroom” by TU Delft (2012) (1).

For modern double-hull **tanker vessels** (length classes 85-130 m), the survey of shipping companies revealed a higher power demand of about 8-9 kW, even if the ship is not using its own pumps at the unloading point.

The electricity supply of moored vessels is usually provided by one of the diesel generators on board. On inland vessels, several diesel generators are often available. It can be assumed, that the smallest generator on board is used for this electricity demand, which is then operated in the low-load range.

An important basis for the emission calculations is therefore the knowledge of the generator equipment available in the inland navigation fleet and its emission behavior. The estimation of the quantity of emissions caused by cargo vessels and tankers at berth, can be carried out by including the following data:

1) Vessels at berth, classification by length size class of vessels (AIS data).

2) Differentiation into tankers and cargo ships (AIS data).

3) a) Determination of the average power of the "smallest" generators per ship class. b) If applicable, summary of the generator characteristics of ship classes.

4) Distribution of emission levels in the generator pool of the individual ship classes.

5) Emission factors for the different emission levels.

6) Diesel consumption (g/kWh) of generators in the low load range.

7) Assumption of a power consumption of approx. 2 kW (conservative estimate).

8) Determination of berthing times (AIS data).

9) Determination of the berthing locations to determine the characteristics of the emission sources (AIS-Data).

2.2 Tankers using their onboard pumps for unloading

In the case of tankers, it can be assumed that additional energy is required when unloading the ships, because the unloading is usually carried out by the pumps on board, which are powered by the largest generator on board.

In addition to the data listed under chap. 2.1, further information is required for tankers:

10) Storage capacity per hour of the shore facility.

11) Capacity of the (submersible) pumps on board.

12) Determination of the required unloading times.

13) Energy requirement of the onboard pumps to be used for the respective intake capacity of the shore facility, which is usually generated by the largest generator on board.

14) a) Determination of the average power of the "largest" generators per ship class. b) Summary

of the generator characteristics of ship classes, if applicable.

15) Distribution of emission levels in the respective generator pool of each ship class.

16) Emission factors for the different emission levels.

3. Data on the stock of generators on cargo and tanker vessels

For the determination of emissions, no detailed data on the generator equipment of the Central European inland fleet was available. For this reason, LANUV examined the existing databases as part of CLINSH. An analysis of the IVR database maintained by the "Bundesverband der Deutschen Binnenschifffahrt e.V. (BDB)" (extract requested for CLINSH 2017)[(2)] showed that some of the data on the main engines was not up-to-date and that the data on the generator fleet was neither up-to-date nor complete and therefore not suitable for the research question.

Similar to vehicles in road and rail transport, inland vessels are inspected at regular intervals for safety and functionality. Ship owners are free to choose in which EU Member State they have their vessels inspected. In the course of the administrative assistance, LANUV NRW requested the data available at the German ZBBD database (German Ship Inspection Commission) [(3)] on the engines and generators on the ships inspected by the German Commission. The data used is mainly from German ships, but also included are about 100 Dutch and Belgian ships. In total, data sets from 280 tanker vessels, 609 cargo vessels and 34 river cruise vessels were available, which at least contained in minimum information on the power of one of the generators on board.

Unfortunately, despite repeated requests, the data from the Dutch and Belgian Inspection Commissions could not be provided by either the Province of Zuid Holland or Belgian port authorities in the course of administrative assistance to CLINSH. The inclusion of additional Dutch and Belgian data would have led to an even more reliable result. Nevertheless, due to the relatively high number of ships, the evaluation of the generator fleet, using the German ZBBD database, provides a representative picture that can be used for the emission estimates. The tables 1a and 1b show the analyzed data of the ships and the generators, separated into freight and tanker ships.

3.1 Power capacity and age of the "smallest" generators

For a total of 889 tanker and cargo vessels, power data (kW) is available on the ship generators and partly also on their year of construction and emission level. The ships were classified according to the ship length classes of the CEMT (European Conference of Ministers of Transport, ***C**onférence **E**uropéenne des **M**inistres des **T**ransports)*[(4)] *(Fig. 1).*

Size Class	Type of ship
I	 **Spitz, Peniche** **Length** 38,5 m - **width** 5,05 m, **draught** 2,2 m - **cargo capacity** 350 t
II	 **Campine vessel** **Length** 55 m - **width** 6,6 m, **draught** 2,50 - **cargo capacity** 655 t
III	 **Dortmund-Ems-canal vessel** **Length** 67 m - **width** 8,2 m, **draught** 2,50 - **cargo capacity** 1000 t
IV	 **Rhein-Herne-canal vessel** **Length** 85 m - **width** 9,5 m, **draught** 2,50 - **cargo capacity** 1350 t
Va	 **Large Rhine vessel** **Length** 110 m - **width** 11,4 m, **draught** 3,0 m - **cargo capacity** 2750 t
Vb	 **Large Rhine vessel** **Length** 135 m - **width** 11,4 m, **draught** 3,5 m - **cargo capacity** 4000 t

Fig. 1: Size classes of cargo and tanker vessels in this report, analo-gous to the CEMT-classification [(4)]

Ship Graphics: Buerau Voorlichting Binnenvaart

a) Cargo vessels: When evaluating the power of the smallest genera-tors on board in each case, a fairly homogeneous picture emerges for the class I-Va (up to 110 m length) of cargo vessels. The average output is in the range of 23 - 33 kW. The smallest generators on the ships with lengths over 110 m have an average output of about 55 kW. Since there are only 10 ships in the large class (111-135 m), the power determination for this class remains a bit more uncertain.

In the case of the cargo motor ships, two power classes can be defined for the smallest generators at a time. For ships up to 110 m in length, these generators are in a power range around 20-30 kW, for larger ships (111-135 m) around 55 kW.

In the case of the cargo vessels, information on the year of construction of the smallest generator is available in 370 cases. In 188 (31%) cases, the emission stage is also indicated. The average age (Tab. 1a) of these generators, depending on the ship class, 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 the year of construction of the generators is unknown for 239 ships (39%). These presumably fall predominantly into the two worst TREMOD[(5)]-(Transport Emission Model of the German Federal Environment Agency, UBA) emission levels (built before 1991).

Cargo vessels	Size Class of ships					
	< 40 m	41-67 m	58-67 m	68-86 m	86-110 m	> 110 m
Ships						
Number	14	29	69	361	185	12
Year of construction	1876-2002	1884-2017	1902-1965	1889-1996	1897-2017	1970-2007
Mean year of construction	1943	1948	1945	1950	1974	1989
Mean age (years)	77	72	75	70	46	31
Main engine						
Power range (kW)	65-353	121-780	147-616	276-1491	456-2700	993-2030
Average power (kW)	230	302	383	616	1066	1281
Year of construction	1957-2014	1937-2018	1950-2017	1949-2019	1959-2019	1972-2006
Mean year of construction	1985	1979	1969	1980	1997	1996
Mean age (years)	35	41	51	40	23	24
With Emission stage	1	5	3	79	89	3
Generators						
Indication of power (kW)	6	19	59	336	178	11
Generators on board						
1	3	15	24	61	13	4
2	2	4	28	174	83	5
3	1	--	6	83	64	2
4	--	--	--	11	17	--
5	--	--	--	2	1	--
"Smallest" Generator						
With year of construction	2	17	29	192	122	8
Year of contruction	2006,2015	1960-2018	1953-2017	1955-2018	1968-2019	2001-2014
Mean year of construction	2011	2004	1998	2006	2005	2007
Mean age (years)	9	16	22	14	15	13
Power range (kW)	7-77	5-121	5-310	3-137	5-83	30-83
Average power (kW)	24	25	23	23	33	55
With emission stage	2	6	6	96	72	6
"Largest" Generator						
With year of construction	3	14	30	208	135	8
Year of contruction	1996-2015	1960-2016	1953-2018	1961-2018	1981-2019	2001-2011
Mean year of construction	2006	2008	2000	2005	2007	2006
Mean age (years)	14	12	20	15	13	14
Power range (kW)	7-77	5-121	6-310	6-699	23-357	53-83
Average power (kW)	28	25	29	37	56	61
With emission stage	2	5	8	122	102	6

Tab. 1a: Overview of the analyzed data on cargo vessels (German ZBBD database, 2019)[3]

Tanker vessels	Size Class of ships				
	< 40 m	41-67 m	68-86 m	86-110 m	**> 110 m**
Ships					
Number	37	9	118	135	5
Year of construction	1886-2017	1937-2016	1954-2016	1956-2015	1990-2009
Mean year of construction	1955	1969	1993	1996	2003
Mean age (years)	65	51	27	24	17
Main engine					
Power range (kW)	71-447	221-632	315-1492	588-2236	1491-2290
Average power (kW)	224	389	778	1164	1681
Year of construction	1955-2018	1958-2016	1957-2018	1961-2016	2001-2008
Mean year of construction	1992	1985	2000	2001	2005
Mean age (years)	28	35	20	19	15
With Emission stage	11	3	76	82	4
Generators					
Indication of power (kW)	27	8	113	127	5
Generators on board					
1	18	4	16	1	1
2	8	4	45	41	--
3	--	--	45	53	4
4	--	--	5	20	--
5	--	--	1	3	--
"Smallest" Generator					
With year of construction	19	4	94	115	4
Year of contruction	1985-2016	1999-2016	1971-2018	1981-2018	2001-2008
Mean year of construction	2001	2009	2008	2007	2005
Mean age (years)	19	11	12	13	15
Power range (kW)	9-270	12-109	8-155	13-153	36-61
Average power (kW)	49	35	54	66	50
With emission stage	6	2	76	91	2
"Largest" Generator					
With year of construction	21	5	94	126	5
Year of contruction	1960-2017	1997-2016	1971-2018	1956-2018	2001-2008
Mean year of construction	2001	2007	2007	2004	2005
Mean age (years)	19	13	13	16	15
Power range (kW)	9-270	12-357	20-465	13-511	56-447
Average power (kW)	66	74	159	174	242
With emmission stage	9	3	77	99	4

Tab. 1b: Overview of the analyzed data on tanker vessels (German ZBBD database, 2019) [3]

b) Tanker vessels: When estimating emissions from tankers at berth, a distinction must be made between berthing conditions without the use of on-board pumps (usually loading operations) and with the use of on-board pumps (usually unloading operations or waiting times).

