Survey of the in-situ NO_x emissions from the boilers and burners on the Danish market

Trends and evolution

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INTRODUCTION and MAIN CONCLUSION

In 2013-2014 DGC has been working at evaluating as accurately as possible the overall real NO_x emissions from domestic gas boilers (**power below 120 kW**) on the Danish market and at foreseeing their evolution. The results of the work are to be used for discussion of the actual taxation of NO_x emissions of appliances in Denmark.

The method is based on:

- The detailed knowledge of the population of appliances: we know for each domestic installation:
  - The boiler type and model installed
  - The date of installation
  - The annual gas consumption
- A good knowledge of boiler emissions through laboratory tests
- A validated method (model) for the calculation of annual performances of boilers (including NO_x emissions)

The main conclusions are as follows:

- The emission factor for 2012 for Denmark is about 28 g/GJ, and it is continuously decreasing with the replacement of older technologies.
- A further reduction of the emission factor will come from the new Ecodesign regulation that will impose rather severe limits to NO_x emissions of gas boilers.

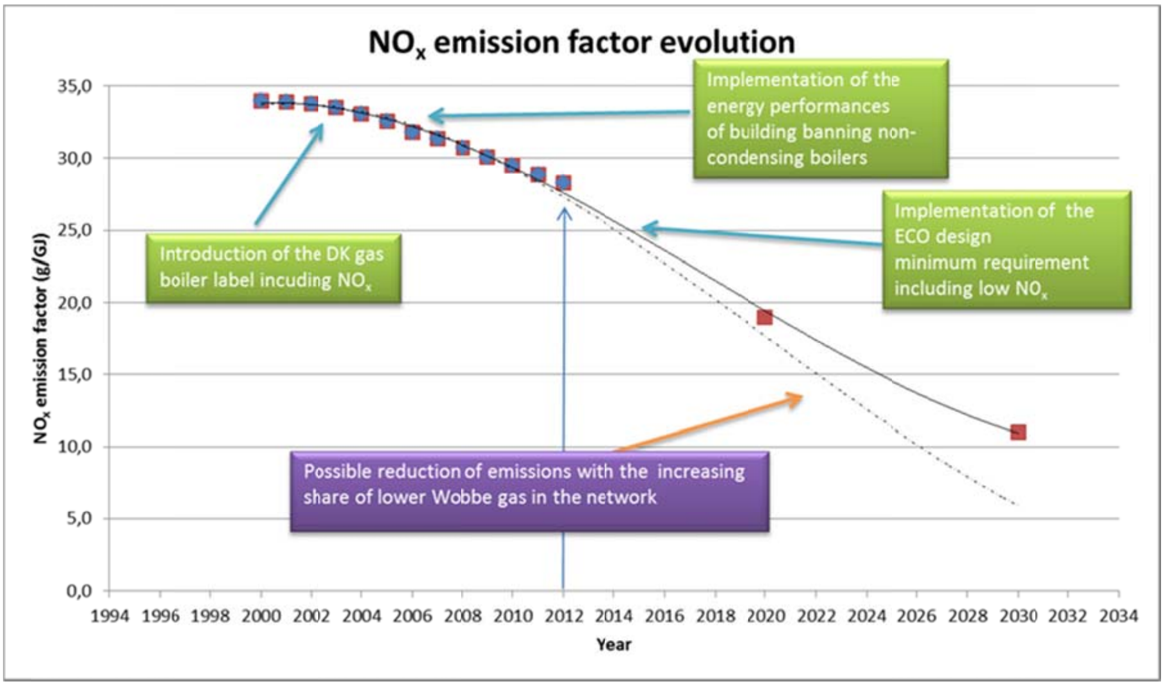


Figure 1 Overall results

In addition, the gas quality expected in the future in Denmark will result in further reduction of the emission factor.

- This means that all in all, we expect the emission factor to be in the range of 5 to 10 g/GJ within the next 15-20 years.

