Global warming potential of flue gas from log-fired single room heaters – double effect of catalytic emission control

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Abstract Log-wood combustion has a significant share in renewable heat provision. Wood from sustainable forest management is considered as CO_2-neutral with regard to climate aspects. Flue gas emissions from single room heaters are discussed intensively according to health aspects. New research results on climate impacts of black carbon emphasize the balancing of these emissions when investigating the greenhouse gas emissions of these furnaces. Even, if there is a lack of exact information, it is shown that the consideration of black carbon emissions of single room heaters should be a natural consequence.

Treibhausgaswirkung von Scheitholz-Einzelraumfeuerungen – doppelter Effekt katalytischer Emissionsminderung

Zusammenfassung Scheitholzverbrennung hat einen signifikanten Anteil an der erneuerbaren Wärmebereitstellung. Einerseits wird Holz aus nachhaltiger Waldbewirtschaftung als nahezu CO_2-neutral bei der Energiebereitstellung angesehen, andererseits werden die Abgase aus Einzelraumfeuerstätten bezüglich ihrer Gesundheitswirkungen breit diskutiert. Aktuelle Erkenntnisse zur Klimawirkung von Rußpartikeln unterstreichen die Bedeutung ihrer Berücksichtigung bei der Erstellung von Treibhausgasbilanzen. Selbst wenn es noch offene Fragen bei der genauen Gewichtung der Rußemissionen im Vergleich zu Kohlenstoffdioxid gibt, zeigt der Beitrag, dass zukünftig die Berücksichtigung von Rußemissionen bei der Bewertung der Energiebereitstellung aus Einzelraumfeuerstätten selbstverständlich sein sollte.

1 Background

As a result of the Paris Agreement the transition of the global energy provision to renewable energies is necessary [1]. Today, bioenergy contributes the most to this transition process both worldwide and in Germany [2; 3]. Although wind and solar energy will take the lion‘s share in the near future, bioenergy will still play a significant role.

Especially in the heating sector biomass often generates more than 90% of the renewable heat [2]. Even in developed countries, stoves and other single room heaters contribute considerably to this renewable heat provision. For example, in Germany approximately 11 million single room heaters are installed providing around 35% of the total renewable heat [2; 4]. However, the used technology often is quite simple and users sometimes act arbitrarily, thus causing challenges that are not solved yet. As a result, the combustion of biomass often leads to high emission levels of dust, polycyclic aromatic hydrocarbons (PAH), black carbon (BC) and other pollutants. Up to now, the advantage of a positive climate effect has been facing the disadvantage of an elevated load with air pollutants so that both sides had to be weighed out depending on the local conditions. Nevertheless, recent research activities show now that the greenhouse effect of the total amount of dust particles in the atmosphere is almost zero whereas BC has a substantial impact on the increase of the radiation effect [5 to 7].

Accordingly, reducing particulates (i.e. especially unburned components) is not only important for the health protection but also for active climate protection.

This is the first work to assess climate impacts of log-wood fired single room heaters under considering BC emissions and to investigate the effect of emission abatement systems for CO and black carbon from the perspective of climate protection. To this end, pertinent data collections of the DBFZ Deutsches Biomasseforschungszentrum concerning black carbon emissions of small scale furnaces and recent publications regarding the greenhouse gas (GHG) effectiveness of black carbon emissions are analyzed.

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2 Methodology

The question of how emission abatement systems in log-wood fired single room heaters effect the climate causes two methodical challenges. On the one hand, representative emission data of single room heaters (i.e. BC emissions in particular) need to be stipulated. On the other hand, a procedure that takes the GHG balance into account needs to be developed on the basis of recent research activities concerning the wide range of GHG effectiveness of BC particles.

2.1 Emission data of log-wood fired single room heaters

There is a wide variety of different types of single room heaters available (e.g., rarely used fireplaces, often used stoves with a flat firing system, brick-built heating chimneys with heat storage). Moreover, each type consists of different versions, forms, sizes, used building materials and processing qualities so that it is impossible to define a single model representing all single room heaters for the purpose of an investigation. Even if such a model combustion unit can be identified, the question of a general validity of the collected emission data would still remain. In addition, log-wood fired single room heaters are fed manually by different users with different log-wood qualities. Therefore, the actual emissions of one and the same unit can vary massively. Consequently, standardized and repeatable test methods, such as type testing, only reflect a restricted part of reality and often underestimate clearly real emissions. Alternative test bench methods could be more realistic but even they cannot show the worst case emissions.

