IEA Bioenergy
Technology Collaboration Programme

Nitrogen flows in biomass combustion systems

Part II: Options for maximising reactive nitrogen capture and case studies

May 2025

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May 2025

ISBN 979-12-80907-74-5

Summary

This is the second report of IEA Bioenergy on the topic of reactive nitrogen (Nr) flows in biomass combustion systems. This study was done in the period 2023-2024 as a follow up activity of a first parametric study on the same topic to provide more in-depth understanding of relevant formation mechanisms for reactive nitrogen during combustion, and illustrate the system perspective with additional examples from real life combustion plants.

As already elaborated in the first report, reactive nitrogen from various societal activities may lead to unwanted eutrophication when deposited on nature conservation areas, changing vegetal habitat in an undesired manner. Deposition of nitrogen may not only lead to eutrophication, also the pH is lowered.

There is however a fundamental difference between reactive nitrogen emissions originating from biomass combustion and other sources like engines or fertilizers. While the NO_x emission from solid biomass combustion is typically only related to the nitrogen contained in the fuel and can never exceed that level in practice due to the relatively low combustion temperatures, NO_x emissions formed from fossil sources typically result in additional reactive nitrogen that was not in our ecosystem before. In practice, only a fraction of the reactive nitrogen absorbed in biomass fuels is released again as reactive nitrogen during combustion. In a system perspective, biomass combustion can thus act as a net sink of reactive-nitrogen, while fossil based sources are generally responsible for eutrophication.

There are however differences in effectiveness of the nitrogen capture in fuel, release of reactive nitrogen during various combustion systems, flue gas cleaning technologies applied and flue gas distribution pathways. The previous study showed how reaction pathways from fuel nitrogen to NO_x may be influenced in the combustion system, by using proper combustion technologies, flue gas cleaning etc.

In this follow up study, additional attention is given to the conversion of fuel nitrogen to NO_x and how this reaction can be minimised. In addition, case studies are provided to illustrate how the impact of the nitrogen cycle can be minimised in practise. By providing more in depth understanding with this report, the authors hope to contribute to the societal debate about the role of biomass combustion systems in the nitrogen cycle in a positive manner.

Contents

1. Introduction

1.1 FORMATION AND ENVIRONMENTAL EFFECTS OF NITROGEN SPECIES

Reactive nitrogen emissions from various processes in society have become a significant environmental issue in several countries around the world. In contrast to unharmful elemental nitrogen (N_2) that is present in abundance as the main component of the ambient air we breathe, reactive nitrogen species such as ammonia (NH_3) and nitrogen oxides (NO_x) are of increasing concern due to their negative effects on air quality and unwanted eutrophication of nature conservation areas.

In this respect, Ammonia (NH_3) is typically formed from animal husbandry and the use of NH_3-based fertilizer applications, but it may also be released from industrial processes, vehicles and volatilization from soils and oceans. Ammonia is a gas that also contains reactive nitrogen, and therefore has similar effects on our ecosystem as NO_x in terms of eutrophication and acidification.

Nitrogen oxides (NO_x) are oxidised forms of nitrous gases such as nitrous oxide (N_2O), nitrogen monoxide (NO) and nitrogen dioxide (NO_2). Here, N_2O or laughing gas is formed mainly in cases of intensive agriculture, if there is insufficient oxygen available for full oxidation of nitrogen compounds. It is also a strong greenhouse gas (300 times the GHG warming effect of CO_2). As it is converted back to NO using ozone in the stratosphere, it also contributes to depletion of the ozone layer.

NO and NO_2 are formed and emitted during various combustion processes, such as happening in residential and industrial facilities and road transport. NO_X contributes to the formation of ozone and particulate matter (smog) and may thus deteriorate local air quality. Upon atmospheric chemical reactions, it may also be deposited as acid rain on nature conservation areas and thus lead to unwanted nitrogen enrichment or eutrophication.

The presence of additional reactive nitrogen from airborne ammonia has a direct toxic effect on slow-growing species such as lichens and mosses that originally live in our natural environment, leading to increased vulnerability to drought, frost damage and pests. Excess nitrogen also encourages the growth of nitrogen-loving species such as grasses and nettles (see cover photo), which are fast growing and which outcompete the original vegetation. In coastal areas, it may cause excessive growth of phytoplankton, microalgae (e.g., epiphytes and microphytes), and macroalgae (i.e., seaweed). These, in turn, can lead to other impacts such as loss of subaquatic vegetation, change in species composition, coral reef damage, low dissolved oxygen, and the formation of dead zones (oxygen-depleted waters) that can even lead to ecosystem collapse if nitrogen deposition becomes really severe. For every individual ecosystem, one can thus define a critical load as a quantitative estimate of exposure to reactive nitrogen (in mol/ha/year), above which significant harmful effects on specified sensitive elements of the environment may occur.

In order to mitigate their negative effects on ambient air quality, emission limits for NO_x and NH_3 are often imposed by national or regional authorities for various applications, including biomass combustion. This report shows how this NO_x is formed during the combustion process, and what can be done to mitigate nitrogen emissions. For three specific combustion plants, the nitrogen balance is shown to illustrate the environmental impact.

1.2 NO_X EMISSION FROM BIOMASS COMBUSTION

With regard to NO_x emission from combustion processes, there is a fundamental difference between combustion of fossil fuels and biomass fuels. During combustion of fossil fuels, NO_x is predominantly formed from oxidation of elemental nitrogen present in combustion air (N_2) due to relatively high combustion temperatures far above 1000°C. The so-called thermal NO_x leads to additional reactive nitrogen in the ecosystem. During combustion of solid biomass however, combustion temperatures are typically much lower than 1000°C and NO_x is predominantly or completely formed from oxidation of part of the nitrogen species that are already present in the biomass fuel. The amount NO_x formed from fuel nitrogen during the combustion process depends on

- the amount of fuel nitrogen (more fuel nitrogen implies more NO_x)
- the amount of oxygen available to oxide nitrogen species to NO and (to a lesser extent) NO_2. Here, more oxygen also implies more NO_x
- The necessity to increase temperature and oxygen to achieve full combustion of organic compounds and achieve low CO concentrations.

After the formation of NO_x, there are different methods (catalytic and non-catalytic) to reduce its emission in the flue gas. Overall and depending on the combustion and flue gas cleaning technologies used, no more than about 10-50% of the nitrogen contained in wood fuels is emitted as NO_x. As the fuel nitrogen species were originally formed during the growth of the plant or tree by capturing reactive nitrogen from the soil, the energetic use of this biomass results in a net negative N_r balance. This balance may be less favourable for nitrogen fixing species that are able to capture molecular nitrogen from the air, or if nitrogen containing fertilisers were applied to grow this biomass fuel, since these are formed from molecular nitrogen using the Haber Bosch process.

To illustrate the system perspective, three cases are presented hereafter.

2 Case studies

This section describes three cases where the nitrogen cycle was assessed:

1. A 500 kW wood chip fired boiler in a rural setting in the northern part of the Netherlands
2. A 3.2 MW wood chip fired boiler in an urban setting in western part of the Netherlands
3. A straw fired CHP plant for district heating in Slagelse, Denmark

2.1 CASE 1: SMALL SCALE COMBUSTION OF WOODY BIOMASS IN MARUM, NETHERLANDS

2.1.1 Background

In the northern village of Marum in the Netherlands, the company Bio Forte operates a 500 kWth wood chip fired boiler for district heating in the village. This installation is in use since 2012. The boiler is fuelled with wood chips that originate from sustainable landscape maintenance that is done by farmer cooperatives in the characteristic landscape around Marum. Here, woody windbreaks serve since centuries to separate grasslands where cattle is held by farmers. While in past centuries the wood originating from these woodlands was used for heating by households and small industries, the need for using this wood was diminished in the 1970’s with the introduction of inexpensive natural gas. As a result, wood produced in these windbreaks from landscape maintenance was no longer valued, and often piled up and burned, creating unwanted air pollution in the areas.

Figure 1: The typical landscape around the village of Marum consist of grasslands, separated by woody windbreaks

In 2008 the idea arose to introduce a wood chip fired boiler for district heating in the village of Marum, where the residues can be used to replace natural gas of villagers. As a result, it was no longer needed to burn wood residues in the open field. Since the boiler plant was taken into operation in 2012, farmers chip these residues and deliver them to a covered fuel storage, close to the village. From here, the fuel is delivered to the underground fuel storage of the biomass boiler plant, which is located in the heart of the village.

By burning the wood residues in a biomass boiler instead of in the open field, a solution was found for the local air pollution problem, while at the same time stimulating the local economy by creating additional jobs and income for farmers and others, and avoiding the use of more expensive natural gas for heat customers.

Figure 2: The annual maintenance of the woody windbreaks is carried out in farmers cooperatives.

In the covered fuel storage, wood chips are typically stored for about 3-9 months until they are used in the boiler. This filling is done approx. 3 times a week by a worker from the local municipality, operating a small truck (depending on the heat demand).

The boiler plant consists of a moving grate furnace with reliable hydraulically fed fuel supply (produced by Binder, Austria). The flue gas cleaning consists of only a cyclone to reduce dust emission to a level below 100 mg/m^3 @ 11% O_2. This was required when the plant was constructed in 2012. No de-NO_x system is installed to remove NO_x.

Figure 3: The biomass plant in the centre of the village of Marum, with underground fuel storage and mostly underground boiler room.