1. Overall method

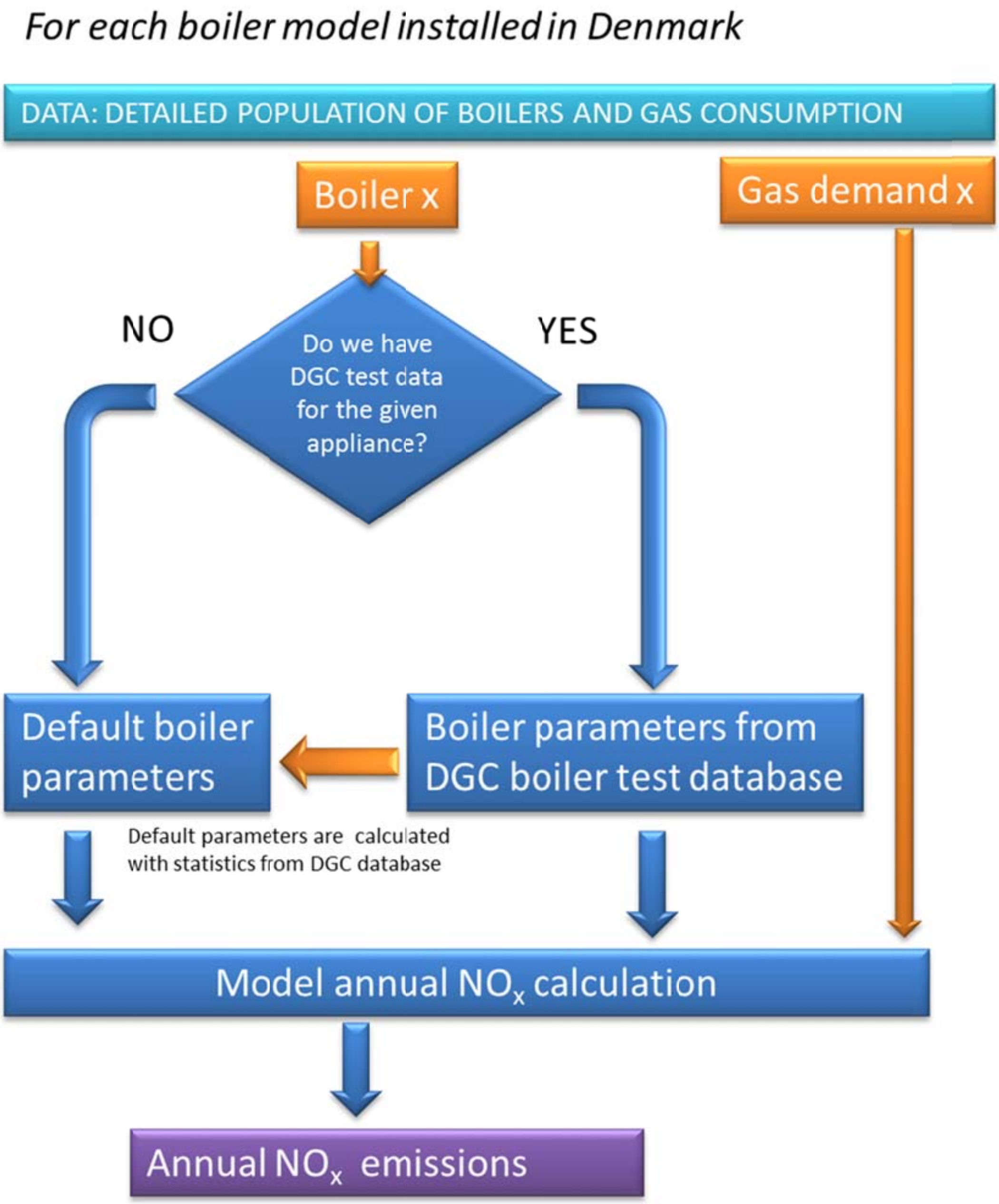


Figure 2 Method

A central part of the method is based on the existing knowledge on NO_x emission from gas appliances that we have from the testing done at DGC. For boilers identified that were tested at DGC, we can directly use test data to calculate annual emission (via a model). For boilers that were not tested, we will use average values based on statistics from our tested boiler database. We have calculated that despite the fact that we have a limited number of tests (compared to the number of models installed) we have data for almost 35% of the appliances installed because they represent a significant share of the existing installed boiler population.
The annual gas demand from each installation (house) is, finally, used to calculate the overall, annual NO_x emission from the given installation.

A few definitions

- **Pmin**: Minimum heat input of a boiler (modulating)
- **Pmax**: Maximum heat input of a boiler
- **Nominal emissions**: Measured in laboratories under standard test conditions (fixed and constant water temperature, load etc.)
- **Annual emissions:** Calculated from **nominal emissions,** taking into account the real operation of installation (climate, heat demand, gas, etc.)
- **Unit:** Unless otherwise specified the NO_x emissions are given in mg/kWh (heat input)

1.1 Identifying the appliance population in detail (by brand and model)

This is done with the existing databases from the gas distribution companies that include the main information we need to know:

1) Brand name and model
2) Year of installation
3) Annual gas consumption

The work consisted in compiling a database to get an aggregated picture of the population of appliances. This means that we do not calculate each individual boiler separately, but we calculate **each model** separately after having done the aggregation. Still, this represents about 2500 different models! The gas consumption used for each model is the average obtained with the given model of boiler.

1.2 Evaluating the nominal NO_x emissions of each brand and model

For domestic boilers the DGC database comprises about 150 boiler test results, and this database will be the main source of information.
It is not realistic to count on having reports and data for all appliances installed. Therefore, we will need to assess the NO_x emissions for a number of appliances for which no data are directly

available. For that purpose we used a simplified calculation/assessment model based on the knowledge we have on similar appliances.

NO_x emissions depend mainly on the burner type. So we made a classification **(= segmentation**) of appliances by burner type and make statistics on the results we do have.

1.3 Evaluating the total annual NO_x emissions

The data we have from DGC's laboratory are quite detailed. In general, we have nominal NO_x emissions measured at maximum and minimum loads of the boilers and at different water temperatures. For approx. 50% of the appliances we also have tests done with pure methane (the other tests were carried out with natural gas). So, in fact we can calculate annual NO_x emissions in various situations, taking into account the user heat demand, the installation (low-temperature or traditional), the control and even the variation of gas quality.

2. Segmentation (appliance classes)

In order to extrapolate results and data from appliances for which we have data to appliances for which we do not, we have used a segmentation of appliances that are supposed to have similar behaviour regarding NO_x emissions. The database was delivered with an existing segmentation from another project:

Group 1 Forced air burners

A   <120 kW   Air/Gas control
B   >120 kW   Air/Gas control

Group 2 Gas boilers

C & D   Floor standing and boiler with tank integrated (atm. burner)
E & F   Trad. boiler (atm. burner)
G & H   Trad. boiler Gas/air control
I   Condensing boiler   Atm. Premix
K   Condensing boiler   Gas/air adjustment with injector change
L   Condensing boiler   Gas/air control

Figure 3   Segmentation appliances classes

It should be noted that the original segmentation included the flue gas evacuation system, which is not a relevant parameter for NO_x emissions. Therefore, those categories or classes are combined (e.g. C&D).