2.2 Used measuring technique and test bed procedure

A firing test bed that allows hot gas measurements was used for measuring emissions. **Figure 1** shows a schematic sketch of the flue gas test section at the DBFZ firing test bed. Thermocouples type K of the company Newport Electronics were used to determine the temperature of the flue

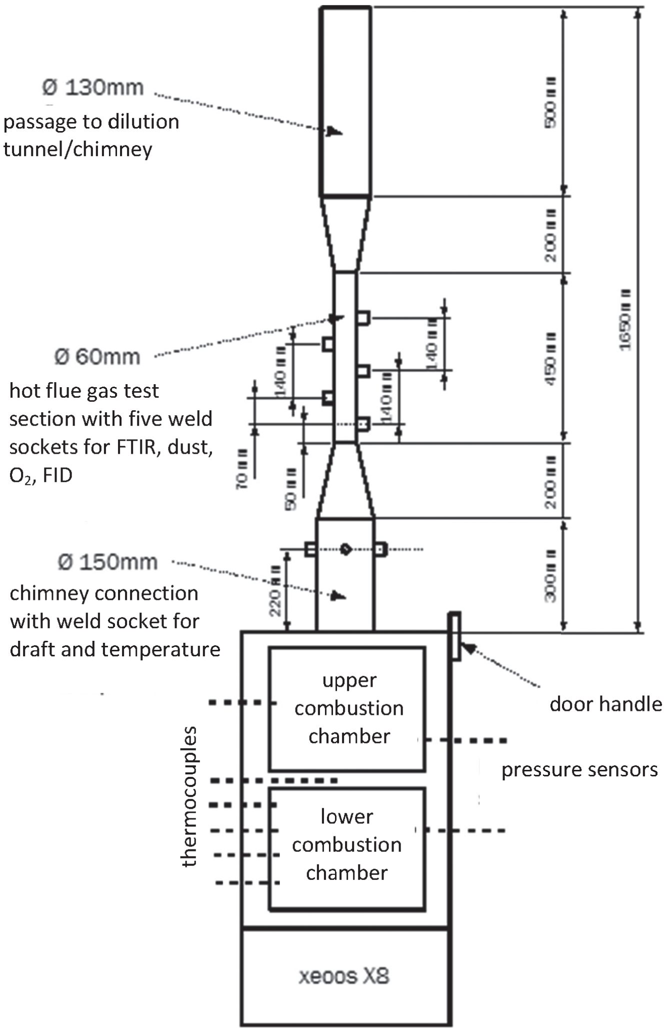


Figure 1. Schematic presentation of the firing test bed with flue gas test section for emission measurements and process characterization of the stove.

gas and combustion chamber. The measurement of the static and dynamic pressure in the flue gas pipe was done by means of a Prandtl Pitot tube of the company Testo. For continuously converting and recording the measured values of the Pitot tube and the pressure measuring connector in the combustion chamber, sensors and the recording tool Almemo of the company Ahlborn were used. The recording of the signals of the thermocouples was done by means of a data logger of the company National Instruments and by using the software LabView.

Gaseous emissions formed during combustion were measured by means of an analyzer cabinet of the company Ansyco. It consists of a gas analyzer on the basis of a Fourier Transformation Infrared Spectrometer (FTIR, producer: Calcmet), a flame ionization detector (FID, producer: Mess- & Analysentechnik GmbH, type: Thermo-FID ES) and a paramagnetic oxygen analyzer (producer: M&C, type: PMA 100). A developed software application made it possible to record quantitatively 44 different components in total.

The volatile organic compounds (VOC) emissions as C1-equivalents could be measured with the FID and also with the FTIR. Within the organic carbon (org.-C) range of concentration below 50 mg/m³ normal conditions at 13% O_2 the measured values of the FID are to be used. Within the range of concentration above 50 mg/m³ (normal conditions at 13% O_2) the measured values of the FTIR should be consulted for comparison purposes.