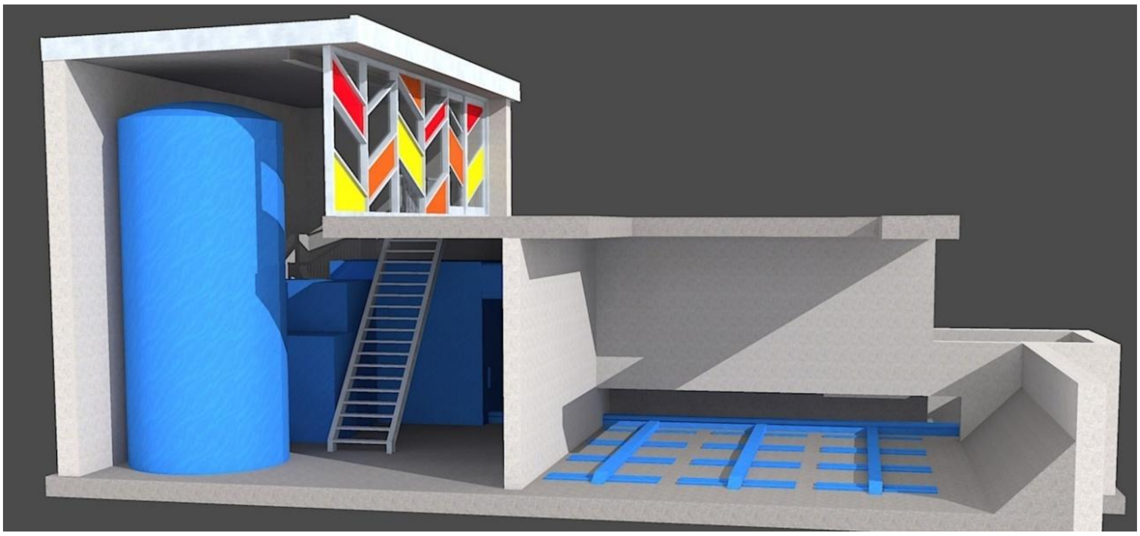

Figure 4: 3D drawing of the biomass plant, with underground fuel storage and mostly underground boiler room. The installation contains a 20 m^3 heat storage buffer to smoothen operation, thereby reducing emissions.

To keep the operational costs low, collaboration with local actors was maximized. The local installer was involved for the hydraulic and electrical installation in the boiler room and at all customers. The technician from the open-air swimming pool was made responsible for operations, and a truck driver from the local municipality ensured timely refilling of the fuel bunker. Additionally, about 10 people from deprived backgrounds have become involved in the fuel supply. A new boiler house was built next to the open-air swimming pool to accommodate the bioenergy plant. To minimise the investment, the boiler capacity was minimised, while short peaks in heat demand are delivered from the heat buffer of 20 m^3. The plant is equipped with reliable hydraulic fuel feeding. The gas-fired boiler, previously used to heat the swimming pool, is now used as peak and backup boiler.

A full plastic pipe heat distribution network (Calpex) was installed with a total trench length of about 1.5 km and 10 consumers, saving approx. 250.000 Nm^3 of natural gas, equivalent to 200 households. While the open-air swimming pool only requires heat in summer time, the other consumers predominantly require heat in winter time. This results in a high number of full load hours for the installation. In 2018 the district heating network was expanded to include a newly built housing area and a commercial building. Other plans for expansion of the network and repowering of the production plant are currently (2024) being developed together with the local municipality.

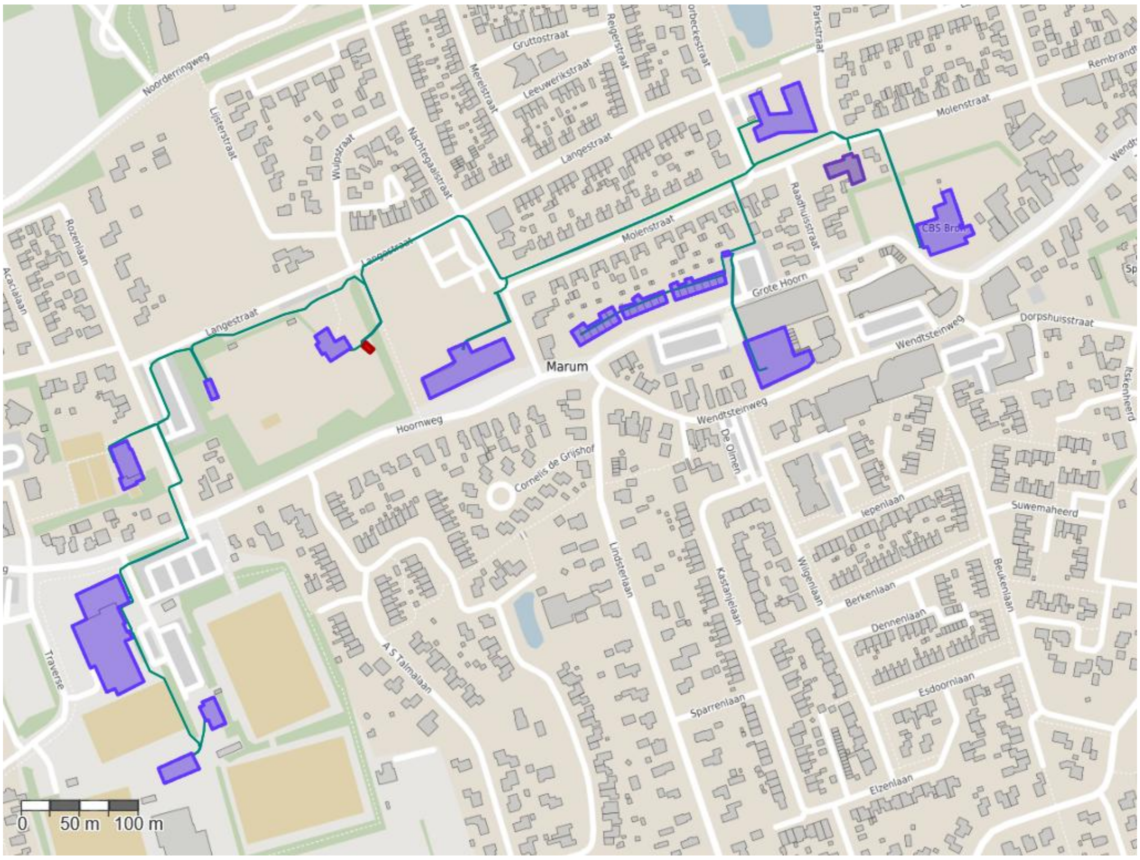

Figure 5: Map of the small scale district heating network in Marum, with 12 larger utility buildings and 19 private households. The location of the boiler plant is indicated in red.

2.1.2 Net nitrogen emissions from the project

The nitrogen balance of the plant was established for the year 2013. This was the year when the lowest outside temperatures were observed and the highest heat demand occurred. It also formed the basis of the calculations for the environmental permit procedure.

In 2013, the buildings attached to the district heating network would amount to 7,229 GJ, excluding 1,706 GJ of heat losses of the district heating network. This means that 9,159 GJ of heat production was required from the biomass heating plant (including backup). If this heat would be generated using the previously existing gas fired boilers, their emission would amount to **158 kg of NO_x**, assuming that all boilers would comply with the national emission standard for gas fired boilers in utility buildings (Activiteitenbesluit, 70 mg/m^3 @ 3% O_2). As there were no emission measurements available and several boilers were installed before the directive was imposed, this seems a conservative assumption.

In addition to emission from natural gas consumption, in the previous situation there were also emissions from the wood residues that were burned in the open field. According to [Urbanski, 2014], the NO_x emission factor for forest fires varies between approx. 1.0-2.1 g NO_x/kg of wood, depending on forest type and whether it is a prescribed fire or a wildfire. For the amount of wood burned in the plant (assumed here is 872 ton/year), this would amount to **872-1,831** kg of NO_x per year.

In real life, 9,159 GJ of heat was to be produced using the biomass heating plant. This was done as shown in Table 1. Of this amount of heat, 8629 GJ (94.3%) was produced by the biomass boiler using 8629 kgs of wood, the remaining 530 GJ was produced using the gas fired boiler. The gas boiler needs to comply with the already mentioned 'Activiteitenbesluit'. This leads to a NO_x emission of only **12 kg of NO_x per year**. The biomass plant needs to comply with an emission limit of 270 mg/m^3, which was also demonstrated during compulsory emission measurements shortly after commissioning. This leads to an emission of **1,004 kg of NO_x** excl gas fired boilers, or 1,016 kgs incl gas fired boilers.

Table 1 Details of heat production and NO_x emission from the biomass heating plant

		Biomass boiler	Gas fired boiler	Total
Share in heat delivery	% on annual basis	94.2%	5.8%	100%
Biomass fuel input	kW fuel	556	538	1,093
Thermisch vemogen	kW th	500	500	1,000
warmteproductie	GJ/jaar	8,629	530	9,159
Number of full load hours		4,794	294	
Biomass consumption	ton/year	872		
Natural gas consumption	m^3/year		20,000	
spec fuel consumption	kg biomass or m3 natural gas per kWh of heat	0.36	0.13	
spec flue gas production	m3 flue gas@6% O2 per kg fuel	4.19	10.65	
NO_x emission	mg/m^3 @ 6%O_2	275	58	
NO_x emission factor	mg/kWh_{th}	419	78	
	g/GJ of fuel	129	19.6	
NO_x emission	kg/year	**1,004**	**12**	**1,016**

Table 2 shows a comparison of the former situation with the new situation.

Table 2 An indicative comparison the NO_x emission before and after realization of the biomass fired district heating network

Former situation	NO_x emission (kg/year)	New situation	NO_x emission (kg/year)
Wood residues burned in open field in the area around Marum	872-1,831	Wood chips burned in biomass boiler	1,004
Heat demand delivered from 12 individual gas fired boilers	158	gas fired backup boiler	12
Total	1,030-1,989		1,016

The case shows that, although the NO_x emission from a biomass boiler is substantially higher than that of a natural gas fired boiler, in this particular case NO_x emissions from open field wood burning can be avoided (872-1,831 kg NO_x/year or approx. 407-855 kg/year or reactive nitrogen). Although this is a significant factor in the assessment, open field burning would still have led to a significantly lower release of reactive nitrogen to the environment than natural decomposition of these residues in nature. At typically 0.2% N in fuel for wood chips, this would have led to approx. 1,700 kg of reactive nitrogen in the fuel, which would be left in the field to decompose in case it would not have been burned. In the actual situation, only about 30% of this amount (1,004 kg NO_x or about 500 kg reactive nitrogen) is emitted during combustion in the boiler.