3. Nominal emissions measured at the laboratory and annual emissions

The actual (annual) emissions of installed appliances are rather different from the **nominal emissions** of appliances measured at the laboratory. Nominal emissions are measured at the laboratory under steady-state conditions. In reality, the boiler starts and stops, modulates etc., and so emissions vary depending on the conditions of installation, climate, heat demand etc.

Three main operating conditions are influencing the NO_x emissions

- Water temperature (in and out of the boiler)
- Load
- Gas composition

NO_x emissions will also depend on other factors, such as air temperature, humidity, but in general they have less influence.

The water temperature influences the NO_x emission by influencing the flame temperature; the magnitude of the influence varies from boiler to boiler. But NO_x emissions increase with water temperature. The reduction of NO_x emissions is about 4% when running boilers at the water temperature set 40/60°C instead of 60/80°C.

But the most influential factor for NO_x emissions is the load, and boilers that modulate have in the vast majority of cases much lower emissions in the lowest range of modulation compared to the maximum range. The average ratio of emissions is about 3 between the two operating conditions! (3 times less emissions at Pmin compared to Pmax.).

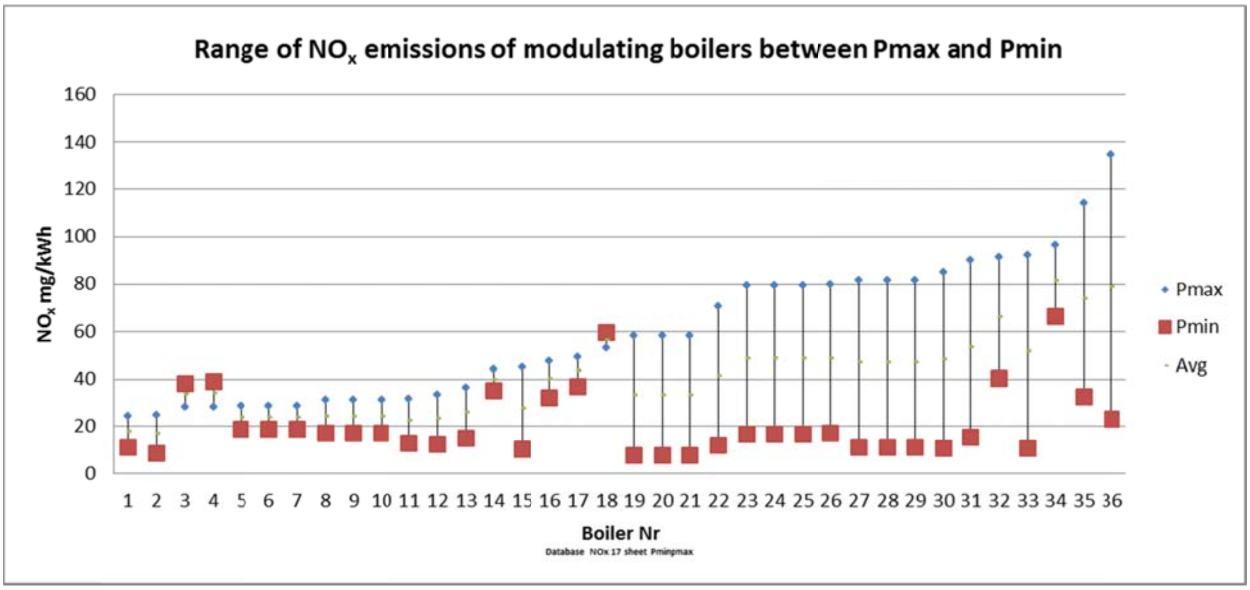


Figure 4 Influence in per cent on NO_x emission increase from Pmin to Pmax of 36 different modulation boilers. Please note some "outliers" (emissions slightly larger at Pmin for three boilers).

The gas composition is another important factor. Tests at DGC are done with natural gas from the grid and with pure CH_4, so we have data to model the impact on NO_x of gas quality change.