Loading procedures: At approx. 9 kW, the power requirement is somewhat higher than for a cargo ship at berth and is required, for example, for the operation of ventilation systems (e.g. explosion protection). It is also generated via the smallest generator. The smallest generators installed on tankers generally have a higher average output in all ship classes. The length classes I (< 40 m), IV (68-87 m), Va (86-110 m) and Vb (> 110 m) show a homogeneous picture. Here, the smallest generators on board are in an average power range of about 50-65 kW.

The middle classes II and III (ship lengths 40-56 m; 56-68 m) are only very weakly represented with a total of 8 ships. Here, the generator output is only in the range of 35 kW. In this case, the determination of power remains rather uncertain.

In 236 cases of tanker vessels, information is available on the year of construction of the "smallest" generator. In 177 (63%) cases, the emission stage is also indicated. Depending on the ship class, the average age of the generators is between 13 and 19 years. The highest average age of the generators is 19 years for tankers in the ship length class I (< 40 m). For the larger ships in the classes IV, Va and Vb, the mean age is between 12 and 15 years.

The actual average age of generators for the ship classes I-IV is probably a little bit higher, as the year of construction of the generators is unknown for 44 ships (16%). These presumably fall predominantly into the two worst TREMOD[5] emission levels (built before 1991).

Unloading procedures: Unloading procedures usually require the "largest" generators on board to provide the electric energy needed for the pumps. (See chapter 6.2)

The "largest" generators used in tanker unloading procedures for the ship classes I, II and III are on average 66-74 kW. Ship classes IV and Va have a significantly higher mean generator output of 159 and 174 kW, while ships of the class Vb (135 m) even have a mean output of 242 kW for the "largest" generators.

For tanker vessels, information on the year of construction of the "largest" generator is available in 251 cases. In 192 (69%) cases, the emission stage is also indicated. Depending on the ship class, the average age of the generators is between 11 and 19 years. The “largest” generators of tankers reach the highest average age of 19 years in the ship class I (< 40 m). For the larger ships in the classes IV, Va and Vb (85-135 m), the mean age is between 13 and 16 years. Here too, the actual average age of the generators for ship the classes I-IV is probably a bit higher, as the year of construction of the generators is unknown for 35 (13%) ships.

3.2 Emission levels of the "smallest" and "largest" generators

3.2.1 Evaluation of the database entries on emission levels

An overview of the data stock on the "smallest" ship generators is compiled in Tab. 2. For the generators with a power rating, information on the respective emission stage (EU II, EU IIIa, EU V or CCNR I, CCNR II) is also available in 189 (31%) cases for the cargo vessels and in 177 (63%) cases for the tanker ships (Tab. 2).

Cargo vessel														
	Total		Length classes of the vessels											
			< 40 m		40-56 m		56-68 m		68-86 m		86-110 m		>110 m	
	Quantity	%	Quantity	%	Quantity	%	Quantity	%	Quantity	%	Quantity	%	Quantity	%
Total	670		14		29		69		361		185		12	
Smallest Generator														
Power indication (kW)	609		6		19		59		336		178		11	
year of manufacture	370	*61*	2		17		29		192		122		8	
Emission level specification														
without specification	420	*69*	4	*67*	13	*68*	53	*90*	240	*71*	105	*59*	5	*45*
with specification	189	*31*	--	--	--	--	--	--	--	--	--	--	--	--
ZKR I	6	*1*	1	*17*	--	--	--	--	--	--	4	*2*	1	*9*
ZKR II	4	*1*	--	--	--	--	--	--	--	--	4	*2*	--	--
EG II	73	*12*	--	--	2	*11*	3	*5*	37	*11*	28	*16*	3	*27*
EG III a	105	*17*	1	*17*	4	*21*	3	*5*	59	*18*	36	*20*	2	*18*
EG V	1	*0*	--	--	--	--	--	--	--	--	1	*1*	--	--

Tanker vessel												
	Total		Length classes of the vessels									
			< 40 m		40-68 m		68-86 m		86-110 m		>110 m	
	Quantity	%	Quantity	%	Quantity	%	Quantity	%	Quantity	%	Quantity	%
Total	304		36		10		118		135		5	
Smallest Generator												
Power indication (kW)	280		27		8		113		127		5	
year of manufacture	236		19		4		94		115		4	
Emission level specification												
without specification	103	*37*	21	*78*	6	*75*	37	*33*	36	*28*	3	60
with specification	177	*63*	6	*22*	2	*25*	76	*67*	91	*72*	2	*40*
ZKR I	28	*10*	--	--	--	--	5	*4*	23	*18*	--	--
ZKR II	12	*4*	1	*4*	1	*12,5*	7	*6*	3	*2*	--	--
EG II	93	*33*	1	*4*	--	--	43	*38*	47	*37*	2	*40*
EG III a	44	*16*	4	*15*	1	*12,5*	21	*19*	18	*14*	..	--
EG V	--	--	--	--	--	--	--	--	--	--	--	--

Tab. 2: Overview of the information on emission levels for the "smallest" generators on cargo and tanker vessel(3)

3.2.2 *Classification of ship generators without information on emission stage and summary of certification according to EU and CCNR requirements*

For 420 cargo and 103 tanker vessels, the database does not contain information on generator certification. The applicable emission levels for these ships can be determined via the year of construction of the generator or, alternatively, by means of the year of construction of the ship. In this case, it is assumed, that the generators met the emission requirements that were necessary in the respective year of construction. For the different power classes of the generators, the EU provided different dates for the entry into force of the regulations. To simplify the evaluation, the emission levels applicable to the year of construction are compiled in Tab. 3. In each case, the beginning of the year was taken as the entry into force date, as only the year of construction was given for the generators, but not the month of the year. Therefore, minor inaccuracies arise in the allocation of the respective emission levels according to the year of construction of the generators.

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. 3: Entry into force of the respective emission limits

There are different dates that the EU specifications for the individual engine power classes came into force. The specifications according to CCNR I and CCNR II are also not fully compatible. A compromise had to be found for a summarized grouping of generators according to EU stage, CCNR regulation and classification according to the year of manufacture, in order to avoid overly complicated calculations in the emission estimation of the fleet.

For generators classified only according to their year of construction or alternatively according to the ship's year of construction, the classification of the emission data was carried out according to TREMOD[(5)]. For those years of construction, an emission certification can be assumed, a uniform classification was made according to EU II (year of construction 2004-2006) or according to EU Stage IIIa (year of construction 2007-2008). Existing certifications with CCNR I were combined with the EU Stage II level, certifications with CCNR II with the EU Stage IIIa level. The emission calculations were carried out for the average output of the "smallest" or "largest" (tankers) generators using the output classes according to TREMOD[(5)].

a) Classification of generators only with information on the year of the generator´s construction:

For 184 cargo and 47 tanker vessels, only the respective generator´s year of construction is known. Based on this data, the emission level can be inferred from the regulations applicable in the year of construction using the above-mentioned procedure. The years of construction before 2003 were classified according to the classification of emission data according to TREMOD[(5)] (Tab.7).

b) Without information on emission certification and generator´s year of construction

In the case of 236 cargo and 29 tanker vessels, only power data on the generator is available, but no information on the year of construction of the "smallest" generator. In this case, an age estimate can only be made on the basis of the ship's year of construction. This assumes that new generators are always installed in new buildings. With this approach, most generators are assigned to the oldest class, built before 1981, based on the ship's year of construction. The actual emissions are likely a little bit overestimated, as some of these generators have probably already been replaced and are thus younger than 1981.

Fig. 2: Modern 85 m tanker vessel (Foto: Arne Harms)

3.3 Overall assessment of the distribution of emission stages present on the vessels

Tables 4a and 4b, generated with the methods presented, give an overview of the assumed composition of the emission levels of the "smallest" generators of the inland navigation fleet, as it can be determined from the data provided by the WSV in administrative assistance.