2.1.3 Impact on nitrogen deposition in nearby nature conservation areas

Using the above emission sources, an impact assessment was done on deposition in nearby nature conservation areas using the Aerius Calculator model as prescribed by the national authorities.

In the calculations, the local provincial authority requested that avoided emissions of reactive nitrogen in the reference situation (both from wood residues in the open field and the previously used natural gas fired boilers) had to be kept out of the equation as the practice of open burning was formally already illegal before the realization of the bioenergy plant, and the emissions of the gas fired boilers were also uncertain. Further, the assessment should be done on the basis of a maximum operation of the plant that would be realistically possible (6500 full load hours and a total heat delivery of 13 TJ, leading to 1390 kg NO_x). For the assessment, the NO_x emissions of fuel logistics were also included (6 kg).

The situation of the facility in respect to nearby Natura 2000 areas is indicated in Figure 6. The "Bakkeveense Duinen" are located approximately 5.8 km South from the facility. The "Leekstermeergebied" is about 10 km from the facility, and the "Wijnjeterper Schar" is approximately 11 km away.

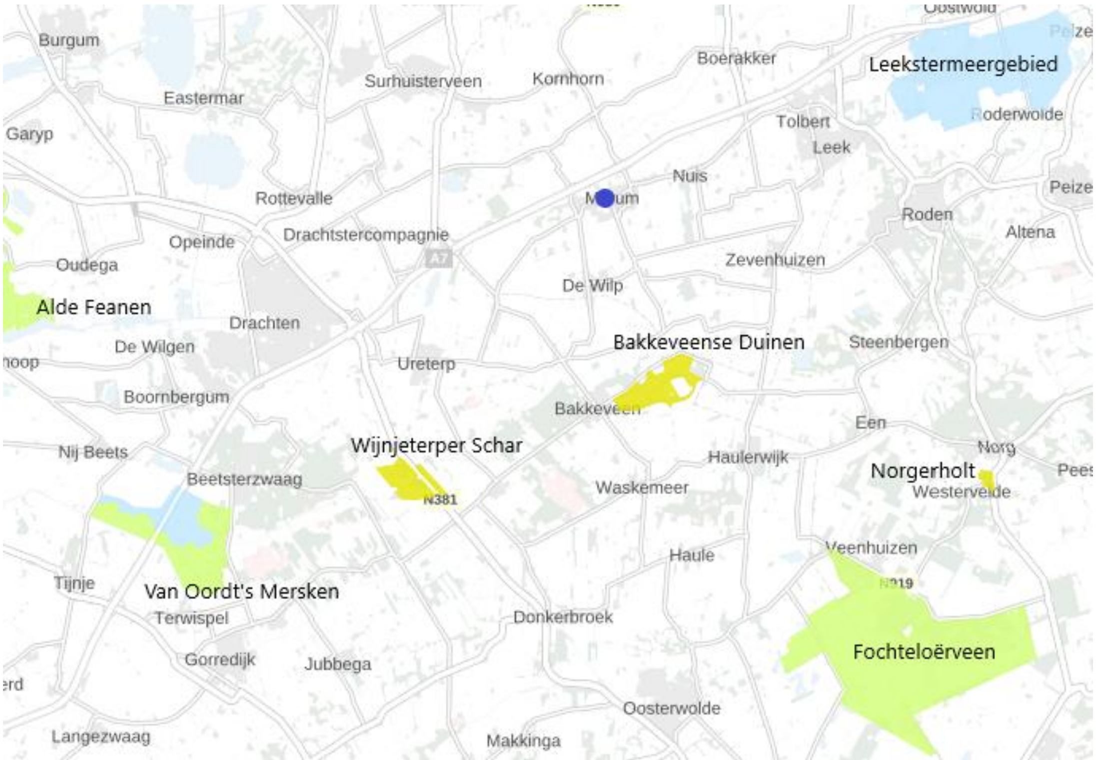

Figure 6: Map of the area around the Marum, with relevant nature conservation areas indicated in yellow, blue and green.

The results of the analysis indicate that the use of the biomass combustion plant leads to an increase in nitrogen deposition in the mentioned Natura 2000-areas of 0.01-0.02 molN/ha/year, see Table 3. As the areas already receive too much reactive nitrogen to avoid eutrophication, this was considered too much.

Table 3 Affected area and maximum increase in nitrogen deposition for the relevant Natura2000 areas, without mitigating measures.

	Area affected (ha)	Highest deposition (molN/ha/y)	Area with increase (ha)	Highest increase (molN/ha/y)	Area with decrease (ha)	Highest decrease (molN/ha/y)
Bakkeveense Duinen	64,87	2.094,37	64,87	0,02	0	0
Norgerholt	21,37	2.323,74	21,37	0,01	0	0
Fochteloërveen	7,07	1.978,53	7,07	0,01	0	0
Wijnjeterper Schar	2,65	1.968,80	2,65	0,01	0	0
Total	95,96	2.323,74	95,96	0,02	0	0

In order to allow operation of the plant, it was decided to implement a mitigation measure to compensate for nitrogen deposition in the respective areas. This was done by negotiating transfer of sufficient nitrogen emission rights from a cattle farmer that is closely situated to the mentioned areas, indicated by (1) in Figure 7. It was agreed that the emission rights of 7 milk cows were transferred, thereby mitigating 86.5 kg of NH_3. The farmer agreed to lower the allowance to keep this livestock accordingly. According to legislation, 70% of this amount was allowed to be used to compensate for emissions from the biomass heating plant.

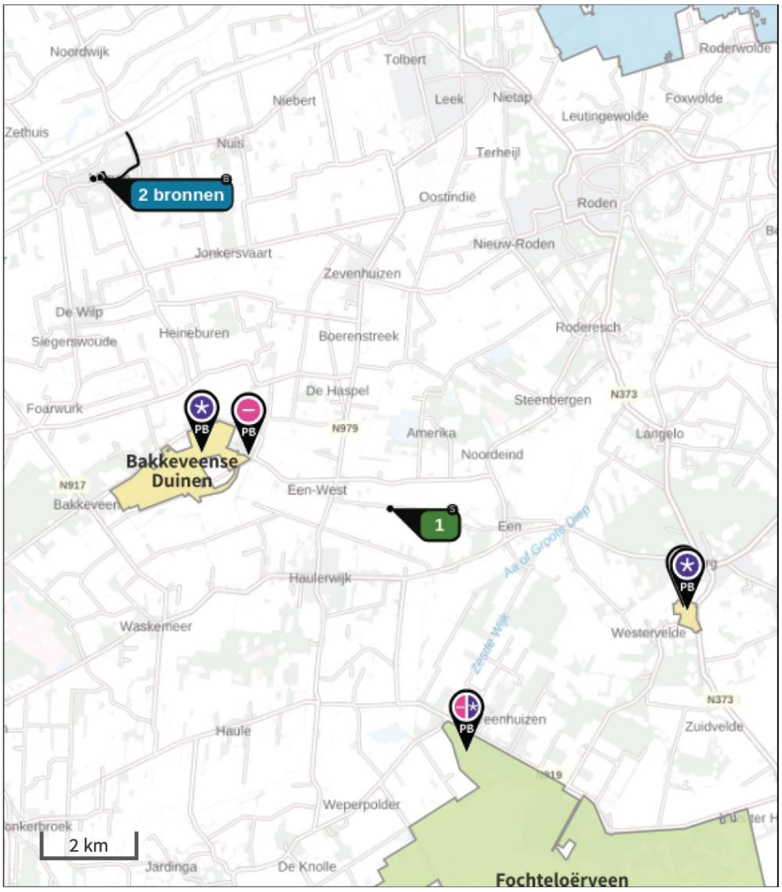

Figure 7: Map of the area around the Marum, the location of the biomass plant in the north, the location of the farmer (indicated by '1') and the location of the Natura2000 areas.

The effect of the mitigating measure is shown below. This shows that there are no longer any areas where deposition is increased.

Table 4 Affected area and maximum increase in nitrogen deposition for the relevant Natura2000 areas, after the mitigating measure.

	Area affected (ha)	Highest deposition (molN/ha/y)	Area with increase (ha)	Highest increase (molN/ha/y)	Area with decrease (ha)	Highest decrease (molN/ha/y)
Bakkeveense Duinen (17)	19,56	2,094.35	0	0	19.56	0.02
Norgerholt (22)	21.09	2,323.72	0	0	21.09	0.01
Fochteloërveen(23)	0.94	1,954,81	0	0	0	0,01
Wijnjeterper Schar (16)	0	0	0	0	0	0
Total	41.59	2,323.72	0	0	41.59	0.02

2.2 CASE 2: BIOMASS FIRED DISTRICT HEATING NETWORK IN ZAANDAM, NETHERLANDS

2.2.1 Background

Zaanstad is a middle sized city of 150.000 inhabitants immediately north of Amsterdam. Historically a relatively large number of food processing industries (coffee roasting, chocolate production, pastry baking) have been located in the centre on the river Zaan. These industries produce substantial quantities of waste heat. In 2012 a study was done on the options to increase the use of renewable energy. The idea was then launched to develop a new district heating network, with industrial waste heat as a dominant energy use, complemented by a biomass heating plant to provide the balance and natural gas fired boilers as peak and backup facilities. During the development phase, however, it was concluded that long term availability of industrial waste heat was too uncertain and no firm heat delivery contracts could be signed. It was therefore decided that the first phase of the project should consist of a biomass fired heating plant as main heat source, with two natural gas fired boilers as backup and peak facilities, while at the same time developing use of industrial waste heat.

In the first phase of the development of the district heating network, approx. 2500 households are heated, with a total heat demand of approx. 40 TJ/year. The ambition is however that the network should organically grow, with multiple sustainable heat sources and a larger transport and distribution network in place. After connecting two newly built housing areas in 2021, the heat demand grew to approx. 60 TJ per year. At this moment, only one producer and one supplier are active. On the longer term, the ambition is to extend the backbone in the district heating network to other parts of Zaanstad, with new city areas and heat sources connected. In order to make this growth possible, the district heating network is organised as an open structure, with the possibility of multiple heat producers and heat suppliers competing and operating on the same network. This is done by strictly separating the roles of producers, network companies and energy suppliers as is already common for electricity and natural gas supply. Ownership and exploitation of the district heating network is established through WNZ, a separate public company with the local municipality of Zaanstad, the province of North Holland and the public energy infrastructure company of Firan as shareholders. A separate company Bio Forte Zaanstad owns and operates the bioenergy plant, while energy company Essent delivers the heat to the final customers.