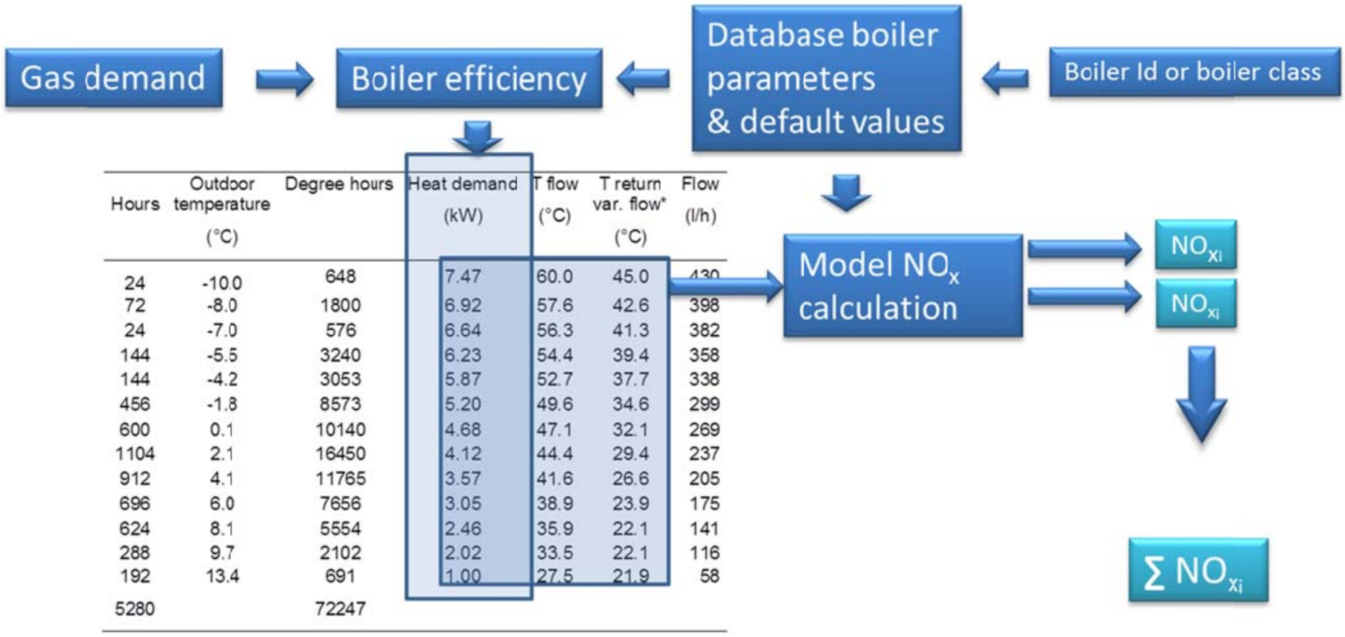
4. Calculating annual emissions

4.1 Real operating conditions for boilers – method overview

The gas used for the tests, for which data are used in this report, is natural gas from the grid. The gas quality can be considered as rather constant for the period of testing covered by the database used and can also be considered as representative for the real operation of the boiler.

Nominal emissions are measured at the laboratory under steady-state conditions. This means that the water temperature, the water flow and the gas flow are constant.
In reality, the boiler starts and stops, modulates etc., and NO_x emissions will vary with the various influences as described in the previous section.

The real operating conditions for boilers will mainly depend on the **heat demand** (building size and insulation, climate, sanitary hot water need) and **installation** (heat emitter type and size, etc.). Other parameters linked to user habits will also influence the operating conditions, but this cannot be taken into account and will have less influence compared to the above.



Hours	Outdoor temperature (°C)	Degree hours	Heat demand (kW)	T flow (°C)	T return var. flow* (°C)	Flow (l/h)
24	-10.0	648	7.47	60.0	45.0	430
72	-8.0	1800	6.92	57.6	42.6	398
24	-7.0	576	6.64	56.3	41.3	382
144	-5.5	3240	6.23	54.4	39.4	358
144	-4.2	3053	5.87	52.7	37.7	338
456	-1.8	8573	5.20	49.6	34.6	299
600	0.1	10140	4.68	47.1	32.1	269
1104	2.1	16450	4.12	44.4	29.4	237
912	4.1	11765	3.57	41.6	26.6	205
696	6.0	7656	3.05	38.9	23.9	175
624	8.1	5554	2.46	35.9	22.1	141
288	9.7	2102	2.02	33.5	22.1	116
192	13.4	691	1.00	27.5	21.9	58
5280		72247				

Figure 5 Annual emission calculation method

The Danish climate can be simply described in a table showing the outdoor temperature and the number of hours, for which the given temperature difference occurs (example 24 hours at -10 °C). 13 periods are sufficient to describe the Danish climate in a synthetic way.
For a given house the outdoor temperature is used to calculate the power needed or heat demand to get an ambient temperature (typically 18 °C). With the gas demand of a given customer and boiler annual efficiency, we can calculate the heat demand (and so the power required from the boiler) for each of the 13 periods. The water temperature and flow are calculated considering a standard well-designed radiator installation. The heat demand, the water temperature and flow are what we call “operating conditions”.
They are used with boiler data to calculate NO_x emissions (NO_{xi}) for each of the operating conditions during the 13 periods. The annual emissions are calculated by summing up the 13 periods’ emissions.

4.2 Emissions below the modulation range of modulating boilers and for non-modulating boilers

The modulating boilers are working close to Pmin when working in on/off-mode. This is a very important point as emissions depend very much on the load, and we have shown earlier that the average emissions at Pmin are about 3 times lower compared to Pmax (this applies for the production of the same heat).
So the control of the boilers out of the modulation range is a determining parameter. Most of the boilers have quite complex control algorithms that are not made public by the manufacturers; however we have made a number of investigations including analysis of field tests to define the way to treat this question.
In the framework of a contract with the EU [6], tests in a real building were made in the beginning of the 2000s with modulating boilers. We carried out measurements over several months, which allowed us to check and fine tune an acceptable approach for the operation and emission calculation of the modulating boilers during on/off periods.
The analysis of the test extrapolated to 40 modulating boilers of DGC’s database allowed us set up a model, and the following empirical formula:

Emissions during start-stop = Emission at Pmin + 5% of emission at Pmax.

More details about the models used can be found in [7].