Cargo vessels "smallest" generator					
Emission level according to TREMOD[(5)]	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 2008)	146	24,0	105	40	1
EU V (from 2018)	1	**0,2**	1	--	--
∑ EU II + CCNR I	110	**18,1**	--	--	--
∑ EU IIIa + CCNR II	150	**24,6**	--	--	--
Total	**609**		**189**	**184**	**236**

Tab. 4a: Combination of the different approaches for determining the respective emission levels for the "smallest" generators of the freight vessels The grey fields are not added up for "total".

An evaluation of the data for the "smallest" generator to classify the emission potential was possible for 609 cargo vessels. In the case of tankers, the classification was possible in 253 cases for the "smallest" generator and in 233 cases for the "largest" generator. For 40 tankers, the database only contained information on one generator. In these cases, the generator is listed as both "smallest" and "largest" generator. As in many cases the classification was only possible via the year of construction of the ship, the emissions are probably overestimated in these cases, so that the results should be assessed as "conservative". Research revealed that tanker traffic to the tank storage farms is almost exclusively handled by vessels of the size classes IV, Va and Vb. Therefore, in Table 4b, the results are only compiled for these size classes.

Tanker vessels "smallest" generator (Ship classes IV, Va, Vb = 68 - 135 m)					
Emission level according to TREMOD(5)	Number	%	According to Emission stage generator	According to year of construction generator	According to year of construction ship
before 1981	17	**6,7**	--	2	15
1981-1990	11	**4,3**	--	5	6
1991-2002	31	**12,3**	--	29	2
CCNR I	28	11,1	28	--	--
CCNR II	12	40,3	12	--	--
EG II (from 2003)	102	40,3	93	8	1
EG IIIa (from 2008)	52	20,6	44	3	5
EU V (from 2018)	--	--	--	--	--
∑ EU II + CCNR I	130	**51,4**	--	--	--
∑ EU IIIa + CCNR II	64	**25,3**	--	--	--
Total	**253**		**169**	**47**	**29**

Tanker vessels "largest" generator (Ship classes IV, Va, Vb = 68 - 135 m)					
Emission level according to TREMOD(5)	Number	%	According to Emission stage generator	According to year of construction generator	According to year of construction ship
before 1981	16	**6,8**	--	2	14
1981-1990	15	**6,4**	--	9	6
1991-2002	30	**12,8**	--	26	4
CCNR I	41	17,4	41	--	--
CCNR II	3	1,3	3	--	--
EG II (from 2003)	74	31,5	73	1	--
EG IIIa (from 2008)	54	23	53	1	--
EU V (from 2018)	--	--	--	--	--
∑ EU II + CCNR I	115	**49,8**	--	--	--
∑ EU IIIa + CCNR II	57	**24,3**	--	--	--
Total	**233**		**170**	**39**	**24**

Tab. 4b: 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 grey fields are not added up for "total".

4. Diesel consumption and emission factors of the "smallest" generators

4.1 Diesel consumption in the low-load range

The determination of diesel consumption and emission factors of generators in a load range of 2 kW (low load range) is not without problems. The power curves of most manufacturers do not usually cover the power range below 25%. In a study by TU Delft ("Walstroom versus Generatorenstroom" (2012)[(1)], the following power/consumption diagrams of various generators, typical on inland vessels, can be found:

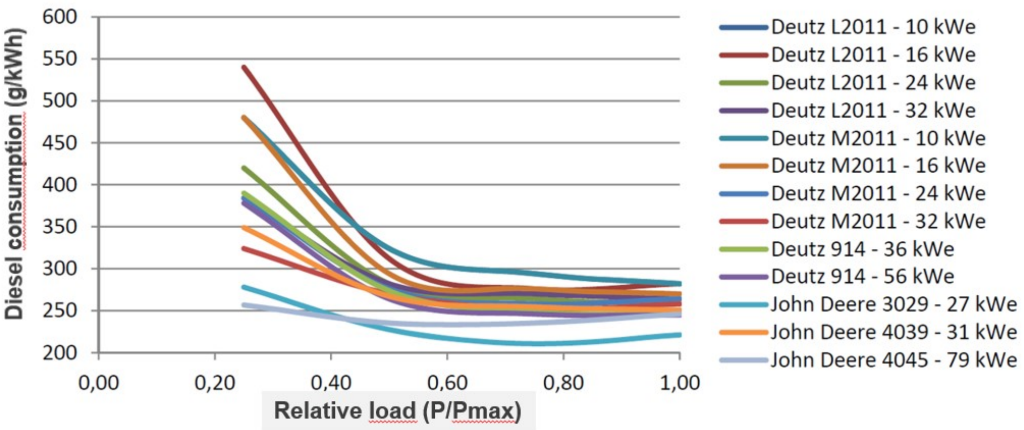

Fig. 3: Specific fuel consumption (grams per electric kWh) of generator sets depending on the load. Modified chart from the TU Delft "Walstroom study" **(1)**

In the TU Delft "Walstroom study", these performance curves were extrapolated into the low-load range (1-2 kW):

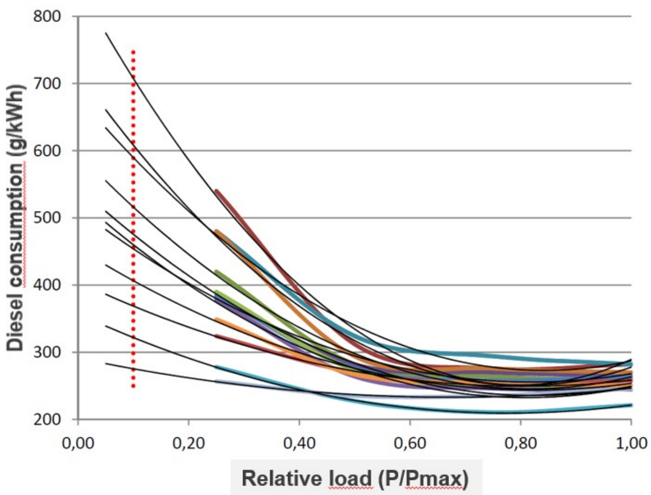

Fig. 4: Extrapolation of the specific fuel consumption (grams per electric kWh) of generator sets to the low-load range of 8 % utilization. Modified chart from the Waalstrom study[(1)]

From these curves, the following diesel consumptions can be estimated for the low-load range of about 8% load output (Fig. 4; Tab. 5). For the power classes of the generators defined for TREMOD[5] (28-36 kW and 37-74 kW), average diesel consumption per kWh can be derived from this.

			Diesel consumption/ 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]

4.2 *Emission factors*

The emission calculation model "TREMOD" (Transport Emission Model)[5] of the IFEU Institute, which is frequently used in Germany, maps motorized transport in Germany in terms of its traffic and mileage, energy consumption and the associated climate gas and air pollutant emissions for the period from 1960 to 2018 and in a trend scenario up to 2050. Here, the emissions from inland vessels and mobile generators are also considered.

For diesel generators in the 18-36 kW and 56-74 kW power classes, the TREMOD model assumes the following emission factors in the "normal" power range for the age composition of the generators assumed for 2020, which however cannot be automatically applied to the "low-load range":

Power class	Pollutant	g/kWh	g/kg Diesel
18-36 kW	NO_X	6,21	23,72
	PM	0,47	1,78
56-74 kW	NO_X	3,75	14,43
	PM	0,16	0,63

Tab. 6: Emission factors TREMOD-MM 5.11, diesel generators, mean value 2020

Since the "smallest" generators on the moored inland vessels with 1-2 kW power demand operate in the low-load range, the "base factors" for mobile generators, also derived from the TREMOD[5], were adjusted mathematically using the diesel consumption per kW, derived from the "Walstroom study"[1].

Table 7a shows the emission factors valid for the respective emission levels. However, these apply to normal power outputs, not to the low-load range below 25% utilization, wherefore higher diesel consumption per kWh must be assumed (see Tab. 7a). Therefore, the emissions per kW were corrected by means of the higher diesel consumption in the low-load range for the emission estimates of the ships at berth by means of the higher average diesel consumption per kWh.

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	0,37	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					
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. 7a: TREMOD[5] base emission factors for mobile diesel engines with adjustment for the low-load range (8% load factor).

Generators with power class 130-299 kW			
Emission level according to TREMOD(5)	Diesel g/kWh TREMOD	NO_x 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

Tab. 7b: TREMOD(5) basic emission factors for mobile diesel engines of the power class 130-299 kW

These generators (Tab. 7b) are used when unloading (pumping empty) the tankers. They supply the large pumps on board with energy and therefore do not operate in the low-load range. Therefore, no factors were determined for the low-load range.

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

With the data compiled above, the NO_X and particulate emissions (PM), caused by ships at berth, can now be calculated as a model. The parameters and procedures used are described below.

5.1 Grouping of generators to TREMOD emission levels

Cargo vessels: For the emission estimates of the vessels at berth, all emissions from the generators are calculated for cargo vessels up to 110 m with the TREMOD(5) baseline emissions adjusted for "low load" for the 28-36 kW power class (see Tab. 7a). The 135 m ships are also added to this class for the subsequent modelling.