2.2.2 Net nitrogen emissions from the project

From the start of the project, Bio Forte decided to commit to much more stringent emission limits than the common national limits. There are two reasons behind this decision:

The plant is situated in a very urban environment, between a hospital, a school and several apartment blocks. As the air quality in the city is already affected by traffic and industry in the North Amsterdam area, Bio Forte did not want to contribute further to deterioration of air quality with significant emissions of dust and NOx. The building and operating permit therefore contains voluntary emission limits that are much more strict than usual.

Table 5: Hourly emission limits for the Zaanstad plant

Component	Normal emission limits (mg/m^3 @ 6% O_2, dry)	Applied emission limits (mg/m^3 @ 6% O_2, dry)
Dust	20	10
NOx	275	100
SO2	200	100

The location of the biomass plant is also located very close to a number of nature conservation areas, directly north of Zaanstad (see Figure 8). Due to the high sensitivity of the existing natural vegetation for nitrogen deposition and the presence of the already mentioned industries, highways and agriculture in the area, these nature areas are already overloaded with nitrogen. New and strict legislation on protection of nature conservation areas installed in 2019 imposed that for any new activity with a possible effect on nitrogen deposition, it should be evaluated if there is a significant impact. As the biomass heating plant replaces existing natural gas fired boilers, any NO$_x$ emission above the level of natural gas fired boilers would result in increased deposition on the areas north of Zaanstad (the dominant wind direction is south west). Nitrogen deposition model calculations showed that this could only be achieved if the biomass heating plant would have an annual average NO$_x$ emission that does not exceed approx. 40 mg/m3 @ 6% O$_2$.

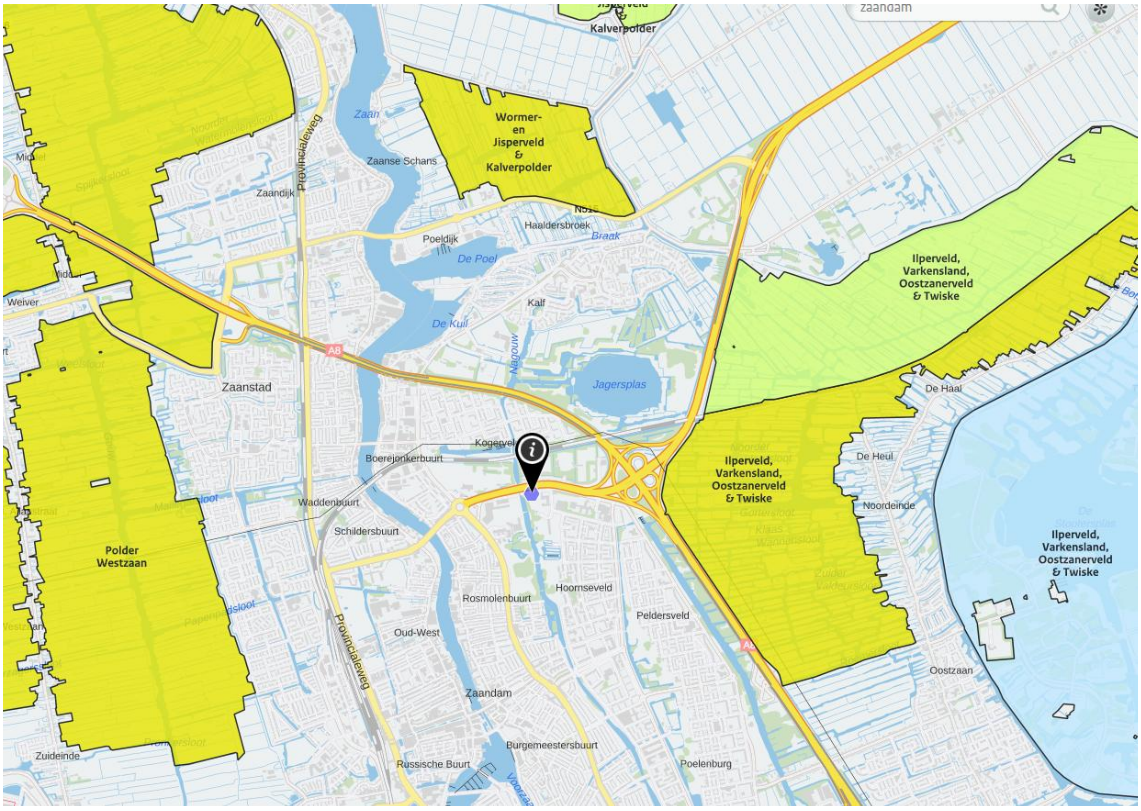

Figure 8 Location of the biomass plant in the city of Zaanstad, surrounded by various nature conservation areas (areas indicated in yellow, green and blue).

2.2.3 Biomass heating plant: technical design

The new biomass CHP plant has a capacity of 3.4 MW$_{th}$ / 0.1 MW$_e$ and was taken in operation by Bio Forte Zaanstad BV in January 2020. The plant consists of two separate biomass boiler installations and was (except for the flue gas condenser) delivered as a turn key system by Uniconfort, Italy:

1. A 1.2 MW woodchip fired boiler delivering up to 2.5 tph of steam (200 °C/15 Bar) to a Heliex genset, which can generate up to 75 kW of electricity before making 1.1 MW of heat on the condenser (max 125 °C) for district heating.

2. A 2 MW woodchip fired boiler, delivering superheated water up to 125 °C. This boiler system includes an innovative flue gas condenser from Terraosave that can generate up to 0.3 MW of additional heat under optimal conditions (see below).

Both boilers have a similar furnace design, aimed at optimal combustion and year-round continuous operation with a heat exchanger cleaning stop every six weeks and an annual plant maintenance plant for large maintenance and repairs.

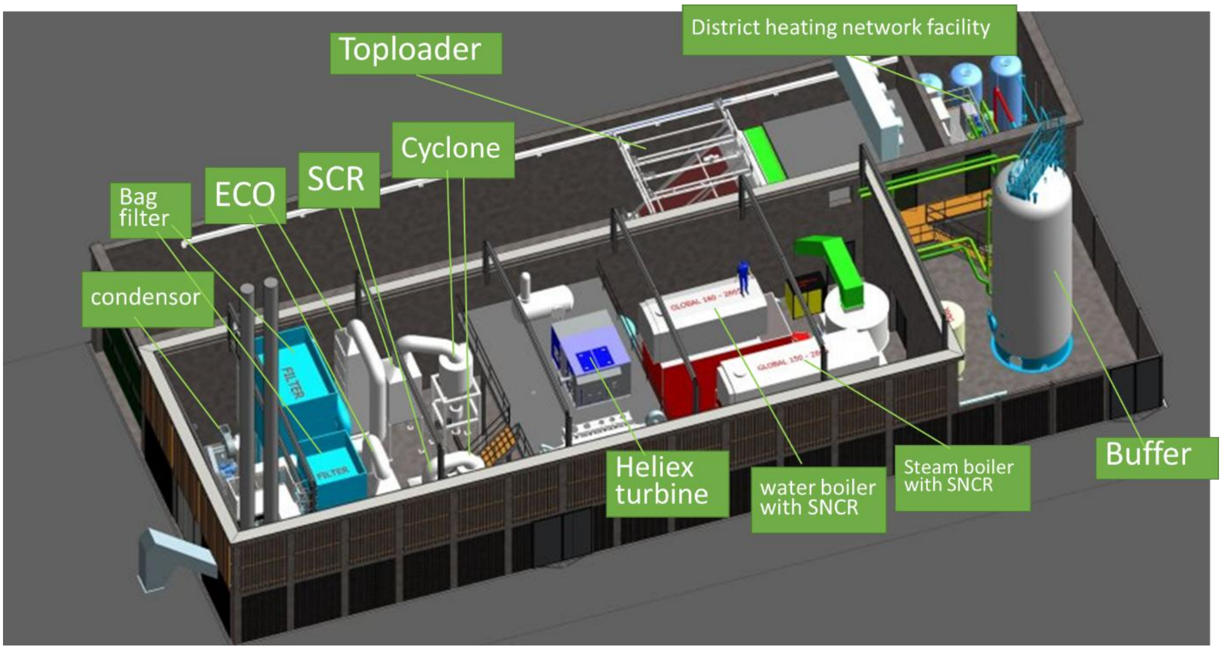

Figure 9 3D impression of the plant

Fuel supply to the boilers is organised from the fuel storage hall. Self-unloading trucks dump the wood chips directly on the floor. From there a toploader stacks the material and pulls it towards the fuel conveyor, which fills the intermediate fuel silo that distributes the fuel over both boilers. Heat produced by both boiler systems can be delivered to the district heating network and buffered via a 60 m^3 heat storage.

The boilers avail of water-cooled grates, automatic soot blowers and deashing of the whole combustion chamber. In order to guarantee optimal combustion, the temperature in the adiabatic combustion chambers is controlled at various locations by adding variable amounts of combustion air at five different locations (primary, secondary and tertiary air), each with variable O_2 content using individual mixtures of fresh air and recirculated flue gas. This results in relatively stable furnace temperatures under varying operating conditions (part load, fuel moisture content etc).