For measuring the concentration of particulate matter in the flue gas dust measurement equipement of the company Paul Gothe was used.

Simultaneously, the following flue gas parameters were recorded:

- oxygen O_2 (paramagnetic O_2-analyzer),
- carbon dioxide CO_2 (FTIR),
- moisture of the flue gas H_2O (FTIR),
- carbon monoxide CO (FTIR),
- volatile organic compounds (VOC) as organic carbon (org.-C) (FID und FTIR),
- nitrogen oxide as nitrogen dioxide equivalents NO_{2equi} (FTIR),
- sulphur dioxide SO_2 (FTIR),
- methane CH_4 (FTIR),
- other volatile organic compounds (alkanes, alkenes, aromatic compounds, alcohols and aldehydes as well as ketones) (FTIR, not evaluated explicitly),
- total dust concentration (VDI 2066, sheet 1),
- flue gas temperature, gas velocity and draft conditions.

The recording of the named measurement values took place continuously except for the total dust concentration. For analyzing the emissions of the experiments, mean values for the dust sampling period were formed. Dust sampling started immediately when refilling logs until exactly five minutes before refilling logs again. Consequently, for a quantity of about 1.3 kg beech per batch a combustion period of 35 min and a dust measuring period of 30 min were reached. Having a chimney draught of 12 Pa (steady adjustment by means of a chimney fan) within the exhaust gas stub with a diameter of 150 mm a fuel heat performance of 8 to 9 kW was achieved while the fuel water content of the used logs was between 10 and 15 w-%.

Particulate matter emissions were sampled discontinuously. The gravimetric analysis of the total dust concentration was carried out according to the guideline VDI 2066, sheet 1, following the principle of the isokinetic sampling of a partial flow from the main exhaust gas stream. Thereby the entrained particles are precipitated by a previously weighed planar filter. As the filter and the filter housing is outside the exhaust pipe, this procedure is called out-stack-procedure. The filter system is heated by a heating sleeve in order to avoid that the dew point of the flue gas is undercut. The temperature was lowered to 70 °C, to ensure that also the semi-volatile hydrocarbons in particle form were precipitated by the filter. After the experiment, the precipitated dust amount can be analyzed gravimetrically and specified considering the measured partial flow rate and oxygen concentration. Planar filter made of micro glass fibers (type MK 360 of the company Munktell, retention 99.998% according to the dioctyl phthalate test) with a diameter of 45 mm were used.

2.3 Examined stoves

The stoves used for the tests are based on the so-called downdraft combustion principle ("Sturzbrandprinzip"). This type of stove is still rarely found on the market. Nevertheless, it was chosen consciously to have a technically advanced device with prospectively low emissions during regular operation. Thus, criticism concerning a possible exaggeration of the difficulties caused by black carbon

Table 1. Determined emission values of the stove xeoos X8.

parameters	emission values mg/m³, normal conditions 13 % O_2
CO	1,718
VOC (C1-equivalent)	156
total dust concentration	19

should be prevented. For identifying reference values without emission reduction, a standard log-wood fired stove type xeoos X8 of the company Specht Modulare Ofensysteme was used with a nominal power of 8 kW [8]. Customary beech logs were used as fuel. During unmodified operation, the emissions as well as the temperature and pressure conditions were analyzed. This reference test was necessary to identify the effects of the technical emission reduction measures. The stove was operated at the beginning of each combustion cycle in the upper combustion chamber for 30 s. Afterwards, it was switched to lower combustion operation for 29.5 min. The concentrations were recorded and averaged in the course of the reference tests over the period of four combustion phases. **Table 1** summarizes some selected emission values of the reference test operation.