Tanker vessels: When estimating emissions from tanker ships at berth, a distinction must be made between berthing conditions without ship-side pumping operations (usually loading procedures) and with ship-side pumping operations (usually discharging operations).

Tankers loading procedures: For the emission estimates of the tankers at berth without ship-side loading activities, all generators are calculated with the TREMOD base emissions of the power class 37-74 kW, adjusted for "low load" (see Tab. 7a).

Tankers unloading procedures: The calculation is carried out with the TREMOD base emissions for the power class 130-299 kW (see Tab. 7b).

5.2 Basis of the calculations

It is assumed that a ship is at berth in a port for an average of 8 h and that an electricity demand of 2 kWh is covered by the "smallest" diesel generator on board. The calculations for NO_X and PM are based on the diesel consumption under low load (see Tab. 7a) and the basic emission factors for diesel generators from TREMOD(5).

In addition, it is determined which emission quantities would arise in a theoretical port if 50 ships were moored there on a daily average for 8 hours each. In the "worst case" (all generators built before 1981), the NO_X emissions in the port area (50 cargo ships/d and generators in the power range 28-36 kW) would reach about 9,2 t/a. If all generators already met Stage V, the annual emissions would drop to 2,48 t/a (Tab. 8).

For tankers at berth (generators in the power range 37-74 kW) with no loading or unloading procedures, there is a higher energy demand of 9 kW than for cargo vessels. Therefore, in the "worst case", about 15 t/a NO_X would be emitted by 50 tankers without shipside unloading activity. If all generators already met the requirements of Stage V, this would result in NO_X emissions of about 4,6 t/a. The generator equipment on tankers is much younger than that on cargo ships and therefore has a much higher proportion of generators that already meet the EU Stage II and IIIa emission standards. The "worst case" can therefore practically not occur (Tab. 8).

Fig. 5: Modern 110 m freight vessel in the port of Neuss (Photo: Busch, LANUV)

Fig. 6: Modern 135 m container vessel in the port of Duisburg (Photo: Busch, LANUV)

Cargo vessels: "smallest" generator with 28-36 kW; demand 2 kW						
Emission level according to TREMOD[5]	**NO_X**	**1 Ship/h**	**1 Ship/8h**	**1 Ship/a**	**50 Ships/8h**	**50 Ships/a**
	g/kWh	g	g	kg	kg/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[5]	**NO_X**	**1 Ship/h**	**1 Ship/8h**	**1 Ship/a**	**50 Ships/8h**	**50 Ships/a**
	g/kWh	g	g	kg	kg/a	t/a
before 1981	11,4	102,6	820,8	299,6	41,0	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	92,0	12,6	4,60

Tab. 8: **Basic table for NO_X emission quantities of freight and tanker vessels at berth from diesel generators with different emission characteristics in the low-load range.**

Cargo vessels: "smallest" generator with 28-36 kW; demand 2 kW						
Emission level according to TREMOD[5]	PM	1 Ship/h	1 Ship/8h	1 Ship/a	50 Ships/8h	50 Ships/a
	g/kWh	g	g	kg	kg/a	kg/a
before 1981	3,5	7	56	20,4	2,8	1022,0
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	1 Ship/h	1 Ship/8h	1 Ship/a	50 Ships/8h	50 Ships/a
	g/kWh	g	g	kg	kg/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 with different emission characteristics in the low-load range.

For tankers without ship-side loading activities (generators in the power range 37-74 kW), in the "worst case", 3.548 kg/a would be emitted. If all generators already met the requirements of stage V, the PM emissions would be 26 kg/a.

6. Estimation of the emissions of inland vessels at berth when operating the "smallest" generators in each case.

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

In practice, it is too time-consuming to determine the emissions of ships and in some cases it is not possible to determine the individual generator data for each moored ship. To calculate the emissions, the expected emission behavior of an average "smallest" generator (hereafter referred to as "fleet generator") was therefore determined from the available data on the distribution of the "generator pool" to the various basic emission levels according to TREMOD[5] and the respective expected emissions per level. Based on these average emissions per hour and the average berthing times, the expected emission quantity of the moored ships can be estimated.

To estimate the order of magnitude of the emission quantities of moored ships, a model calculation was carried out on the basis of the determined data for a port operation of 50 moored ships per day, each with a mooring time of 8 hours. It is assumed that for a **cargo vessel**, there is an average power demand of 2 kW, which is covered by the "smallest" diesel generator on board. According to information from a tanker shipping company, an energy requirement of about 9 kW must be assumed for modern **tanker vessels** (see chap. 6.2). The data (Composition of the emission levels of the generators according to the current inventory 2019) obtained is compiled in Tables 10a and 10b.

If it were a matter of 50 freight vessels at berth, a daily emission quantity of 17,5 kg NO_X would be expected, which would add up to a quantity of 6.400 kg/a over the year (Tab. 10a). For PM, 600 g daily and an annual quantity of 216 kg would be expected, consisting almost entirely of soot (Tab. 10b).

For 50 tankers at berth without ship-side loading activities, higher emissions result from the higher energy demand despite younger, i.e. "cleaner" generator equipment. For NO_X, the expected emissions are 36,2 kg daily and 13,2 t annually(Tab. 10a). For PM, 2,7 kg/d and an annual quantity of 973,5 kg would be expected (Tab 10b).

The assumption of a "model port" with 50 cargo ships or tankers at a time exceeds the actual port activity in Central Europe's largest inland port, Duisburg. However, it vividly illustrates the order of magnitude of the currently expected emissions for NO_X in a single or low double digit ton dimension and for PM in a three-digit kg dimension. Thus, for the power supply of the ships, there are presumably lower emission shares than originally assumed.

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"		50 Ships	
Emission level according	%	g/kWh	g/ 2kWh	g/h	g/8h	kg/8h	t/a
before 1981	**38,4**	31,5	63	24,2	193,5	9,7	3,5
1981-1990	**5,9**	33,6	67,2	4	31,7	1,6	0,6
1991-2002	**12,6**	19,6	39,2	4,9	39,5	2	0,7
∑ EU II + ZKR I	**18,1**	13	26	4,7	37,6	1,9	0,7
∑ EU IIIa + ZKR II	**24,6**	12,2	24,4	6	48	2,4	0,9
EG V since 2018	**0,2**	8,5	17	0,03	0,27	0,01	0,01
Basic data for calculation	Emissions "Fleet generator"			g/h 43,8	g/8h 350,7	kg/8h 17,5	t/a 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"		50 Ships	
Emission level according	%	g/kWh	g/ 9kWh	g/h	g/8h	kg/8h	t/a
before 1981	**6,7**	11,4	102,6	6,9	55,0	2,7	1,0
1981-1990	**4,3**	13,4	120,6	5,2	41,5	2,1	0,8
1991-2002	**12,3**	19	171	21,0	168,3	8,4	3,1
∑ EU II + ZKR I	**51,4**	9,1	81,9	42,1	336,8	16,8	6,1
∑ EU IIIa + ZKR II	**25,3**	6,3	56,7	14,3	114,8	5,7	2,1
EG V since 2018	--	3,5	--	--	--	--	--
Basic data for calculation	Emissions "Fleet generator"			g/h 89,5	g/8h 716,3	kg/8h 35,8	t/a 13,1

Tab. 10a: **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"		50 Ships	
Emission level according to TREMOD[5]	%	g/kWh	g/ 2kWh	g/h	g/8h	g/8h	kg/a
before 1981	**38,4**	3,5	7	2,7	21,5	1075,2	392,5
1981-1990	**5,9**	2,6	5,2	0,3	2,5	122,7	44,8
1991-2002	**12,6**	2,8	5,6	0,7	5,6	282,2	103
∑ EU II + ZKR I	**18,1**	0,7	1,4	0,3	2	101,4	37
∑ EU IIIa + ZKR II	**24,6**	0,7	1,4	0,3	2,8	137,8	50,3
EG V since 2018	**0,2**	0,03	0,06	0	0,001	0,05	0,018
Basic data for calculation	Emissions "Fleet generator"			g/h	g/8h	kg/8h	kg/a
				4,3	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"		50 Ships	
Emission level according to TREMOD[5]	%	g/kWh	g/ 9kWh	g/h	g/8h	g/8h	kg/a
before 1981	**6,7**	2,7	24,3	1,6	13,0	651,2	237,7
1981-1990	**4,3**	1,9	17,1	0,7	5,9	294,1	107,4
1991-2002	**12,3**	1,3	11,7	1,4	11,5	575,6	210,1
∑ EU II + ZKR I	**51,4**	0,4	3,6	1,9	14,8	740,2	270,2
∑ EU IIIa + ZKR II	**25,3**	0,4	3,6	0,9	7,3	364,3	133,0
EG V since 2018	**0**	0,02	--	--	--	--	--
Basic data for calculation	Emissions "Fleet generator"			g/h	g/8h	kg/8h	kg/a
				6,6	52,5	2625,5	958,3

Tab. 10b: **Estimation of PM (particulate matter) emissions from the power generators moored vessels and tankers without ship-side loading activity, taking into account the composition of the emission levels of the "smallest" generators.**

6.2 *Emissions from tanker ships with and without ship-side loading activity, using the example of Duisburg Port: Basin A in 2018.*

Two different berthing situations arise for the tankers:

a) Mooring periods without active ship-side unloading activity with low power consumption of 9 kW, which is covered by using the smallest generator on board.

b) Berthing times with active pumping and high power consumption of the pumps of about 80-100 kW, which is covered by the use of the largest generator on board.