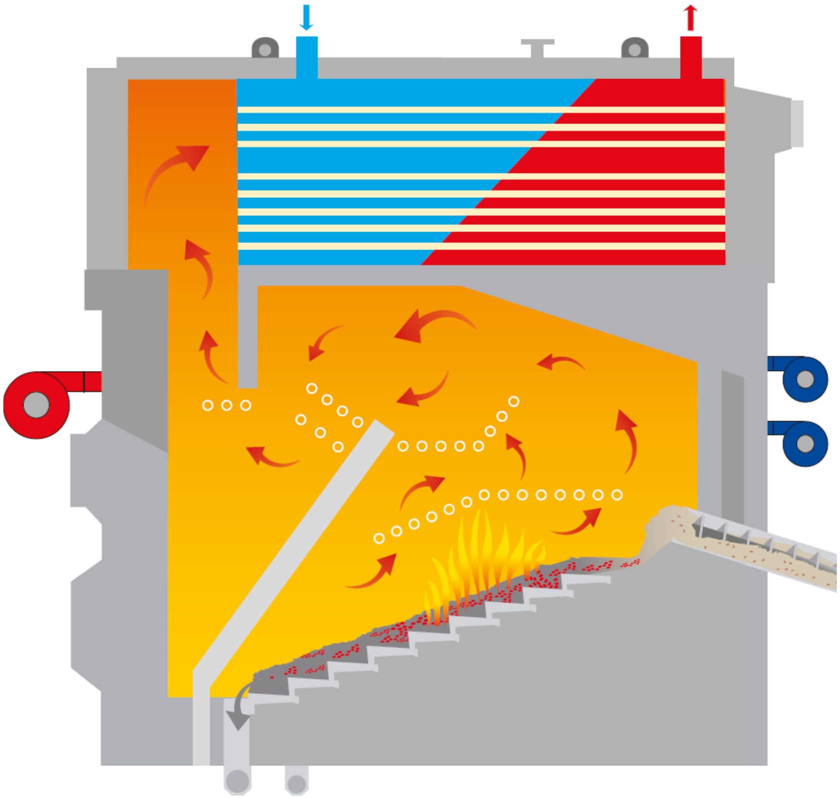

Figure 10 Simplified drawing of the combustion chamber of both boilers. In reality, ash is removed both from above the grate, below the grate and from the post combustion chamber.

2.2.4 Design of flue gas cleaning system

In order to obtain low dust and NO_x emission levels, various secondary emission reduction technologies were applied on both boilers:

1. An SNCR system, with injection of urea on both sides of the post combustion chamber. This system should be able to reduce NO_x emission from approx. 275 mg/m^3 to approx. 125-150 mg/m^3 @ 6% O_2. Flue gases leave the boiler section at approx. 220-250 °C, suitable for the subsequent catalytic $deNO_x$ system.

2. A cyclone to remove coarse dust particles

3. A high dust SCR system, aimed at further NO_x reduction to approx. 40 mg/m^3.

4. An economiser, aimed at reducing the flue gas temperature to approx. 130 °C.

5. A baghouse filter, reducing dust emission to a level of approx. 5 mg/m3.

In addition to the above-mentioned components, there is also an option to lead the flue gases through a Terraosave flue gas condenser (see Figure 9). This system aims not only at recovering latent heat from the flue gases, but can also further reduce emissions of NO_x and ammonia slip, depending on the pH of the condensate.

The Terraosave flue gas condensing technology is a recent innovation, marketed by Poujoulat. While in most other flue gas condensers rising flue gases meet falling cold water droplets as condensation points, in the Terraosave flue gases are injected into a cold water bath, as shown in Figure 11. The producer claims that this results in an improved contact of flue gas with water, leading to a more compact system. Latent and sensible heat is transferred to the water, which is in return cooled by a heat exchanger that transfers this heat to the main heating system.

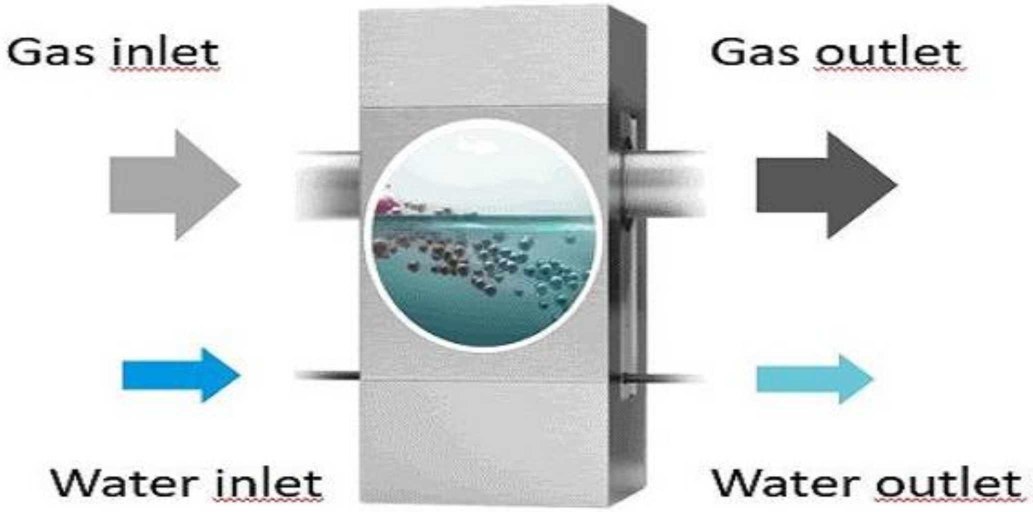

Figure 11 Schematic diagram of the Terraosave condenser

The second function of the Terraosave condenser is to reduce pollutant emissions as it acts as a wet scrubber. Terraosave claims that this can reduce emissions of dust by 85%, VOC by 85%, NO_x by 55% and SO_2 by 85% [2]. In addition, ammonia slip resulting from the $deNO_x$ system can also be reduced significantly. In this case, particularly NO_x emission reduction and ammonia slip reduction are relevant, since all other emissions are already within limits. The NO_x capture reactions follow the below equation:

$NO\ (g) + 1/2\ O_2\ (g) + Na^+(aq) + OH^-\ (aq) \rightarrow NaNO_3 + H_2O\ (l)$

As a result, this reaction requires the consumption of sodium hydroxide, and thus works better at a high pH. On the contrary, the capture of NH_3 slip works better at lower pH:

$NH_3\ (g) + H_2O\ (l) \leftrightarrow NH_3\ (aq) + H_2O\ (l) \leftrightarrow NH_4 +\ (aq) + OH^-\ (aq)$

One thus has to decide at which pH to operate the condenser. Due to the natural dissolution of CO_2 and SO_2 contained in flue gas, the pH by itself drops to approx. 4. Therefore sodium hydroxide can be added to increase the pH. In case of Zaandam, experimental work is still to be done to examine the optimal pH settings for combined removal of NH_3 and NO_x and the role of the SNCR, SCR and flue gas condenser in reducing NO_x and ammonia slip.

In the first phase of the project, the return temperature from the district heating network is too high to operate the Terraosave installation in condensing mode, this is expected to change when new housing areas are connected in the coming years. In order to still benefit from the option to reduce pollutant emissions, the condenser was modified to act as wet scrubber. The operating mode is automatically selected by the control system based on measured return temperatures.

2.2.5 Nitrogen balances of plant and comparison to the reference system

Due to the excessive nitrogen abatement equipment of the plant, the stack emissions of NO_x are lower than the reference situation of individual natural gas fired boilers per building that were replaced by the district heating network. In addition, a natural gas peak and backup boiler was installed that was equipped with low NO_x burners, leading in over 50% to lower NO_x emission than the typical gas fired boilers that were replaced. The below mass balance describes the plant emissions for a year with 60 TJ of heat production, of which is 52.5 TJ is delivered to final customers.

Table 6: Annual heat balance and reactive nitrogen flows the Zaanstad plant

Heat source	**Heat (GJ/year)**	**NO_x (kg/TJ)**	**NO_x (kg/year)**	**NH_3 (kg/TJ)**	**NH_3 (kg/year)**	**N_r (kg/year)**
old situation						
Individual gas fired boilers	52.500,00	21,80	1.145		0	**534**
new situation						
New gas fired peak/backup boilers	20.000,00	9,34	187			87
bioenergy plant	40.000,00	15,78	631	0,155	6,2	300
Minus: heat loss	-7.500,00					
delivered to final customers	52.500,00		818		6,2	**387**

This table shows that the total stack emissions of reactive nitrogen are significantly lower than the emissions that previously occurred. On a systems basis, however, one can argue that the situation is even better. Almost all of the biomass originates from forests as woody biomass residues. With approx. 5500 ton/year of biomass consumption (45% moisture content and 0.1% N), the biomass burned contains approx. 3055 kg of reactive nitrogen which (in the case of non-harvesting) would have led to nitrogen enrichment of the forest soil. As 100% of the fuel used is certified by the better biomass label and originates from sustainably managed forests, one may assume that it does not originate from forests where removing harvesting residues should be avoided for sake of maintaining soil fertility or biodiversity.