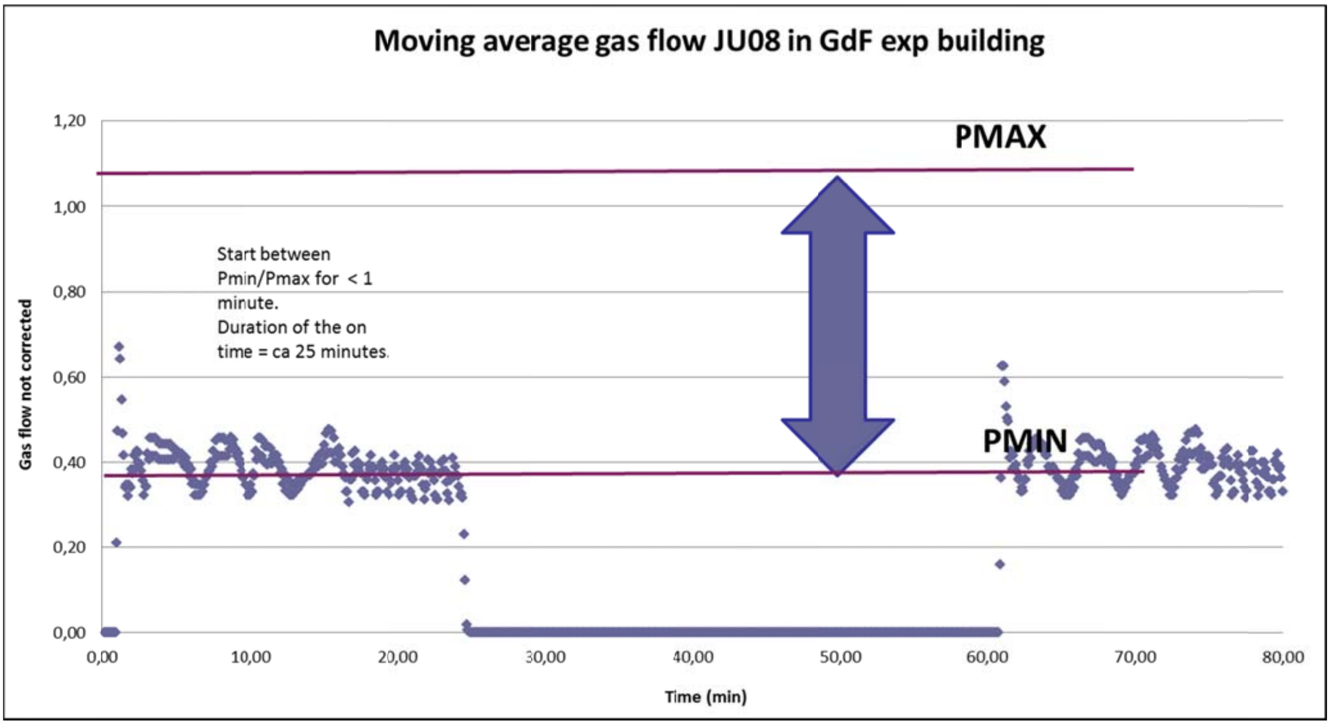


Figure 6 Example of control of a modulating boiler when the heat demand is out of the range of modulation

4.3 Emissions for hot water production

These emissions are also included in the calculation. The average sanitary hot water need is about 2000 kWh/year in Denmark.

5. Statistic results from available tests at DGC. Making default values by class to be used for the appliances, for which no tests results are available

For boilers, the emissions (**nominal emissions)** have been measured during systematic testing at DGC since the beginning of the 90s. The test results are used for informing the end users and installers via the Danish gas boiler label, articles etc.

The NO_x emissions are measured under the following conditions:

With natural gas from the grid:

Pmax 60/80°C Pmax 40/60°C
Pmin 60/80°C Pmin 40/60°C

With pure methane:

Pmax 60/80˚C

The following table shows the aggregated result of the statistical analysis of the test data.

Number of samples for each class & test

CLASS	Pmax 60/80 ˚C	Pmax 40/60 ˚C	Pmin 60/80 ˚C	Pmin 40/60 ˚C
CD	10	10	5	1
EF	17	17	14	2
GH	4	4	4	0
I	5	5	1	0
K	41	37	38	10
L	24	24	24	17

NO_x (mg/kWh)

CLASS	Pmax 60/80 ˚C	Pmax 40/60 ˚C	Pmin 60/80 ˚C	Pmin 40/60 ˚C
CD	119,4	109,5	41,7	11,1
EF	186,2	177,0	101,1	14,0
GH	239,3	231,5	160,4	0,0
I	74,5	68,2	5,5	0,0
K	94,3	96,0	48,0	27,8
L	58,2	57,1	28,2	27,0

STD

	Pmax 60/80 ˚C	Pmax 40/60 ˚C	Pmin 60/80 ˚C	Pmin 40/60 ˚C
CD	77,2	67,9	52,0	0,0
EF	101,6	98,2	55,0	1,0
GH	48,3	44,6	18,5	0,0
I	77,7	72,4	0,0	0,0
K	65,7	65,8	45,2	16,7
L	24,9	27,3	21,3	18,3

databaseNOX17- sheet statistic by class or

(The cases, where we either have no data or only small samples, are marked with yellow)

Figure 7 Statistics on NO_x emissions in mg/kWh per boiler class

From the above we can use the model to calculate the annual emissions, e.g. here for a 10.000 kWh heat demand.