The new development of the lower combustion stove ("NEKO") was carried out in the scope of a research project (short title: DBU-NEKO) [8]. As a result, emissions could be reduced significantly. Furthermore, the door was divided into two parts which lead to a new geometry. Consequently, when refilling, only the door of the upper combustion chamber must be opened so that higher temperatures in the lower combustion chamber can be achieved directly at the point of refilling. The lower combustion chamber was deepened so that a cooling of the flame by touching the floor or ash container could be prevented. The modified stove was operated during the test bed measurements with two different settings. The air supply (ratio of primary air to secondary air) could be controlled by a lever for the primary air regulation flaps. The lever allows a reduction of the primary air supply, while at the same time more secondary air enters via the hollowbottom of the upper combustion chamber. This will reduce the pyrolytic decomposition and gasification in the upper chamber. Simultaneously, the increased secondary air supply provides more oxygen for the oxidation in the flame. Taken together, both measures result in a higher lambda ratio which positively effects the emission levels, especially when lighting refilled wood at the glowing embers. Additionally, the modified geometry of the heater was equipped with a burner ring in the double floor under the grate for optimized secondary air supply. The burner ring includes 20 holes distributed evenly across the circular ring having a diameter of 6 mm each. With this burner ring, the flow resistance of the double plate was reduced so that the mass flow of the secondary air in the stove was increased. In addition, a better mixture of secondary air and fuel gas compared to the standard stove was realized with the burner ring.

Further, two wall catalysts were installed in the lower chamber. These wall catalysts consisted of alumina foam as a substrate and were coated with manganese oxide (MnO_x) with the newly developed RSSA synthesis of the DBU-NEKO project. Further details regarding the catalysts specifically designed for the installation in the high-temperature lower combustion chamber can be found in the research report [8; 9] as well as in the patent application [10]. The catalysts (two units) are located in the lower combustion chamber and are arranged in a way that the flame cannot come into contact but the exhaust gas can flow through the open-celled structure of the sponges with the highest possible temperature.

For the stove having 8 kW nominal power and an installed catalyst volume of 2 x (0.2 x 0.09 x 0.02) m³ = 0.72 x 10⁻³ m³ a nominal space velocity of GHSV = 27,777 h⁻¹ could be achieved.

Furthermore, the combustion of the beech logs showed significantly lower emissions for the prototype "NEKO" compared to the reference model "xeoos". The reason for this is the adjustment of the geometry of the combustion chamber (extended lower combustion chamber) and the optimization of the air supply (burner ring and modified double plate) in connection with the high-temperature resistant metal oxide catalysts immediately after the flame. **Figure 2** depicts a schematic sketch of the front view of the NEKO stove.

2.4 Greenhouse gas (GHG) effectiveness of black carbon particles

BC particle emissions are the second largest driver of global warming. At least in small-scale furnaces the use of catalysts leads to a significant reduction of emissions. In order to quantify this effect, a comparison between GHG balances using catalysts and not using catalysts was carried out, thus, taking into account the climate impact of BC particles.

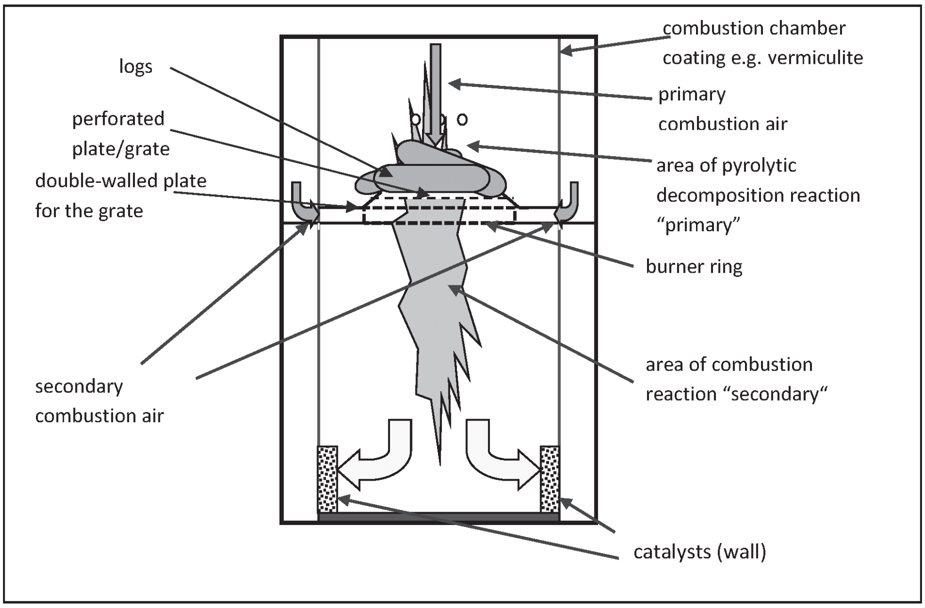


Figure 2. Schematic representation of the basic concept of the NEKO stove and explanation of the arrangement and inflow of the catalyst elements.