Therefore, additional information must be available for the estimation of emission levels. Table 10c compiles the basic data for the estimation of NO_X and PM (particulate matter) emissions from the power generators of tankers at berth with shipboard loading activity, taking into account the composition of the emission levels of the "largest" generators. Here, too, the emissions were determined analogously to the procedure for the "smallest" generators of the average "largest fleet generator" per hour of unloading activity with a power requirement of 110 kW (sum of "moored tanker" and pump energy). On some tankers, the energy demand for unloading is also provided by additional generators in the power range >110 kW. Since these generators predominantly fall into the emission group of engines 130-299 kW according to TREMOD[(5)] or are at least close to this range, separate calculation steps were taken.

Fig.7: Modern 110 m tanker at the unloading station (Photo: C. Dahlhoff)

Tanker vessels: "largest" generator 130-299 kW; (Ship classes IV, Va, Vb = 85				
NO_X	**Share of fleet**	**Basic data per stage**	**Share of emissions to "Fleetgenerator"**	
Emission level according to TREMOD[5]	%	g/kWh	g/kWh	g/110 kWh
before 1981	**6,8**	17,8	1,21	133,144
1981-1990	**6,4**	12,4	0,79	87,296
1991-2002	**12,8**	11,2	1,43	157,696
∑ EU II + ZKR I	**49,8**	5,2	2,59	284,856
∑ EU IIIa + ZKR II	**24,3**	3,2	0,78	85,536
EG V ab 2018	**0**	--	--	--
Basic data for calculation	**Emissions "Fleet generator"**		g/kWh	g/110kWh
			6,80	748,53

Tanker vessels: "largest" generator 130-299 kW; (Ship classes IV, Va, Vb = 85				
PM	**Share of fleet**	**Basic data per stage**	**Share of emissions to "Fleetgenerator"**	
Emission level according to TREMOD[5]	%	g/kWh	g/kWh	g/110 kWh
before 1981	**6,8**	0,9	0,06	6,73
1981-1990	**6,4**	0,8	0,05	5,63
1991-2002	**12,8**	0,4	0,05	5,63
∑ EU II + ZKR I	**49,8**	0,1	0,05	5,48
∑ EU IIIa + ZKR II	**24,3**	0,1	0,02	2,67
EG V ab 2018	**0**	--	--	--
Basic data for calculation	**Emissions "Fleet generator"**		g/kWh	g/110kWh
			0,24	26,15

Tab. 10c: 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.

6.2.1 Routes of transportation and expected loading procedures

The emissions from tanker vessels at berth are more difficult to determine than for motorized cargo vessels, as the unloading of tankers ("discharging") usually takes place using the pumps on board. It is therefore important to first collect some basic information on tanker shipping.

The transport of mineral oil products on the Rhine, such as petrol and diesel ("gas oil"), but also crude oil, is mainly from the coast to inland. This means, that the ships are loaded in the coastal ports such as Rotterdam or Antwerp and then travel upstream to their ports of destination. Sometimes the ships also call at intermediate ports on this journey in order to deliver part of the cargo there. This has the advantage that e.g. to Duisburg the deeper waterway of the Lower Rhine can be used for the large ships. After delivering part of the cargo ("lightering"), the ship has less draught and can then reach ports such as Basel on the Upper Rhine without any problems.

In most cases, there is no return freight for mineral oil products, so that the tankers mostly return to the coastal ports empty (under "ballast"). The transport of petroleum products and crude oil in the inland ports therefore mainly involves unloading procedures, which are carried out on the ship's side via on-board pumps. A tanker transporting mineral oil products, therefore has a significantly higher energy requirement during unloading than a motorized cargo vessel and thus also a higher emission potential.

In the case of liquid industrial chemicals and petrochemical products, there are also more frequent downstream transports. This involves transports between the coastal ports and the industrial sites as well as between the industrial sites. In some cases, there is also a transfer from rail tank wagons to tankers or vice versa at the transshipment facilities.

For industrial chemicals and finished products, too, it is generally the case that only one unloading or loading procedure takes place at the transshipment facilities. I.e. the loaded ship arrives at the berth, is unloaded and departs empty. Or an empty ship arrives and takes on its cargo. A situation in which both unloading and loading take place during a berthing operation does normally not occur in practice.

Depending on the liquid goods, wherefore the respective shore facilities are designed, either the unloading or the loading procedures predominate at the individual facilities, where the moored ships have very different emission characteristics. For a realistic estimation of the emissions emitted by moored tankers, it is therefore important to know not only the parameters that are important for cargo ships, but also the relations between the unloading and loading procedures in the ports under consideration. This relation can only be found out by directly interviewing the operators of the respective shore facilities.

6.2.2 Loading capacities of tanker types on the Rhine in NRW

The main goods traffic with liquid products on the North Rhine-Westphalian section of the Rhine is handled by tankers of the length classes 85 m, 110 m and 135 m in length. The average ship of the respective length class has the following technical data (Tab. 11):

Ship class	Length (m)	Width (m)	Draugth (m)	Number of tanks	Load capacity (m^3)
IV	85	9,5	2,5	5	1.800
Va	110	11,4	3	8-10	3.300
Vb	135	11,4	3,5	14	4.050

Tab. 11: Technical data of tankers of the length classes IV, Va and Vb

6.2.3 Loading and unloading procedures for tankers:

The time required for loading and unloading depends both on the size of the ship and on the pumping and reception capacities of the ship and shore installations. On modern tankers, each tank is usually equipped with a submersible pump. The pump of a Dutch manufacturer (Marflex pump MDPD 80) with a pumping capacity of up to 90 m^3/h is very common. About 75% of the tankers in the Rhine area are said to be equipped with pumps of this type (Reederei Deymann, personal communication). Older "single-product" tankers sometimes had only one pump (300-700 kW) located on deck. On these ships, this pump serves all existing tanks.

6.2.3.1 Loading procedures

The loading of tanker vessels at berth usually is operates by shoreside facilities. The required pumping power is provided by the shore installation. During loading operations, the ship then only needs the energy required for ventilation, living quarters, engine room and wheelhouse. According to information from the Harms shipping company (personal communication), a power requirement of about 9 kW arises on modern tankers at berth and is usually generated by the smallest generator on board. The higher power demand is due to higher safety requirements for ventilation (e.g. engine room, living quarters, etc.) and also due to the use of electrically operated heating systems.

6.2.3.2 Unloading procedures

Unloading procedures are carried out on the ship's side with the pumps on board, which have a considerably higher power requirement. The time required for discharge therefore depends on both the shipboard parameters such as cargo quantity and pumping capacity available on board and the shore-side intake capacity (maximum intake quantity in m^3/h) of the installation. The facilities on the "Oil Island" in the port of Duisburg, for example, each have an intake capacity of 400 m^3/h.

For the unloading of a tanker, a maximum of 4-5 tanks can thus be unloaded at the same time with the onboard pumps. Employees of various shipping companies (personal communication with the shipping companies Jägers and Deymann) estimated the power required in practice for the individual submersible pumps at 20-30 kW each. With an intake capacity of the shore facility of 400 m^3/h, the pumps of 4-5 tanks are usually used, which then each would require about 20 kW of power.

Thus, it can be assumed that a power of about 110 kW must be made available during an unloading process. In practice, this amount of energy is generated with a generator in this power class or with the largest diesel generator on board, which supplies the bow thruster, for example, when the boat is underway. The discharge process is initially "started slowly", i.e. one begins with about half the required flow rate and slowly increases to full power. When estimating the emissions produced during the discharge process, the emissions (TREMOD)[(5)] for engines in the 130-299 kW power class were used uniformly.

For the respective ship sizes, the following active "pumping times" result for the unloading procedures, if the shore unit has an intake capacity of 400 m³/h:

	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

Tab. 12: Average loading times of tankers in the length classes IV, Va and Vb

In addition to the pure "pumping times", 1-2 hours are needed for connecting the ship to the shore facility, for disconnecting the connections after tank emptying and for the respective clearing in and out of the ship at the facility.

6.3 *Capacity of the smallest and "largest" generators on tankers*

For a total of 280 tanker vessels, performance data (kW) is available on the ship's generators and in some cases also on their year of construction and their emission level (Tab. 13).

	Length class ship					
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. 13: Power structures (average power) of the "smallest" and largest generators on tankers. Overview of the analyzed data on tanker vessels (German ZBBD database, 2019)

According to the available data, the calculation of tankers at berth without own loading activity can be done with the TREMOD[(5)] basic factors of the power class 27-74 kW adjusted for the low load (Tab. 7a). The calculations of shipside unloading operations are made with the TREMOD base factors of the power class 130-299 kW (Tab. 7b), the composition of the generators present in the fleet and the hourly emissions of the "average largest fleet generator" determined from this (Tab. 10c).