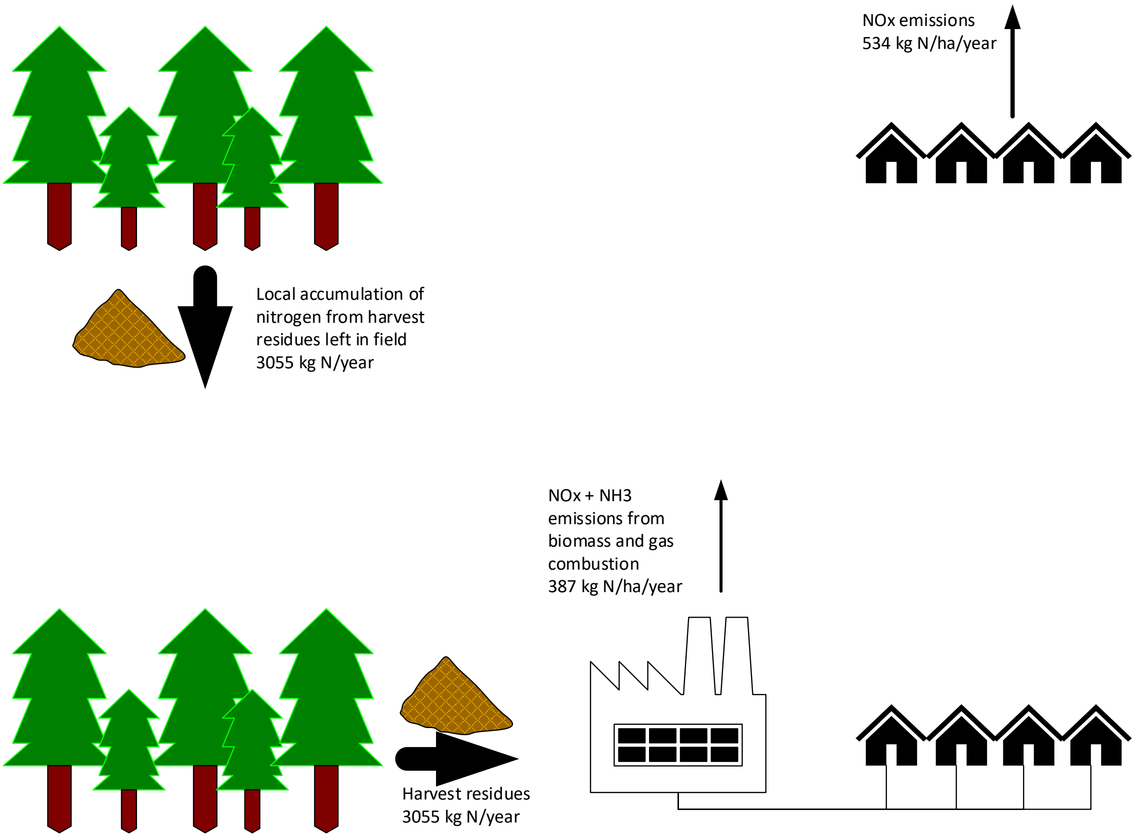

Figure 12 Indicative nitrogen flows before (upper) and after (lower) realisation in the Zaandam biomass fired district heating network.

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2.3 CASE 3: STRAW COMBUSTION AT SLAGELSE KRAFTVARMEVÆRK, DENMARK

The third case concerns the Slagelse Kraftvarmeværk in Denmark. This plant burns approx. 30 kton/year of wheat straw since 1990 for the production of district heat and electricity. Its steam and heat system are integrated with two waste fired boilers as shown below.

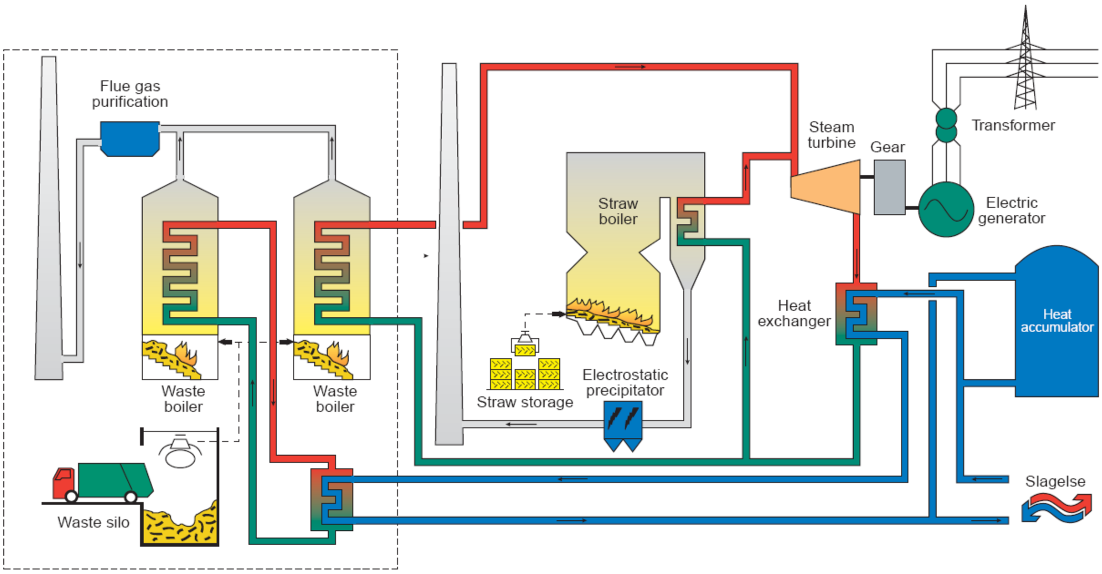

Figure 13 Simplified diagram of the Slagelse plant, with its connection to waste combustion plant [Dong Energy, 2007].

The straw boiler delivers max 16 kg/s of steam (450˚C / 67 Bar) to the turbine, which also receives steam from one of the waste fired boilers. The total output of the plant is max 28 MW heat output and 11.4 MW electricity. At full production, 16-18 bales (500 kg each) are fired per hour and the annual consumption of fuel is approx. 30,000 tonnes of straw.

The estimated nitrogen balance of the plant for 2024 is shown in Figure 14. In this year, the recorded fuel consumption was 31.2 ktons. The fuel energy content can be estimated from the energy in the produced steam (384 TJ) and an assumed boiler efficiency of 90% at 427 TJ. According to [Callessen et al, 2010], weathered straw has a typical nitrogen content of 0.2% nitrogen per ton dry matter or 0,15 kg/GJ fuel. This results in approx. 64 tons of reactive nitrogen in the fuel.

At the same time, actual NO_x emissions were derived from measured NO_x concentrations and flue gas volumes at 37.8 tons NO_x, or 17.6 tons reactive nitrogen. Therefore, in this case only approx 28% of reactive nitrogen in the fuel is again released into the atmosphere, and 72% is converted to inert N_2 gas.

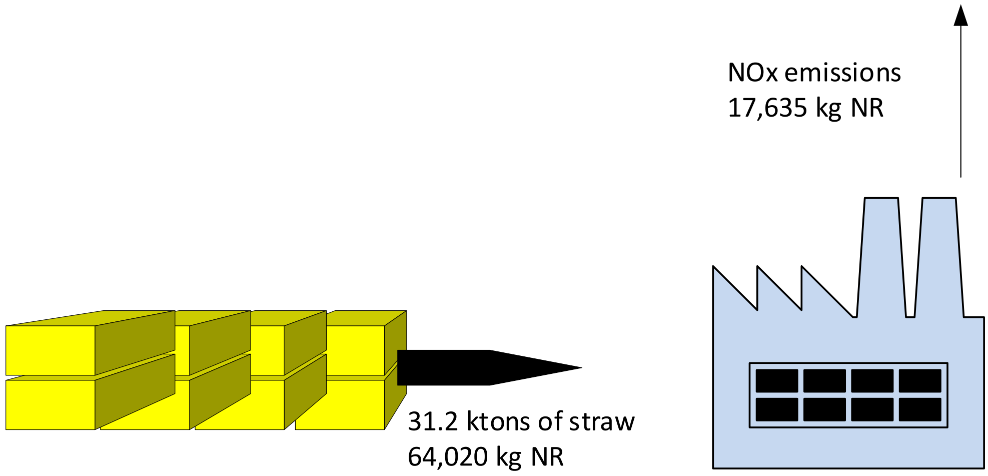

Figure 14 Simplified nitrogen balance of the Slagelse plant.

3 Formation of NO_x during combustion

In the preceeding study, various influencing parameters were identified that have an influence on the nitrogen cycle (from nitrogen takeup to deposition) in systems where biomass combustion is applied. These were:

1. The ability of certain biomass species to fix molecular nitrogen
2. The presence of reactive nitrogen in the direct environment where biomass fuel grows
3. The option of applying fertilizers
4. NO_x emission, released during harvesting or transportation
5. NO_x formation during combustion
6. The presence of post combustion $DeNO_x$ installations
7. Siting of the combustion system in respect to

In this report, the fifth aspect of formation of NO_x is described in more detail. In any combustion plant, NO_x (and eventually also NH_3 slip in case the plant is equipped with de-NO_x equipment) may be formed and subsequently released to the environment. In contrast to combustion of natural gas where molecular nitrogen (N_2) is partly converted to NO_x due to the high flame temperatures, the combustion temperatures for biomass are typically too low to form thermal as well as prompt NO_x. The most relevant if not the sole source for NO_x emissions from biomass combustion is the chemical formation from the chemical bond nitrogen in the biomass. Since nitrogen is an integral part in the proteins and amines of biomass the reactions are always existent in the combustion process. Therefore, most if not all NO_x formed during combustion originates from fuel nitrogen. Nitrogen conversion can follow different reaction routes and depending on the combustion conditions the shares of molecular nitrogen (N_2) and reactive nitrogen like NO_x vary (Figure 15). The goal is a maximum share of N_2.

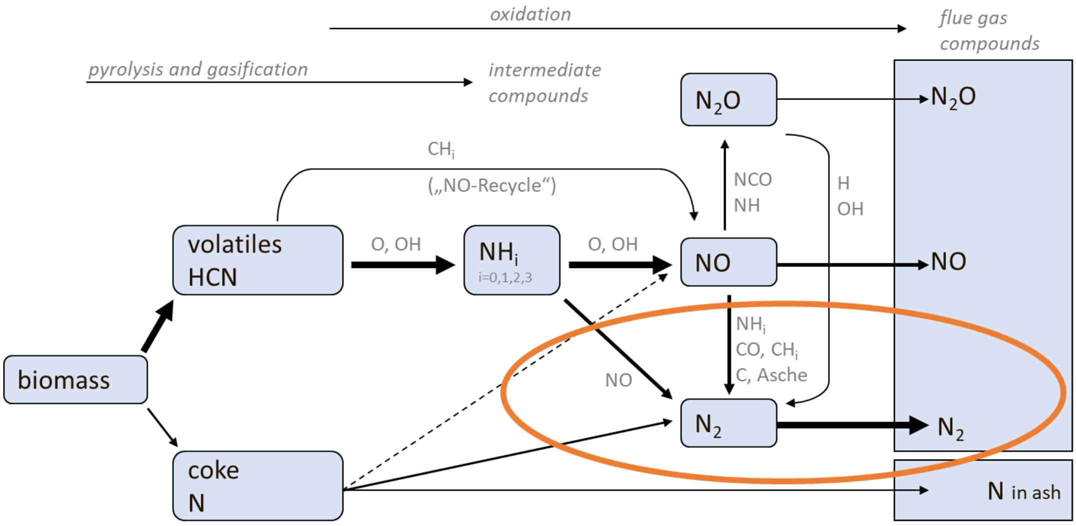

Figure 15: Conversion routes of fuel nitrogen at biomass combustion. (adapted from Baumbach et al. 2016)

The main decisive factors for the formation of NO_x from biomass combustion are

- the nitrogen content in the fuel,

- the oxygen content in the combustion chamber and
- the degree of combustion conversion in the flue gas.