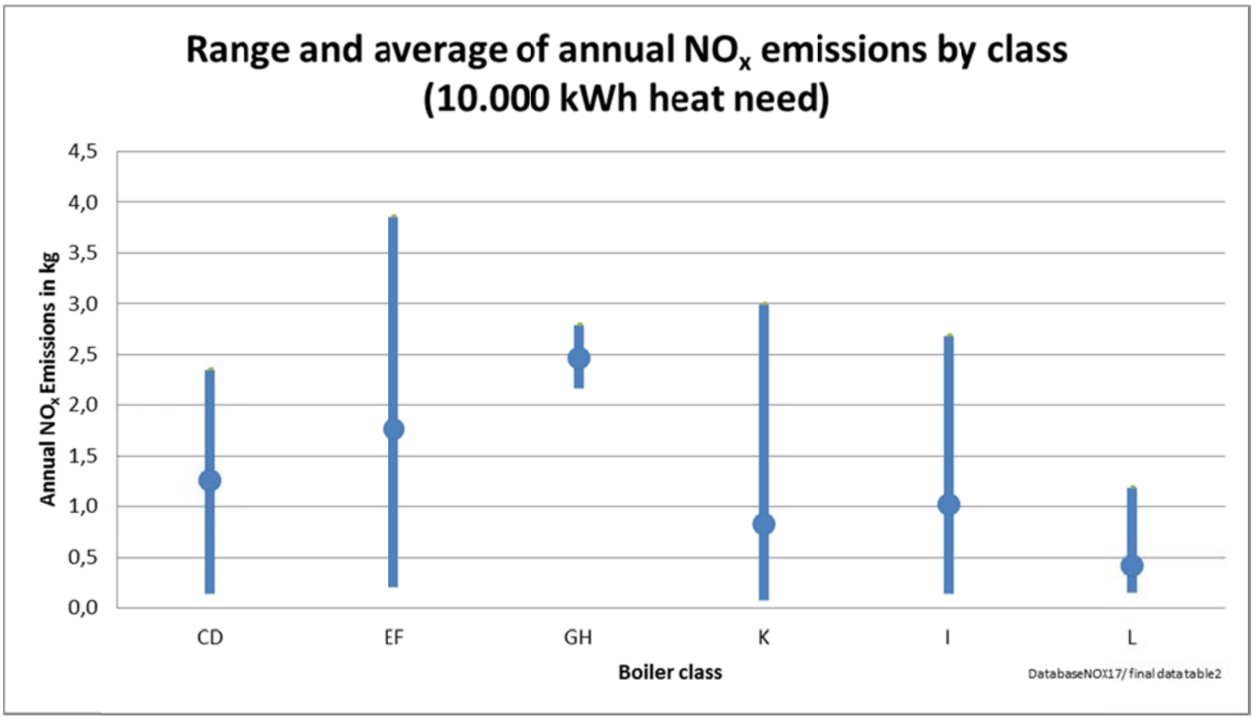


Figure 8 *Range of variation of NO_x emissions in kg/year for various boiler classes and for a heat demand of 10.000 kWh/year*

The results show that segments are not very homogenous. Still, there is a difference between segments that makes it worth to differentiate them instead of using a unique and global average for all classes.

6. Calculation of annual emissions and global NO_x emission factor. Linear interpolation method.

For each boiler model in the database, NO_x emissions are calculated for different annual gas consumptions.

The figure shows an example for a boiler of the variation of the annual NO_x emissions with the gas used (the quantity of gas used is known for each installation). For simplification's sake we will assume that the NO_x emissions are a linear function between two points, 10.000 kWh and 30.000 kWh, which is the range where probably 90% of the Danish installations will be found.

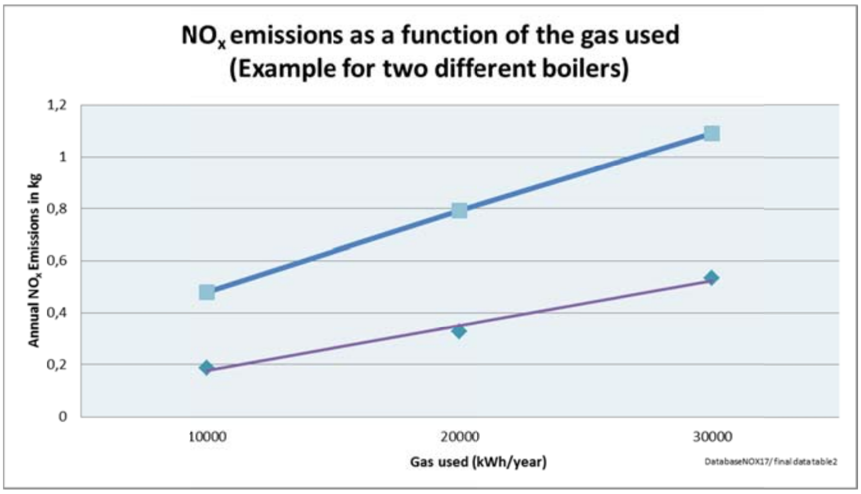


Figure 9 Annual emissions (in kg NO_x) expressed as a function of the gas used (heat demand + hot water demand)

The table of **default average values** is used for the interpolation when we have to calculate emissions from boilers, for which we do not have test results. Note that when the boiler is tested, we use the real value measured and not the class average.

	Heat input (kWh):		
	10000	20000	30000
Class	AVG in kg/year		
A	0,91	1,61	2,32
CD	1,26	2,24	3,22
EF	1,77	3,12	4,39
GH	2,47	4,31	6,06
K	0,83	1,52	2,22
I	1,02	1,81	2,60
L	0,42	0,77	1,16

Figure 10 Average annual emission by class as function of the gas used (heat input) (in kWh)

7. Calculation of NO_x emissions for the whole population of appliances, now, in the past and in the future

7.1 Overall emission factor obtained

Each of the 2500 lines of our database represents an individual appliance model (manufacturer + model of the appliance). For each appliance model, we have the class, the number installed and the average gas consumption.

The actual emission for a boiler type is obtained by calculating (interpolation of) the emissions for the given gas consumption (= heat input).
For each boiler type (= line in the table) we calculate total emissions in g and total gas used or heat input in GJ. The calorific value of the gas used here is obtained from Energinet.dk (Data Gas 2012).
1 m^3 = 10,985 kWh (Hi)
Finally, total emissions and heat input are summed up and the ratio total NO_x emission/total heat input is calculated to obtain a figure in g/GJ.

With the method described we have obtained a final figure of 28.2 g/GJ (for 2012).

7.2 Future evolution of the population of appliances

The work is based on data from year 2012. The vast majority of old appliances (class CD; EF; GH) are replaced by the newest appliances (Class I, K,L) with the lowest emissions. It should be noted that some of these old appliances are now banned form the market (non-condensing boilers).

Also, in 2004 a gas boiler label was introduced in Denmark, and the label had an immediate and very significant effect on the appliances sold on the market, as shown in the figure below.