Table 2. Comparison of the reference stove "xeoos" (without catalyst) and the newly developed stove "NEKO" (with catalyst) according to the measured emission values.

parameters	emission values "xeoos" mg/m^3, normal conditions 13 % O_2	emission values "NEKO" mg/m^3, normal conditions 13 % O_2
CO	1,718	621
VOC (C1-equivalent)	156	36
total dust concentration	19	9

2.5 Evaluation method

There are different methodological approaches for the investigation of lifecycle GHG emissions from products or services. The assessment of lifecycle GHG emissions is often part of a Life Cycle Assessment (LCA) which is standardized and generally defined within ISO 14040 and ISO 14044 standards. LCA is an appropriate method for evaluating the GHG. Requirements for conducting an LCA are detailed in the international standards ISO 14040 [11] and ISO 14044 [12]. According to these standards, the analysis covers the complete product life cycle from the production of the raw material to the final disposal of the product after the use phase, including all pre-products and energy carriers used.

2.5.1 Goal and scope

The present GHG balance aims at comparing single room combustion units used for heat provision being equipped with and without oxidation catalysts with respect to their GHG potential. Therefore, the assessment is carried out alongside the complete process chain from the fuel conditioning to the transport, to the conversation plant, to the combustion and provision of useful heat.

2.5.2 Life Cycle Inventory (LCI) data

The Life Cycle Inventory (LCI) collects all relevant input and output flows taking into account all processes being connected to the heat provision of single room heaters. The processes contain energy and feedstock inputs, the application of auxiliary and operating materials, products and by-products, waste, emissions into the air, the water and the ground.

This environmental assessment is based primarily on the results of the DBFZ emission measurements, data from the DBFZ data base and the internationally accepted Ecoinvent database for Life Cycle Inventories Version 2.1 [13]. The LCI data for each process step is descripted in detail below with respect to the database.

Feedstock provision: The LCI data for the feedstock provision (logs, mix ex forest, 607 kg/m^3; LHV: 15.5 MJ/kg) come from the Ecoinvent database for Life Cycle Inventories Version 2.1.

Conversion/treatment: The data for the conversion process (i.e. combustion emissions, material and energy flows of the combustion processes) are results of DBFZ measurements. The inventory data from the production of the oxidation catalyst has been taken from the Ecoinvent database. The emissions during the construction of the plant have not been considered because the influence of these emissions over the total life cycle on the specific GHG emissions for a heat provision of 1 MJ is quite small.

2.5.3 Impact assessment

During the impact assessment phase the LCI data is analyzed with respect to potential impacts for the environment. To this end, specific impact models are assigned to the LCI data, are aggregated with the help of characterization factors and are described with regard to a reference substance. Thus, GHG emissions are calculated according to the IPCC method [14] and presented by means of the characterization factor as carbon dioxide equivalent (CO_2-eq). According to the IPCC method process related biomass CO_2 emissions are not included in the calculation because it is expected that biomass has absorbed the same CO_2 concentrations from the air during its growth.

Similarly, BC particle emissions are not considered according to the recent IPCC methods. However, for estimating the GHG potential of the emitted BC particles the calculation method in this balance also includes BC particles as climate-relevant emissions. BC particles that are spread in the air have different origins and impacts on the climate which depend on many factors. Hence, there can be found a wide range of data in the literature (210 to 1.500 $kgCO_{2\text{-eq}}$ per kg BC particle) [15]. In this work a mean characterization factor of 680 $gCO_{2\text{-eq}}$/g black carbon was chosen for a temporary estimation of the GHG potential.

3 Results

3.1 Comparison of the emission values

The effectiveness of the integrated catalyst was measured on the basis of mean values gained from at least four consecutive batch combustions. Further, the measurements were carried out with the methodology and combustion procedure described in section 2.2. However, the first combustion which was used to ignite the stove was not assessed, because during ignition the downdraft combustion stove operated according to the so-called upper combustion system without flowing through the catalysts. **Table 2** compares the measured emission values of the reference stove "xeoos" (without catalyst) to the newly developed stove "NEKO" (with catalyst) in order to evaluate the effects of emission control.