6.4 Calculation of emissions from real tanker traffic at the "Oil Island" in the port of Duisburg for the year 2018.

In the Port of Duisburg, a tank storage farm is operated on the so-called “Oil Island” between port basins A and B. The seven facilities for handling tanker ships are all located to the east of the Oil Island in port basin A. The shore facilities each have an intake capacity of 400 m³/h. The unloading of the ships takes place by ship. The tanker vessels are unloaded using the ship’s onboard pumps, while loading is done on the shore side using shoreside pumps.

The operator of the tank storage farm kindly provided us with the vessel movements for the year 2018. During this year, a total of 1,864 tankers were berthed at the facilities. 40% of these were size class IV (85 m) vessels and 60% were size class Va (110 m) vessels. Class Vb ships only call at the facilities infrequently (about 1-2 ships per month). For this reason, an additional 5 unloading and 12 loading procedures were included in the estimate. Tankers of the smaller length classes can not be handled at the facility. In 715 cases the ships were unloaded, in 1149 cases the ships were loaded. (Tab. 14)

The calculation of the emissions of the tankers at berth without shipside loading activities is carried out analogously to the procedure for the cargo motor ships by offsetting the number of moored ships, the average berthing time and the emission estimate for the assumed average "smallest fleet generator" of the tankers, which was determined for the length classes IV, Va and Vb.

„Oil Island“ Duisburg	Loading activities		Ship class	
2018	**Number**	**% share**	**IV**	**Va**
		%	**85 m (40 %)**	**110 m (60 %)**
Unloadings	715	38,4	286	429
Loadings	1149	61,6	460	689
Total	1864			

Tab. 14: Loading and unloading procedures for tankers in port basin A of the port of Duisburg.

From the analysis of the "largest" generators, an assumed average "largest fleet generator" of the tankers of the length classes IV, Va and Vb can also be derived from the factors of power and emission behavior. The emissions of the tankers with ship-side loading activity are then calculated from the number of loading operations per ship class, from the assumption of the total power required of 110 kW, the number of the respective unloading times per ship class and from the emission estimate for the assumed average "largest fleet generator", using the TREMOD[5] baseline emissions for mobile diesel engines in the 13-299 kW power class. Since the ships require an additional berthing time of approx. 1h for clearing in and out, an "emission allowance" of 715 h with running time "smallest generator" was additionally determined for all unloading processes. For the loading procedures, this time was calculated from the first. The calculation results were compiled in Table 15.

In total, the 1864 tankers, handled for the "Oil Island" in port basin A in 2018, resulted in an emission quantity of 5,2 t NO_X and 221 kg PM for the berthing times.

Unloading operations: Ship facilities Total : 715	Ship class	IV 85 m	Va 110 m	Vb 135 m
	Unloading time	6 h	9 h	12 h
Emissions per unloading	NO_X (kg)	4,49	6,74	8,98
	PM (g)	156,88	235,32	313,76
Unloading operations:	Quantity	286	429	5
Emissions 2018	NO_X (kg)	1284,5	2890,1	44,9
	PM (kg)	44,9	101,0	1,6
Surcharge for clearing (in and out), 1 h with "smallest" generator	NO_X (kg)	64,78		
	PM (kg)	4,79		
unloading	Ship's emissions Duisburg 2018 Tanker unloading operations in port basin A NO_X (t) 4,28 PM (kg) 152,2			
Loading operations: Shore facilities Total: 1149	Ship class	IV 85 m	Va 110 m	Vb 135 m
	Loading time	7 h	10 h	13 h
Emissions per loading	NO_X (g)	634,2	906	1177,8
	PM (g)	46,9	67,0	87,1
Loading operations	Quantity	460	689	12
Emissions 2018	NO_X (kg)	291,7	624,2	14,1
	PM (kg)	21,6	46,2	1,1
Surcharge for clearing (in and out)	already included in the loading times			
loading	Ship's emissions Duisburg 2018 Tanker loading operations in port basin A NO_X (t) 0,93 PM (kg) 58,8			
2018	Ship's emissions total Duisburg 2018 Tanker vessels at berth In the port basin A "Oil Island" NO_X (t) 5,2 PM (kg) 221			

Tab.15: Estimation of the NO_X and PM emissions generated by the tanker vessels, loading or unloading at the "Oil Island" in port basin A in Duisburg for the year 2018.

7. Estimation of emissions from passenger vessels (cruise and hotel operations)

During a river cruise, the inner city areas are usually called, where the ships spend extended periods of time moored for the purpose of sightseeing and night-time rest. These berthing activities often lead to complaints from local residents about noise and exhaust pollution. The planning of new berths or their modification involves complex approval procedures, wherefore the level of expected emissions must also be determined. Therefore, the pollutant and noise emissions associated with berthing times become particularly relevant for air pollution control planning in cities located on major waterways.

7.1 Energy demand of berthing river cruise vessels

As a rule, the river cruise ships dock at their daily destination in the early afternoon and continue the journey the next morning. The berthing times are about 18-19 hours. The energy demand of the ships usually increases proportionally to the number of passengers on board, so it must be assumed that smaller ship sizes (85-100 m) have a lower power demand than the large 135 m ships. The energy demand also fluctuates over the course of the berthing period. It is highest during the day when all passengers are active and the restaurant business is running at meal times. If an empty ship waits a long time for new passengers to embark or at the end of the voyage, the energy demand can be significantly lower. Surveys of German shipping companies with river cruise ships revealed quite different figures for the hourly power requirements of berthing river cruise ships in the order of magnitude between 30 and 230 kW. One of the companies gave more detailed information on the energy demand of river cruise ships vessels: Average length of stay in Düsseldorf 8 h, average energy demand 82 m ship: 130 kW; 110 m ship 180 kW; 135 m ship: 230 kW. Such figures reflect the dimensions of the actual energy demand, but only provide a rough estimate of the emissions.

Real data on the actual energy demand of cruise vessels can be obtained from the power consumption at existing shore power facilities. Original data on the energy demand at berth from a Dutch shore power operator in Nijmegen (Netherlands) from the years 2019 and 2020 could be evaluated within the framework of CLINSH. These are four shore power facilities at the Waal quay in the inner city area, which are mainly used by river cruise ships.

In 332 cases (61%), data on the respective ship lengths were available in addition to the energy consumption, so that the energy demand can be classified according to the ship lengths. For these ships, average values could be derived for the respective average expected energy demand when the ships were underway with passengers. No length data was available for 39% of the ships moored at the shore power facilities. These ships were assigned to a size class based on the energy demand.

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

Energy consumption of less than 30 kW was not evaluated, as it can be assumed, that some of the ships were docked without passengers, e.g. at the beginning of the voyage to embark. (Example 110 m ship, arrival 04.05.2019, 7:27 hrs, departure 12:30 hrs, average power consumption 22,4 kW).

From the 332 consumption data entries with information on the respective ship length, the following orders of magnitude can be derived for estimating the average power demand of a river cruise ship with passengers. Power demands of less than 30 kW were not included in the averaging, as these are more likely to occur at rest periods without passengers (Tab. 17). During off-season rest periods in winter, the power demand can also be in the range of 1 - 2 kW.

Shore power	**Size class**		
Nijmegen	**< 110 m**	**110 m**	**135 m**
Quantity	28	131	154
Mean (kW)	**70,3**	**95,7**	**113,7**
Min (kW)	31,3	30,4	30,0
Max (kW)	126,8	179,5	203,5

Tab. 17: 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:

Power consumption below	30 kW	Ship is in idle mode without passengers and on-board operation.
Power consumption	30-80 kW	Small ships up to 100 m, or the ship was here at the beginning or end of the voyage and moor temporarily without passengers.
Power consumption	80-105 kW	Ships in the length class 110 m
Current consumption	> 115 kW	Ships in the range of the length class 135 m.

The data compiled in Table 18 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	Energy 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

* Estimate, as data basis is too small

Tab. 18: 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 vessels

In order to be able to estimate the emissions from berthing river cruise vessels at inner-city berths, knowledge of the generators on board and their emission behaviour is also necessary. To analyze the composition of the generator pool, data from 34 river cruise vessels of the corresponding length classes (IV, Va and Vb) were available in the German ZBBD Database (German Ship Inspection Commission)[(3)]. The number of ships in the database is relatively small but can nevertheless be used to estimate the composition of the generators, at least for the ships in the size classes Va and Vb (Tab. 19). A calculation basis for estimating emissions can also be obtained from this. However, the representativeness of the composition for ship sizes around 85 m remains rather low. Within the framework of CLINSH, it would have been helpful if the data of the river cruise ships investigated by the Dutch and Belgian ship investigation commissions had also been available.

The level of emissions depends both on the required energy demand of the ships and on the age of the generators used and their emission behaviour. The higher the proportion of "young" generators that already meet one of the EU or CCNR emission requirements, the lower the emissions. The generators of the 110 m vessels were on average about 20 years old (Tab. 19), only 52% of the generators was already subject to the mandatory emission regulations. Most of the 135 m ships in the cruise fleet were built after 2010, so that here all generators are already subject to emission regulations (Tab. 21). This also explains the significantly lower emissions per berthing hour compared to the 110 m ships (Tab. 21a,b).