Higher nitrogen contents can be expected from stalky materials like straw and Miscanthus with average values of above 0,5 wt% (daf - dry and ash free; Figure 16). Woody materials are at least by average lower in nitrogen contents. Although contents of bark and particularly of leaves in a woody bulk material may lead to an significant increase of the nitrogen content. However, as shown by the standard deviation indicated by the whiskers, nitrogen contents of individual materials scatter in a wide range. Ultimately, the risk for NO_x formation strongly depends on the individual charge of biomass fuels.

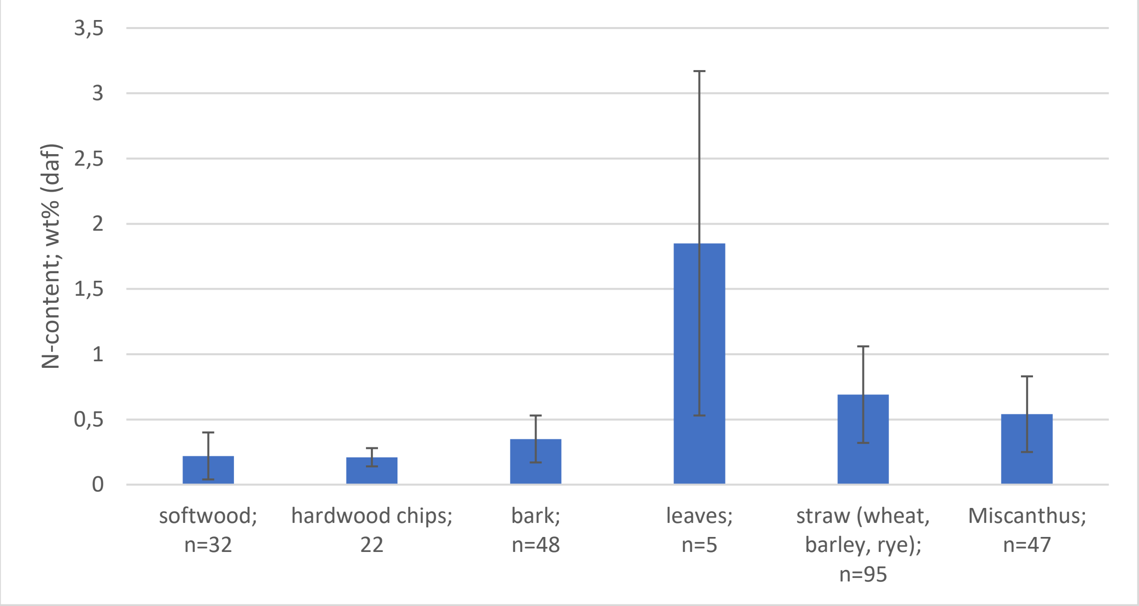

Figure 16: Mean values of nitrogen contents of different biomass fuels. (daf=dry and ash free basis; whiskers indicate the standard deviation; Values from phyllis.nl)

Although a high nitrogen content in the fuel implies higher emission potential of NO_x the conversion rate to NO_x shows a decreasing dependency on fuel nitrogen concentration, as shown in Figure 17. For a modern furnace equipped with staged combustion, typically between 10-70% of fuel nitrogen is converted to NO_x, the other 30-90% is converted to inert N_2. It is interesting to see that for nitrogen-rich species with fuel-N contents exceeding 0.5%, only about 10% is converted to NO_x. For woody biomass with less than 0.5% fuel N, typically about 30-50% is converted to NO_x. (Adam *et al*. 2024)

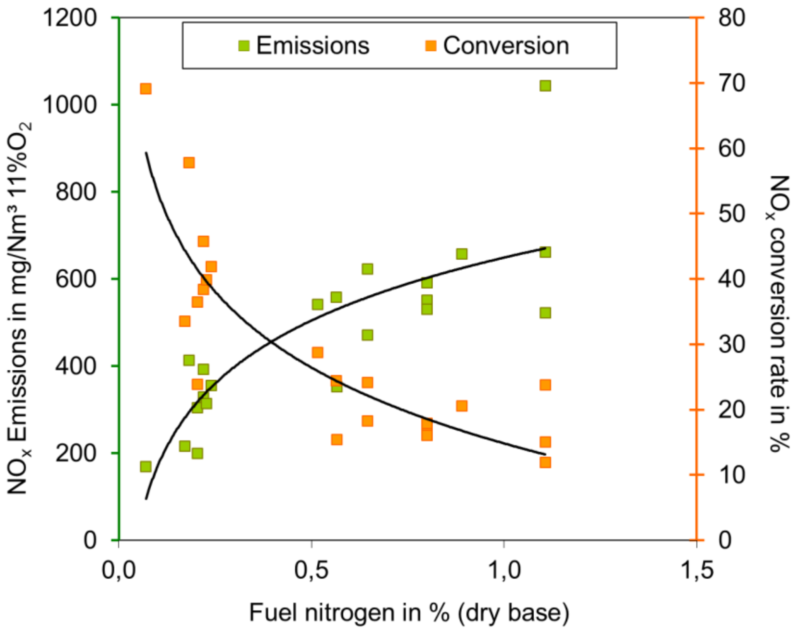

Figure 17: Correlation of N content and (a) NO$_x$ emssions as well as (b) fuel-N conversion to NO$_x$ from different biomass combustion furnaces (source: BEST GmbH)

The determining process factors are the loading rate of the combustion chamber, the homogenization of the combustion gases on the grate and the flow configuration of the fuel to the combustion air.

In order to convert the fuel nitrogen to a maximum share to molecular nitrogen and produce low NO$_x$ emissions, three types of primary technological measures can be implemented, namely:

- flue gas recirculation,
- air staging and
- fuel staging.

Flue gas recirculation uses the effect of NO$_x$ reduction by further reactions of NO$_x$ with radicals, CO and solid carbon. Moreover, the improved flue gas mixing allows for a lower amount of excess air resulting in both, lower CO and lower NO$_x$ emissions (Figure 18).

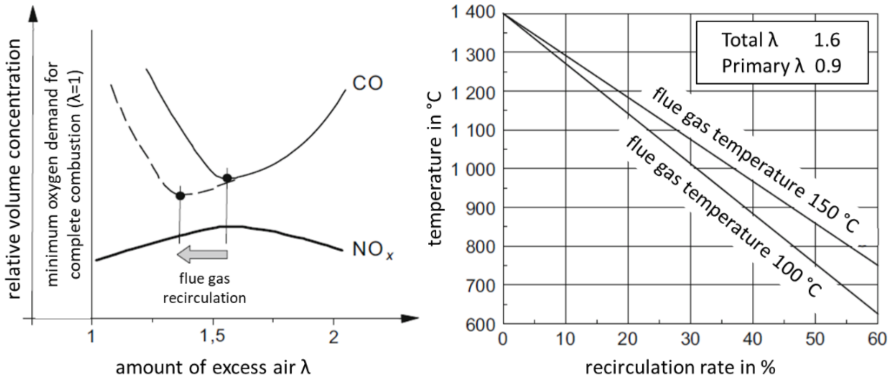

Figure 18: Impact of flue gas recirculation on CO and NOx emissions (adapted from Adam et al. 2024)

At air staging NO_x formation is prevented to some extent due to sub-stochiometric conditions in the primary combustion zone respectively in the gasification zone (λ<1; see Figure 19). An enhanced decrease of NO_x emissions can be achieved by implementation of an additional reduction zone in the design of the combustion furnace. However, even without a distinct reduction zone after the primary zone, significant NO_x emission reduction can be realized by single air staging. Subsequently after addition of the secondary air the further combustion takes place at oxygen enriched conditions (λ>1) allowing for oxidation of the combustion gases. Lowest NO_x emissions can be achieved when even then the total excess air ratio is kept on a low level.

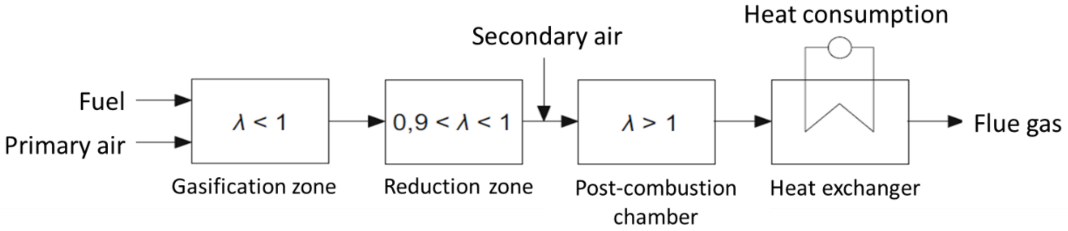

Figure 19: Scheme of air staging (adapted from Adam et al. 2024)

Similarly to air staging at fuel staging reducing conditions can be achieved by addition of secondary fuel leading to a lambda below one (Figure 20). Previous formed nitrogen oxides are then reduced by NH- and CH-compounds originating from the conversion of the secondary fuel.