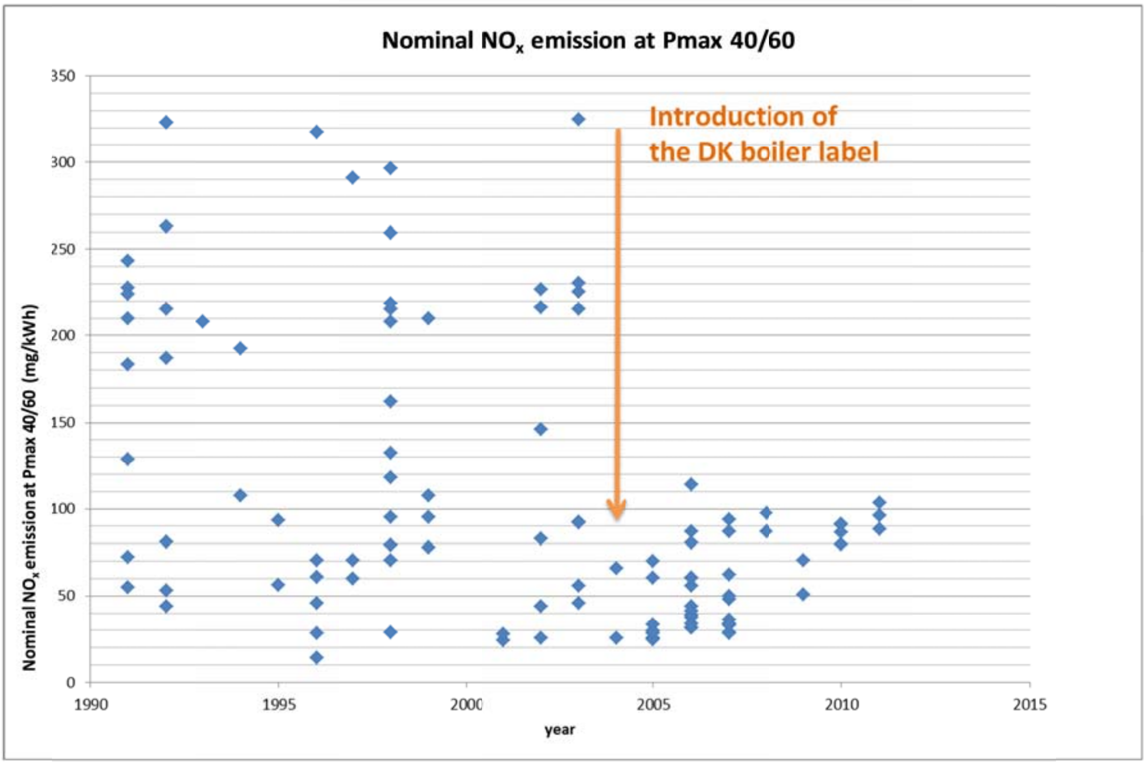


Figure 11 Nominal emission evolution after the introduction of the boiler label in Denmark

The future will see further improvements because of the application of the ecodesign minimum requirements that are setting new and very severe limits for NO_x emissions.
As a result of the replacement of boilers, real emissions in 2013 are already lower than the ones calculated on the basis of the year 2012.

The “new” technologies (I, K, L) are representing 46 % (expressed in gas volume used) of the population of boilers installed (year 2012). In the long term, the other, older classes will disappear in favour of the latest technology, and, globally, NO_x emissions will decrease.

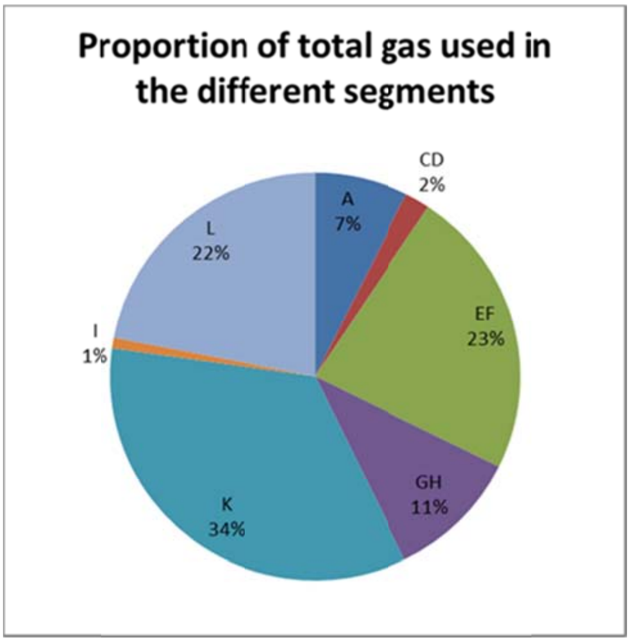


Figure 12 Segment share on the exiting market (2012) - by gas volume used

We know that about 16,000 (conservative figure used for the calculations to come) to 20,000 gas boilers are replaced annually in Denmark. With this rate we can calculate the evolution of the emissions.

7.3 Scenarios for the evolution of NO_x emission factors

We have calculated 3 cases:

1) The **present** situation (based on 2012 data).
2) **2020**. With the hypothesis that only 10% of the old technologies will still be there (this is very probable with the actual boiler replacement rate), and that the older appliances are replaced by one of the present technologies (so we use the class “M”). The actual total heat input is assumed constant.
3) **2030 or long term** will see a market with only appliances respecting the present directive’s NO_x levels or better. We have used the hypothesis that all appliances are in a

new class N (with the same performance as the actual best on the market = Class L). This can be discussed, but it is quite realistic: On the one hand **not all appliances will be replaced** (the indestructible ones), making the real figure of emissions a bit higher, and on the other hand there will be a technological evolution and new and more severe requirements (compared to actual known Ecodesign requirements) for boiler emissions (making the emission lower). So all in all, the hypothesis is reasonable. The actual total heat input is again considered constant.