The emissions were estimated using the emission levels according to TREMOD[(5)] (engine class 130-299 kW; Tab. 20) and taking into account the actual composition of the generator pool under allocation to the emission levels. Using this data, an average "mean fleet generator" was determined per ship size class, which can then be used to estimate the average NO_X and particulate matter emissions per berthing time (Tab. 21).

It can be seen, that ships on cruise or hotel operations can generate quite different emissions per ship length class (Tab. 22a,b). The lowest average emissions were 429 g/h NO_X and 11,5 g/h PM from the 135 m ships that were exclusively equipped with generators of emission level EU Stage II (or CCNR I) and EU Stage IIIa (or CCNR II). The average age of the generators on the 135 m vessels studied was 11 years. The ships in the 110 m length class had significantly higher average emissions of 761 g/h NO_X and 30,4 g/h PM. The emissions for both pollutants were somewhat lower for the 85 m length class, but this is likely to be less representative due to the low number of 85 m vessels analysed. The average age of the generators on the 85 and 110 m vessels was about 20 years.

Fig. 8: **Three river cruise ships and a day excursion ship are moored in front of the historical city of Cologne** (Photo: D. Busch, LANUV)

River cruise vessels	Size class of ships		
	68-86 m	86-110 m	> 110 m
Ships			
Number	4	19	11
Year of construction	1979-2000	1961-2011	2002-2016
Mean year of construction	1992	1996	2009
Mean age (years)	28	24	11
Main engine			
Power range (kW)	440-882	1176-1732	1324-1600
Average power(kW)	745	1.472	1.439
Year of construction	1998-2017	1961-2017	2002-2016
Mean year of construction	2008	2000	2009
Mean age (years)	12	20	11
With emission stage	3	11	11
Generators			
Indication of power (kW)	7	60	32
Generators on board			
1	2	1	--
2	1	1	3
3	1	7	6
4	--	9	2
5	--	1	--
"Smallest" Generator			
With year of construction	4	19	11
Year of construction	1979-2018	1983-2017	2002-2013
Mean year of construction	1999	2000	2008
Mean age (years)	21	20	12
Power range (kW)	70-390	47-403	37-587
Average power (kW)	230	150	240
"Largest" Generator			
With year of construction	4	19	11
Year of construction	1979-2018	1980-2010	2002-2013
Mean year of construction	1999	2000	2008
Mean age (years)	21	20	12
Power range (kW)	70-390	118-403	418-587
Average power (kW)	230	288	461

Tab. 19: **Composition of the generator pool on cabin vessels according to excerpt from the German ZBBD Database [3]**

Generators with power class 130-299 kW			
Emission level according to TREMOD	Diesel g/kWh TREMOD	NO_x 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

Tab. 20: TREMOD[5] basic emission factors for mobile diesel engines of the power class 130-299 kW

Cabin vessels : Emission relays of the generators on board with a power > 130 kW						
Emission level according to TREMOD	**bis 85 m (IV)**		**bis 110 m (Va)**		**bis 135 m (Va)**	
	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	50,0	11	25,0	22	73,3

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

Based on the available data, the emission behaviour of an "average fleet generator" can also be determined from the composition of the respective generator pool and thus also the expected emission quantity per kWh. Based on the average energy demand to be expected for the ship size, the frequency of visits and the emission quantity/kWh, it is then possible to estimate the emissions to be expected at the berth in each case.

Cabin vessel, 85 m, generator class 130-299 kW, power requirement 70 kW						
NO_X	Share of fleet	Basic data per stage	Basic data per stage	Power 70 kW	Medium "fleet generator"	
Emission level according to TREMOD2	%	g/kWh	g/kWh	g/h	g/h	g/18h
before 1981	16,7	17,8	2,97	1.246,0	208,1	3.745
1981-1990	--	12,4		868,0	--	--
1991-2002	33,3	11,2	3,73	784,0	261,1	4.699
∑ EU II + ZKR I	--	5,2		364,0	--	--
∑ EU IIIa + ZKR II	50,0	3,2	1,60	224,0	112,0	2.016
EG V since 2018	--	0,4	--	28,0	--	--
Basic data for calculation	Emissions "Fleetgenerator"		8,30		581,2	10.461

Cabin vessel, 110 m, generator class 130-299 kW, power requirement 95 kW						
NO_X	Share of fleet	Basic data per stage	Basic data per stage	Power 95 kW	Medium "fleet generator"	
Emission level according to TREMOD2	%	g/kWh	g/kWh	g/h	g/h	g/18h
before 1981	4,55	17,8	0,81	1.691,0	76,1	1.370
1981-1990	13,64	12,4	1,69	1.178,0	160,2	2.884
1991-2002	29,55	11,2	3,31	1.064,0	313,9	5.650
∑ EU II + ZKR I	27,27	5,2	1,42	494,0	134,9	2.428
∑ EU IIIa + ZKR II	25,00	3,2	0,80	304,0	76,0	1.368
EG V since 2018	--	0,4	--	38,0	--	--
Basic data for calculation	Emissions "Fleetgenerator"		8,03		761,0	13.699

Cabin vessel, 135 m, generator class 130-299 kW, power requirement 115 kW						
NO_X	Share of fleet	Basic data per stage	Basic data per stage	Power 115 kW	Medium "fleet generator"	
Emission level according to TREMOD2	%	g/kWh	g/kWh	g/h	g/h	g/18h
before 1981	--	17,8	--	2.047,0	--	--
1981-1990	--	12,4	--	1.426,0	--	--
1991-2002	--	11,2	--	1.288,0	--	--
∑ EU II + ZKR I	26,70	5,2	1,4	598,0	159,7	2.874
∑ EU IIIa + ZKR II	73,30	3,2	2,3	368,0	269,7	4.855
EG V since 2018	--	0,4	--	46,0	--	--
Basic data for calculation	Emissions "Fleetgenerator"		3,73		429,4	7.729

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

Cabin vessel, 85 m, generator class 130-299 kW, power requirement 70 kW						
PM	Share of fleet	Basic data per stage	Basic data per stage	Power 70 kW	Medium "fleet generator"	
Emission level according to TREMOD2	%	g/kWh	g/kWh	g/h	g/h	g/18h
before 1981	16,7	0,9	0,15	63	10,5	189,4
1981-1990	--	0,8		56	--	--
1991-2002	33,3	0,4	0,13	28	9,3	167,8
∑ EU II + ZKR I	--	0,1		7	--	--
∑ EU IIIa + ZKR II	50	0,1	0,05	7	3,5	63,0
EG V since 2018	--	0,015	--	1,05		
Basic data for calculation	Emissions "Fleetgenerator"		0,33		23,3	420,2

Cabin vessel, 110 m, generator class 130-299 kW, power requirement 95 kW						
PM	Share of fleet	Basic data per stage	Basic data per stage	Power 95 kW	Medium "fleet generator"	
Emission level according to TREMOD2	%	g/kWh	g/kWh	g/h	g/h	g/18h
before 1981	4,5	0,9	0,04	85,5	3,8	69,3
1981-1990	13,6	0,8	0,11	76	10,3	186,0
1991-2002	29,5	0,4	0,12	38	11,2	201,8
∑ EU II + ZKR I	27,3	0,1	0,03	9,5	2,6	46,7
∑ EU IIIa + ZKR II	25,0	0,1	0,03	9,5	2,4	42,8
EG V since 2018	--	0,015	--	1,425	--	--
Basic data for calculation	Emissions "Fleetgenerator"		0,32		30,4	546,5

Cabin vessel, 135 m, generator class 130-299 kW, power requirement 115 kW						
PM	Share of fleet	Basic data per stage	Basic data per stage	Power 115 kW	Medium "fleet generator"	
Emission level according to TREMOD2	%	g/kWh	g/kWh	g/h	g/h	g/18h
before 1981	--	0,9	--	103,5	--	--
1981-1990	--	0,8	--	92	--	--
1991-2002	--	0,4	--	46	--	--
∑ EU II + ZKR I	26,7	0,1	0,027	11,5	3,1	55,3
∑ EU IIIa + ZKR II	73,3	0,1	0,073	11,5	8,4	151,7
EG V since 2018	--	0,015	--	1,725	--	--
Basic data for calculation	Emissions "Fleetgenerator"		0,1		11,5	207

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

7.3 Estimation of the emission quantities to be expected from river cruise ships at berths near the city centre.

Based on the data presented in Tab. 23 an estimate of the order of magnitude of emissions caused by moored cabin vessels can be made. The average emissions caused by a cabin vessel of 110 m length during a mooring time of 18 h should likely be around 13,7 kg for NO_X and 550 g for PM. The ships of the 135 m size class make a smaller contribution to air pollution with about 7,7 kg NO_X and about 210 g PM. Due to the small number of ships (4 ships) analysed in the 85 m size class, no reliable emission data can be derived on the basis of the generator composition. The expected emissions are likely to be lower than those of the 110 m vessels.