These measured values show that a significant reduction of emissions could be achieved by the integration of the catalysts. For example, carbon monoxide has been reduced by nearly 64%, volatile organic compounds by 77% and total dust by about 53%. While only a small extent of the dust was precipitated on the ceramic foam structure the major dust reduction took place within the catalyst by oxidative degradation of carbon-rich compounds like BC, PAH and non volatile organic compounds. Therefore, the reduction of the total dust concentration by 53% can completely be attributed to oxidative degradation of black carbon.

Figure 3. GHG emissions without the consideration of black carbon emissions.
w/o: without; w: with

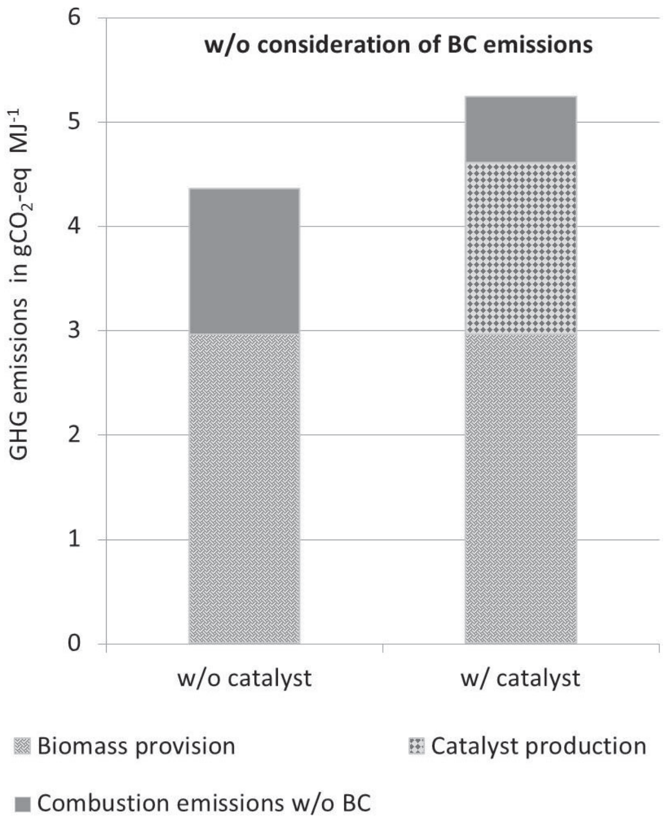
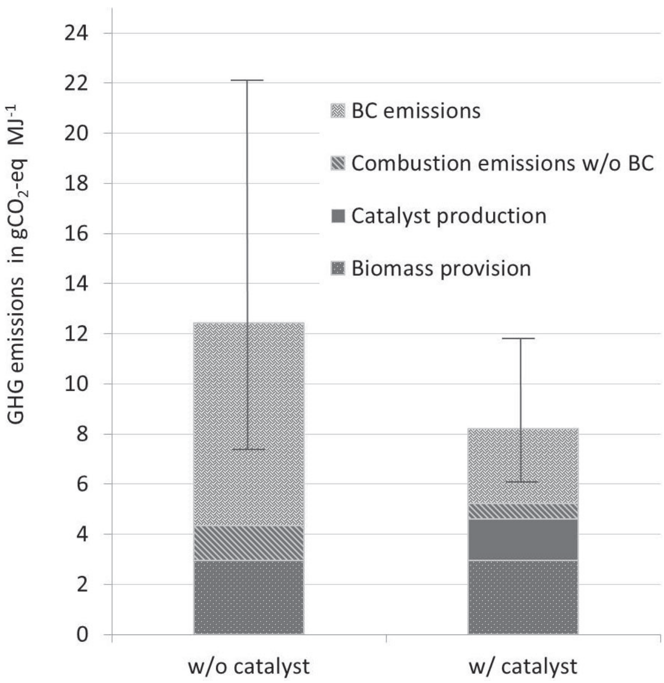


Figure 4. GHG emissions with the consideration of black carbon emissions.
w/o: without; w: with



3.2 Production and stability of the catalysts

The production of the catalysts takes place according to the following procedure. This procedure must be considered for the life cycle inventory and the evaluation of the inventory data of the oxidation catalyst.