Present situation			
		Today	2012
	A	B	A*B
	g/GJ	GJ	g
A	22	2105135	4,71E+07
CD	31	561292	1,75E+07
EF	43	6530947	2,83E+08
GH	60	2974294	1,78E+08
K	21	9803410	2,06E+08
I	25	240502	6,04E+06
L	11	6251621	6,69E+07
M	18		0
N	11		
Total		2,85E+07	8,05E+08
		Factor	28 g/GJ

Scenario ca 10% annual removal of old by M. It will take ca 8 years to remove the old. 10 % remains			
			2020
	A	B	A*B
	g/GJ	GJ	g
A	22	210514	4,71E+06
CD	31	56129	1,75E+06
EF	43	653095	2,83E+07
GH	60	297429	1,78E+07
K	21	9803410	2,06E+08
I	25	240502	6,04E+06
L	11	6251621	6,69E+07
M	18	10954501	1,96E+08
N			
		2,85E+07	5,28E+08
		Factor	19 g/GJ g/GJ

All are L or better			
			2030
	A	B	A*B
	g/GJ	GJ	g
A	22		
CD	31		
EF	43		
GH	60		
K	21		0,00E+00
I	25		0,00E+00
L	11		0,00E+00
M	18		0,00E+00
N	11	28467201	3,05E+08
		2,85E+07	3,05E+08
		Factor	11 g/GJ

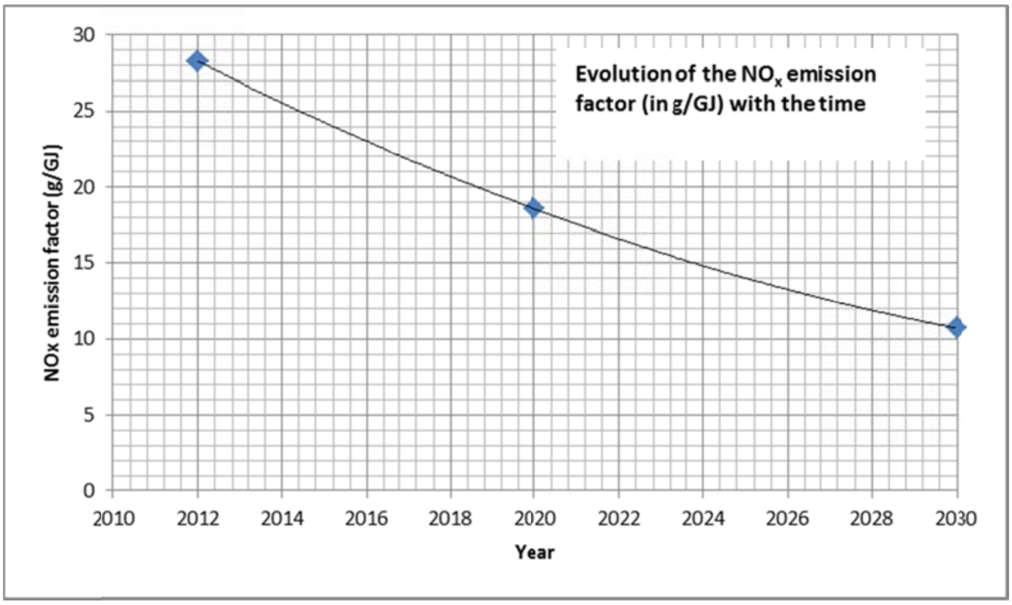


Figure 13 Expected evolution of NO_x emission factor in the future 20 years

This means that when most of the boilers are replaced (avg. lifetime = about 20 years) the emission factor will be **about 10 g/GJ.**
Technological evolutions may even bring the real figure below 5 g/GJ.

See details on the scenarios and assumptions in [7].

7.4 Gas quality change

The gas quality change and future gas quality in Denmark may also have a considerable influence on the emission factor. A richer gas (e.g. high-wobbe LNG) will bring higher emission factors, whereas gas coming closer to CH_4 (as Russian gas) will bring lower emissions.

		Danish gas	Russian H	North Sea	Libya
Hi (0/15)	MJ/m^3	37	34	36	40
Em. Fact.	g/GJ	27	22	24	31
Difference (reduction or increase)		0 %	20 %	10 %	-14 %

(Hi value source K Altfeld [5])

The above table was calculated with a linear variation of emission factor with the calorific value and with the hypothesis that emissions are 20% lower with Russian gas (closer to CH_4) compared to actual Danish gas.

The most plausible scenario today is more gas from Russia as it has already occurred during the last few years resulting in a **decrease of the emission factor**.

8 Conclusion

The work done shows that the emission factor of 2012 for Denmark is about 28 g/GJ, which is below the value used for the taxation (40 g/GJ).
With the replacement of older technologies with especially the modulating boilers (that have much lower emissions compared to most of the existing non-modulating boilers) the emission factor is rapidly decreasing and we estimate that it is probably between 25 and 26 g/GJ in 2014.
It will further decrease in any case, but the new Ecodesign regulation that will impose rather severe limits to NO_x emissions of gas boilers will bring another acceleration of the decrease in the next few years. This will favour the development of new low-NO_x technologies on the heating market.

Finally, the gas quality expected in the future for Denmark will result in a further reduction of the emission factor. This means that all in all, we expect that the emission factor will be in the range of 5 to 10 g/GJ within the next 15-20 years based on the rather solid hypothesis.

We can also take it for granted that new measures or new set of minimum requirements will be adopted again within the next 15-20 years, and these will further lower the figure given.

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