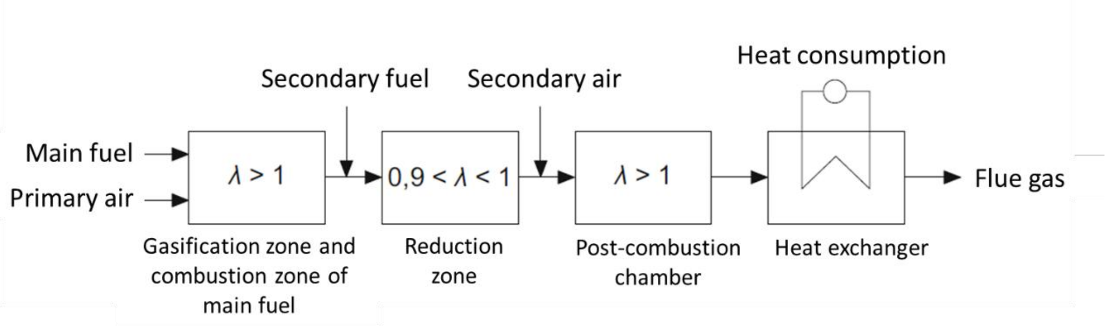

Figure 20: Scheme of fuel staging (adapted from Adam et al. 2024)

The impact of double air staging with subsequent increase of the λ (primary zone: 0,25, secondary zone: 0,5 – 1,2, tertiary zone: 1,5) has been recently shown by Essl *et al*. 2024. The impact of the oxygen concentration expressed as λ in the secondary combustion zone on the reduction of nitrogen species in the combustion gases after the secondary zone as well as after the tertiary zone is presented (Figure 21). The most efficient reduction of nitrogen species of 90% occurred at a λ of 0,9 in the secondary zone. The main goal of the research was the numerical simulation of the kinetic mechanisms in order to be able to predict NO_x emissions from biomass furnaces. These developments will contribute to further develop technological solutions for the evaluation of the optimum operation window for the efficient reduction of NO_x from biomass combustion. Adam *et al*. 2024

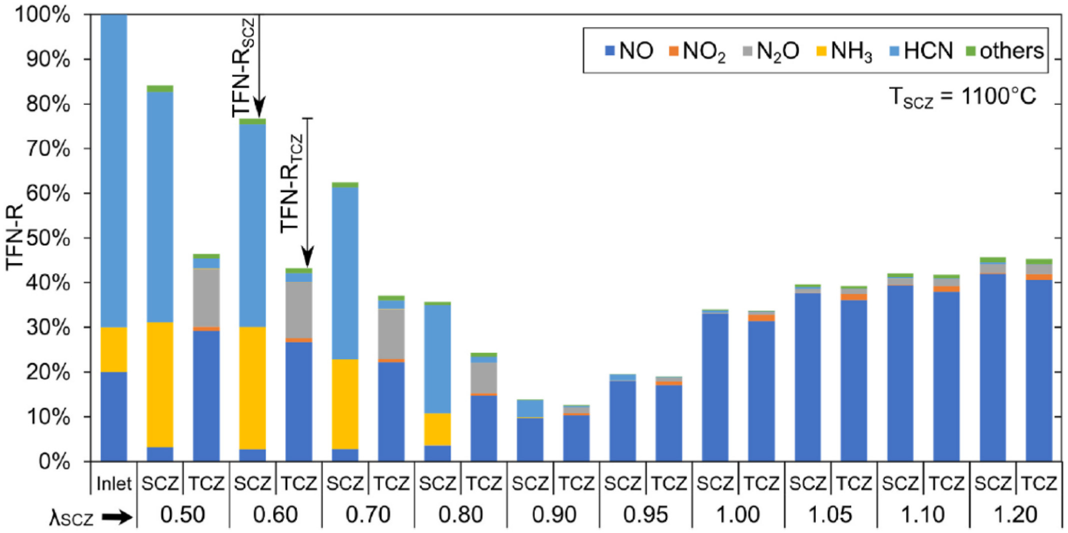

Figure 21: Conversion of dominant N-speices after the secondary and teriary combustion zone at a termperature in the secondary zone of 1100 °C. (Essl et al., 2024)

4 Conclusions

The findings of this study underscore the **complex and multifaceted role of biomass combustion in the nitrogen cycle**. While biomass combustion systems are often viewed as contributors to nitrogen emissions, a **holistic system perspective** reveals that they can function as an integral part of a sustainable nitrogen management strategy. The implications of these findings extend beyond combustion technology and environmental impact assessments; they call for a **reassessment of regulatory frameworks, emission control strategies, and biomass sourcing practices**.

Biomass combustion is not inherently detrimental to the nitrogen cycle

A prevailing assumption is that biomass combustion leads to excessive NO_x emissions, thereby worsening air quality and nitrogen deposition in sensitive ecosystems. However, this study confirms that:

- NO_x emissions from biomass combustion are fundamentally different from those of fossil fuels, as they originate primarily from **fuel-bound nitrogen** rather than from the oxidation of atmospheric nitrogen.
- In many cases, **only a fraction** of the nitrogen in biomass is actually released as NO_x, while a significant portion is retained in ash or converted back to inert N_2.
- The case studies suggest that **in some circumstances, biomass combustion can act as a net sink of reactive nitrogen**, particularly when compared to open-field burning or natural decomposition of biomass.

Emission control technologies must be optimised for biomass-specific NO_x formation

While post-combustion NOx reduction technologies such as **SNCR and SCR** are effective, they are not always implemented due to cost and operational complexity. However, this study highlights that:

- **Primary measures** such as **air staging, fuel staging, and flue gas recirculation** should be prioritised in biomass combustion systems, as they can drastically reduce NO_x formation at the source.
- Post-combustion control measures **must be tailored** to the specific chemical composition of biomass flue gases to avoid unintended consequences such as ammonia slip or excessive energy penalties.
- The variability in NO_x formation across different biomass fuels and combustion technologies necessitates **adaptive emission control strategies**, rather than a one-size-fits-all regulatory approach.

Policy and regulatory frameworks need to account for the full nitrogen cycle

Current emission regulations often treat NO_x emissions from biomass combustion in the same way as those from fossil fuels. This study demonstrates that such an approach is **overly simplistic** and fails to recognise the broader nitrogen cycle implications:

- Biomass combustion **recycles** nitrogen that was already part of the terrestrial ecosystem, rather than introducing new reactive nitrogen into the environment.
- Strict NO_x limits that do not consider the full nitrogen cycle **could discourage biomass combustion in favour of fossil fuel alternatives**, leading to unintended negative consequences.

- Regulations should **differentiate between nitrogen-neutral biomass sources and nitrogen-intensive fuels**, and should consider **lifecycle nitrogen balances** rather than focusing solely on stack emissions.

Site-specific environmental assessments are critical

The impact of biomass combustion on nitrogen deposition varies significantly based on local environmental conditions, making **site-specific assessments** essential:

- The **geographical proximity** of combustion plants to nitrogen-sensitive ecosystems determines whether emissions contribute to eutrophication.
- In some cases, **emission offsets** or **compensatory mitigation measures** (such as nitrogen rights trading or afforestation) can neutralise the local impact of biomass NOx emissions.
- Policymakers should integrate **regional nitrogen budgeting** into permitting processes to allow for a more nuanced assessment of biomass energy projects.

Future research and innovation should focus on nitrogen recovery and circular economy approaches

Beyond emission reduction, the findings suggest opportunities to **further close the nitrogen cycle** through technological and operational improvements:

- **Ash valorisation**: Research into the recovery of nitrogen from combustion residues could turn biomass ash into a valuable fertiliser, reducing the need for synthetic nitrogen fertilisers.
- **Optimised fuel sourcing**: Understanding how different biomass sources contribute to nitrogen emissions will help optimise supply chains to favour low-emission feedstocks.
- **Integration with nitrogen capture technologies**: Future bioenergy systems could be designed to **not only reduce NO_x emissions but also actively remove reactive nitrogen** from the atmosphere, further mitigating environmental impacts.

Final Considerations

This study challenges conventional perspectives on biomass combustion and its role in nitrogen emissions. Instead of being seen as an isolated emitter, biomass combustion should be viewed **as a potential tool for nitrogen management** when optimised combustion, emission controls, and policy measures are implemented effectively.

The way forward requires a **multi-disciplinary approach** that bridges combustion engineering, atmospheric science, ecosystem management, and policy development. By aligning technological innovation with regulatory adaptation and ecosystem-based management, biomass combustion can continue to play a vital role in **both energy security and sustainable nitrogen cycling**.

5 References

Adam, R., Fendt, S., Gaderer, M., Gölles, M., Haimer, J., Hartmann, H., Hofbauer, H., Höfer-Sanning, I., Hülsmann, T., Kaltschmitt, M., Keil, F., Kupts, D., Lenz, V., Siegmund, T., andd Spliethoff, H. 2024. Vollständige thermo-chemische Umwandlungsverfahren (Verbrennung). In: Kaltschmitt, M., Hofbauer, H. (Editors), Energie aus Biomasse Thermo-chemische Konversion, Wiesbaden, Springer-Vieweg. 199 ff.

Baumbach, G., Hartmann, H., Höfer, I., Hofbauer, H., Hülsmann, T., Kaltschmitt, M., Lenz, V., Neuling, U., Nussbaumer, T., Obernberger, I., Schule, A.-L., Wilk, V., Winter, F. 2016. Grundlagen der thermochemischen Umwandlung biogener Festbrennstoffe. In: Kaltschmitt, M., Hartmann, H., Hofbauer, H. (Editors), Energie aus Biomasse, Grundlagen, Techniken und Verfahren, Berlin-Heidelberg, Springer Vieweg. 579 ff.

Cassesen, I., Carter, M.S., Østergård, H. 2010. Efficient use of reactive nitrogen for cultivation of bioenergy: less is more. GCB Bioenergy (2011) 3, 171-179.

Dong Energy (2007). Bioenergy for electricity and heat – experiences from biomass-fired CHP plants in Denmark. https://energiforskning.dk/files/slutrapporter/slutrapport_6523_1.pdf (visited on 20.03.2025)

Eßl, M., Scharler, R., Schulze, K., Anca-Couce, A. 2024. Numerical investigation of reaction mechanisms on NOx emissions from biomass combustion with enhanced reduction. Biomass and Bioenergy 191 (2024), 107441

Urbanski, S (2014). Wildland fire emissions, carbon, and climate: Emission factors, Forest Ecology and Management, vol 317, 1 april 2014, p 51-60

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