The alumina foams with a catalytically active coating are produced by immersing cleaned sponge bodies into 1 M $Mn(NO_3)_2$-solution, drying them subsequently at 80 °C and afterwards treating them thermally at 180 °C. These steps are performed five times in total. Finally, the treatment is carried out at 1,000 ° C for twelve hours.

The stability of the catalyst was estimated on the basis of practical field measurements by means of a demonstration stove. Therefore, the catalysts were aged in a demonstration stove over 600 hours of operation (equals two or three heating periods) and then it was measured again at the described firing test bed. The results show no reduced degradation performance and consequently no significant aging. Therefore, a lifetime of 600 hours of operation was assumed for the subsequent balance. Probably, the achievable lifetime will be even longer depending on the user behavior, but this is still to prove by extensive practical measurements. To this end, practical experiences based on pilot series must be collected in the future.

3.3 GHG emissions

On the basis of the recorded inventory data and the results of the emission measurements two scenarios have been modeled in the LCA software and first GHG balances have been created. In order to show the impact of the BC particle emissions on the total emissions, the balance has been carried out according to the conventional IPCC method as well as the extended method with included BC particle emissions.

Figure 3 shows the GHG emissions from the provision of 1 MJ useful heat with and without using catalysts and without considering the climate effects of BC particles. It can previously be stated that the total emissions (i.e. 4.4 without catalyst and 5.2 $gCO_{2\text{-eq}}$ MJ^{-1} with catalyst) are quite low in comparison to fossil reference systems (e.g. heat mix gas/oil heating 87,6 $gCO_{2\text{-eq}}$ MJ^{-1} [16]). The direct combustion emissions primarily consist of methane (CH_4) emissions which can be reduced by using the catalysts. However, the emissions from the production of the catalysts, which are mainly caused by mining, are significantly higher than the achieved reduction of climate-related CH_4 emissions from combustion. Considering the low emissions of the starting scenario, the advantageousness of using catalysts cannot be presented at this point when solely regarding the conventional GHG emissions.

In contrast, **Figure 4** shows the situation when BC particle emissions are included in the calculation of the GHG emission. On the one hand, the high proportion of BC particle emission with regard to the total emissions becomes evident. On the other hand, a significant reduction of the total GHG emissions when using the catalyst is apparent. As already mentioned, the climate potential of BC particle emissions is specified in a wide range due many influence factors. The whiskers in the figure show the amount of emissions between the upper and lower limits when applying the emission factors. Moreover, they illustrate with regard to the adopted minimum climate impact of BC particle emissions, that the use of the catalyst has a positive influence on the climate efficiency of the process in any case.

4 Discussion and results

The gaseous air pollutants (CH_4 in particular) are responsible for approximately one third of total GHG emissions. The use of catalysts in single room furnaces, required for health protection, shows a slightly increased GHG effectiveness due to a comparatively high GHG effectiveness during production and the difficult removal of methane. However, the effectiveness is still significantly lower than the effectiveness of the current natural gas/fuel oil heat mix.
Including the effect of the BC particles leads to a tripling of the total GHG emissions during real operation even if a modern combustion system is used and only a medium-sized GHG effectiveness of BC particles from the existing range in publications is assumed. This shows the absolute importance of taking into account the BC particle emissions when evaluating single room heaters. Moreover, it underlines the need to develop and demand effective measures to reduce these emissions.
Catalysts can be such a measure. The observed dust reduction makes it plausible to assume a reduction of BC particles which leads to an evident saving of GHG equivalents in the overall view. As a result, log-wood furnaces achieve a significantly more positive GHG effectiveness than fossil heat deployment options.
During further investigations of this issue a characterization of the dust emissions is necessary in order to define the exact percentage of the amounts of BC with and without catalysts.
Additionally, it is necessary to demand on the basis of these findings the inclusion of BC particle emissions into future assessments of the GHG emissions of biomass combustion units.
Due to the wide range with regard to the evaluation of the climate effectiveness of BC particles, further investigations of the issue will lead to a better specification of the expected effectiveness.
From the perspective of the BC problem, it is important to demand a nationwide use of precipitators or catalysts for BC post-combustion at least for the today available manually operated log-wood fired single room heaters without automatic air control and combustion monitoring.
As far as the catalysts are concerned, further investigations should focus on the reduction of the production efforts, the increase of the precipitation efficiency regarding BC and methane, as well as the extension of the lifetime.
The results presented in this work should be followed by in-depth investigations and analyses to further validate and specify the issue, in particular, with regard to the exact composition of the dust, as well as the possibilities of producing catalysts and using these catalysts in different types of furnaces. Furthermore, similar studies should be carried out for automatically operated biomass boilers.