Pollutant emissions from lying 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

A jetty close to the city center that is frequently used during the season for river cruises can be visited by cruise ships up to 280 times a year. If this jetty was only visited by ships of the 110 m size class, NO_X emissions of about 3,8 t/a and PM emissions of about 153 kg/a would be expected. If used exclusively by ships of the 135 m size class, the annual emissions would be in the order of 2,17 t NO_X and 58 kg PM. The actual emissions occurring at an onshore power facility, when visited by mixed ship size classes, would then be expected to be in the order of 3 t/a NO_X and 100 kg/a PM, assuming an even distribution of visiting ships between size classes Va (110 m) and Vb (135 m). For more precise analyzes, typical for the location, the exact composition of the ship size classes and the number of berthing hours would have to be determined. The extent to which these emissions contribute to air pollution in the neighbouring settlements depends on the distance between the berth and the settlement, the prevailing wind directions and the morphology of the riverbank and settlement.

7.4 More accurate estimates of the pollutant quantities emitted by cruise vessels based on a real recording of the energy consumption at OPS facilities.

If more precise data is available, such as the number of moored ships, their distribution among the size classes, exact mooring times and/or actual energy consumption, more accurate estimates of the emission quantities to be expected are possible. Within the framework of CLINSH, such data was available for the four OPS facilities in Nijmegen. These OPS plants are located in front of the old town directly on the left bank of the Waal and are mainly visited by cruise ships on tour. The calculation was made for the year 2019. In the Corona year 2020, the OPS facilities were used significantly less, by only 118 vessels.

In 2019, the four OPS facilities were visited by a total of 531 ships (Tab. 24). One of the facilities was visited very infrequently because of works at the quay. The three frequently used facilities were each visited by ships on average about 173 times. A total of 8592,5 hours of berthing time were accumulated in the year (Tab. 25). The energy output was 467.499 kWh. It can be assumed, that the average energy demand of cruise ships is proportional to the length of the ship or the number of passengers on board.

7.4.1 Classification of ships at the OPS facilities in Nijmegen:

If the length of the visiting vessels is known, they can be assigned to the respective size classes. It is assumed that the ships occupied by passengers are on a river cruise. The emissions from hotel ships with catering operations are likely to be in a similar order of magnitude. For some of the ships (n=263), unfortunately, few length data were available. In these cases, the ship length was assigned on the basis of the power consumed (kW) as follows (Tab. 24):

Size class ship	**2019**	**Power demand**
	Quantity	kW
unknown	44	< 30
< 110 m	112	30-80
110 (105-115) m	167	80-105
135 (ab 130) 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*

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

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

the amount of emissions to be expected per berth, which would have occurred, if no OPS had been available. The basis for the calculation is again the emission behaviour of an "average fleet generator", which represents the composition of the generators on the ships of the respective length classes. The sum of the emissions of all berthing operations in a year then results in the annual emission quantity.

The alternative allocation of ships without length information to the classes remains uncertain due to the high range of power consumption of the ships, but is necessary as an alternative for calculating the emissions. For the 44 ships with a power consumption of less than 30 kW that remain "unknown" even after this allocation, the calculation was made using the emission factors of the "average fleet generator" of the < 110 m class. Due to the low number of ships and the low power consumption, the share in the emissions and the error rate associated with this procedure is low. It can be assumed, that either cruise ships without passengers or cargo ships or private yachts were located here.

The calculation is made for each individual ship by multiplying the number of kWh consumed by the respective emission factor of NO_X or PM belonging to the size class of the ship (see Tab. 7 & 8). The sum of the individual results for all ships is then calculated for each pollutant.

Ships	**Mooring time**	**Energy consumption**	**NO_X**	**PM**
Quantity	h	kWh	t	kg
531	8.593	467.499	2,6	93,0

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

After evaluating all the available data, the emission savings made possible by the OPS systems in Nijmegen are summarized in Table 25. Without OPS systems, NO_X quantities in the order of 2,6 t and PM quantities of 93 kg would have been emitted by the river cruise vessels in Nijmegen in 2019.

8. Emissions from ships at berth due to ship heating

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

Domestic heating systems usually have an output in the range of 20-40 kW. The system on the NRW laboratory ship "Max Prüss", for example, has an output of 37 kW. An estimation of emissions from ship heating systems can therefore be derived analogously to the procedure for small and medium-sized combustion plants. The bases for such derivation are maintained nationwide by the **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
Fine dust	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 report 2016 (LUBW, Landesanstalt für Umwelt, Baden-Württemberg) (6)

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

Based on these data, the following calculation for the emissions of the heating system on the Max Prüss 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

When estimating the emission quantities, 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 particulate matter 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 energy 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
PM_{10}	0,013	0,104	5,2	1,90

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

9. Outlook

The results presented show that the dimensions of the emissions of moored inland cargo, tanker and passenger vessels are lower than previously assumed.

In the future, the method described could be used to estimate more realistic emission quantities from ships at berth in inland ports. The basis for this could be the real ship numbers and berthing times derived from AIS data or the port operators' data on real ship traffic in the reference year under consideration. The emissions could then be estimated using these traffic figures and the emission factors of the "average fleet generators" derived within the framework of CLINSH.

Currently, the exact numbers, berthing times and berthing locations of the ships in the NRW ports are being determined with the help of the AIS data. The LANUV is planning to carry out more precise calculations for the ports of Duisburg and Neuss/Düsseldorf with the data bases presented and the exact determination of the berthing events based on the evaluation of the AIS data (location and time). The emissions of the moored ships determined in this way are geo-referenced as a point or line source.

The method described in this report forms an important basis for the calculation of emissions caused by moored ships in the port and is used by the LANUV in the emission calculations in the ports of Duisburg and Neuss/Düsseldorf.

Based on the results of the monitoring of the air quality in the port areas carried out within the framework of CLINSH and further surveys of the real emissions of the sailing ships (AIS data, onshore emission factors), the NRW emission register and the newly recorded or calculated emissions from ship and port operations, a precise root cause analysis of the measured air pollution (load shares of the various sources) is to be carried out.

The results will be published in the report sections:

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" and in the report section

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

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12. List of figures

13. List of Tables

14: Annex

Tab. 28 : **Example of the data on the energy consumption of the ships at the shore power facilities in Nijmegen**

Opera-tion	Start time	Duration	Location	Size class ship	Power consumption	Power demand
				m	kWh	kW
1	26-06-2020 15:54:00	20:23:07	Labyrinth	110	15	0,74
2	27-06-2020 13:19:13	187:20:31	Labyrinth	110	1898	10,13
3	02-01-2019 17:35:59	163:49:20	Grote Straat	110	8235	50,27
4	12-03-2019 19:25:33	15:18:34	Oude Haven	110	1383	90,34
5	17-03-2019 02:01:32	10:29:15	Oude Haven	110	1245	118,71
6	08-04-2019 07:04:38	16:46:56	Grote Straat	110	1762	104,99
7	09-04-2019 02:25:21	14:38:11	Grote Straat	110	1909	130,43
8	09-04-2019 10:33:41	5:05:27	Oude Haven	110	410	80,54
9	16-04-2019 02:24:24	15:26:12	Grote Straat	110	2051	132,87
10	20-04-2019 07:12:05	5:30:38	Oude Haven	110	537	97,45
11	26-04-2019 09:00:35	8:39:07	Grote Straat	110	284	32,82
12	02-05-2019 08:09:03	4:21:46	Labyrinth	110	123	28,19
13	03-05-2019 06:53:19	5:44:41	Grote Straat	110	405	70,50
14	04-05-2019 07:27:53	5:02:21	Labyrinth	110	113	22,42
15	06-05-2019 09:17:27	14:09:19	Grote Straat	110	1472	103,99
16	08-05-2019 21:01:39	19:12:36	Labyrinth	110	386	20,09
17	10-05-2019 14:52:14	13:09:06	Grote Straat	110	1131	86,00
18	12-05-2019 01:06:15	11:35:59	Oude Haven	110	1252	107,93
19	13-05-2019 23:28:36	12:36:28	Oude Haven	110	1151	91,29
20	14-05-2019 12:51:55	6:53:12	Grote Straat	110	807	117,18
21	26-05-2019 07:09:11	4:51:54	Oude Haven	110	570	117,16
22	03-06-2019 08:01:14	17:18:40	Grote Straat	110	1871	108,08
23	09-06-2019 01:52:54	10:26:02	Labyrinth	110	317	30,38
24	27-06-2019 07:09:33	5:14:06	Oude Haven	110	643	122,83
25	30-06-2019 03:30:30	7:51:39	Grote Straat	110	1055	134,21
26	30-06-2019 10:26:35	13:30:25	Oude Haven	110	1799	133,19
27	01-07-2019 06:57:49	16:22:19	Grote Straat	110	1880	114,83
28	01-07-2019 13:38:08	4:33:49	Oude Haven	110	367	80,42
29	06-07-2019 02:18:20	12:08:17	Oude Haven	110	1570	129,35
30	07-07-2019 01:15:17	11:48:29	Grote Straat	110	1192	100,95
31….	….	….	….	….	and so on	

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