References

[1] United Nations: Paris Agreement. 12 December 2015. http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

[2] Erneuerbare Energien in Zahlen. Nationale und internationale Entwicklungen im Jahr 2015. Bundesministerium für Wirtschaft und Energie (BMWi). Berlin 2016.

[3] World Energy Outlook 2015. International Energy Agency (IEA). Paris 2015.

[4] *Lenz, V.; Naumann, K.; Bloche-Daub, K.; Rönsch, C.; Kaltschmitt, M.; Janczik, S.*: Erneuerbare Energien. BWK 68 (2016) No. 5, pp. 60-80.

[5] *Agostini, A.; Giuntoli, J.; Boulamanti, A.;Marelli, M.*: Carbon accounting of forest bioenergy. Conclusions and recommendations from a critical literature review. https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/carbon-accounting-forest-bioenergy-conclusions-and-recommendations-critical-literature

[6] *Bond, T. C.; Doherty, S. J.; Fahey, D. W.; Forster, P. M.* et al.: Bounding the role of black carbon in the climate system: A scientific assessment. J. Geophys. Res.: Atmospheres 118 (2013) No. 11, pp. 5380-5552.

[7] Integrated assessment of black carbon and tropospheric ozone. United Nations Environment Programme (UNEP). www.unep.org/dewa/Portals/67/pdf/BlackCarbon_report.pdf

[8] *Bindig, R.; Butt, S.; Hartmann, I.; Dvoracek, D.; Einicke, W.-D.; Enke, D.; Specht, B.; Werner, F.*: Neuartiger emissionsarmer Kaminofen (DBU-NEKO). DBFZ-Report Nr. 27. Leipzig 2016. www.dbfz.de/fileadmin/user_upload/Referenzen/DBFZ_Reports/DBFZ_Report_27.pdf

[9] *Bindig, R.; Butt, S.; Hartmann, I.; Dvoracek, D.* et al.: Entwicklung, Untersuchung und Einsatz neuartiger katalytisch wirksamer Baugruppen zur Darstellung eines besonders emissionsarmen Kaminofens. Abschlussbericht DBU. Leipzig 2015. www.dbu.de/OPAC/ab/DBU-Abschlussbericht-AZ-28412_02.pdf

[10] Patentverfahren 10 2013 020 398.8: Brennraum, Vorrichtung mit Brennraum, Verfahren und Nachrüstset. Eingereicht am 10. Dezember 2012.

[11] ISO 14040: Environmental management – Life cycle assessment – Principles and framework. Geneva: International Organization for Standardization 2006.

[12] ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines. Geneva: International Organization for Standardization 2006.

[13] Ecoinvent v2.1: Ecoinvent v2.1 for umberto 5.5, Swiss centre for life cycle inventories, 2009.

[14] *Eggleston, H. S.; Buendia, L.; Miwa, K.; Ngara, T.; Tanabe, K.*: IPCC Guidelines for National Greenhouse Gas Inventories. Vol. 4 agriculture, forestry and other land use, prepared by the National Greenhouse Gas Inventories Programme. IGES, Japan, 2006.

[15] *Agostini, A.; Giuntoli, J.; Boulamanti, A.*: Carbon accounting of forest bioenergy. European Commission. Joint Research Centre. Ispra 2014.

[16] *Thrän, D.; Pfeiffer, D.; Adler, P.; Brosowski, A.* et al.: Methodenhandbuch: Stoffstromorientierte Bilanzierung der Klimagaseffekte. Schriftenreihe des BMU-Förderprogramm „Energetische Biomassenutzung“. Leipzig DBFZ 2013.