Executive Summary:
Background
Residential wood combustion (RWC) appliances have been identified as major source of air pollution in Europe. As the thresholds for ambient levels of harmful particulate matter (PM10 and PM2.5) are exceeded in many regions, the public authorities are forced to implement effective emission reduction measures. Prohibition as the most effective measure, however, is clearly in conflict with Europe’s renewable energy targets. Hence there is a need to identify and implement effective measures for reduction of emissions especially in real life performance. The optimization of primary combustion and the integration of oxidation catalysts in RWC appliances for reducing emissions of CO, VOC and PM seems
feasible especially under real life performance.

Objectives
The BioCAT - project aimed at a significant CO and PM emission reduction of batch-wise fired room heating appliances. Therefore in a first step specific primary optimization measures for each combustion appliance will be implemented. Subsequently secondary optimization by integration of a honeycomb catalyst is performed. By these means target values for CO emission concentrations of 200 to 1000 mg/Nm³ (STP, 13% O2) and PM emission concentrations of 20 to 25 mg/Nm³ (STP, 13% O2) will be achieved. The performance of each developed product will be evaluated and demonstrated under laboratory conditions, under type testing conditions and under real life conditions. Finally five near-to-market products of integrated catalyst systems for each SME partner will be available.

Approach
Within the project four existing and one newly developed firewood and briquette stoves were primary optimized. In a second step oxidative honeycomb catalysts were integrated into the appliances. The performance of final BioCAT solutions were evaluated by standard type tests at certified testing institutes. Further special methods for determination of the catalyst performance itself as well as the overall performance of integrated BioCAT systems were developed and evaluated by comparative combustion tests.

Results
Within the BioCAT project five near to market products of batch wise fired room heating appliances have been developed. For these products significant improvement of system performance have been achieved by integration of oxidation catalysts following a primary optimization. The targeted emission indicated I have been achieved for all final BioCAT solutions of each SME partner. This was confirmed and evaluated by successful standard type tests at certified testing institutes. The abatement effects of the secondary technology are particularly advantageous during ignition phase of the appliance as well as during malfunction. In these phases significant CO emission reductions up to 80 percent have been achieved. The methods for determination and evaluation of catalyst performance as well as for integrated catalyst systems were developed as well as tested successfully by both RTD partners (TFZ and BE2020+). The testing method for determination of catalyst performance was introduced into the development process of a new VDI Guideline for secondary abatement technologies for residential room heating appliances (VDI 33999).

Conclusions
Honeycomb catalysts integrated in primary optimized firewood room heating appliances appear to be a promising technological approach towards a solution of the conflict of interest between air quality and climate change concerns. The long-term durability of such systems particularly under field operation conditions, however, still has to be further investigated.

Project Context and Objectives:
Context of the BioCAT project.
The EU climate and energy strategy for 2020 is summarized in the 20-20-20 targets. Until 2020 the greenhouse gases shall be cut by at least 20 % of 1990 levels, the use of renewables shall be increased to 20 %
of total energy production and the energy consumption shall be cut by 20 % of projected 2020 level (Directive 2009/28/EC).

In 2008 the total gross inland consumption of energy was 1,800 Mtoe from which 1,500 Mtoe were imported. (Eurostat 2010). Biomass is the most important renewable resource providing 105 Mtoe (5.8% of the total consumption), corresponding to 70% of the renewable energy sources. The consumption of biomass in households was estimated to be 32 Mtoe in 2008 (Eurostat 2010), resulting in a 14 % overall share of biomass for heating purposes. In most countries of the EU almost a third of all the biomass is used as wood logs or wood pellets in small-scale stoves or insets (Witt et al.2008: Renewable Sources of Energy - Status quo 2008 Worldwide and in Europe).

As residential heating with biomass is economically competitive with fossil based heating technologies as well as the most economic way to reduce CO2, residential heating with biomass is the silver bullet for achieving the EU targets in 2020. In addition solid fuel room heaters are very popular in Europe. Approximately 66 million biomass based room heating appliances are installed in European homes, which mean that on the average one biomass room heating appliance is installed in every third domestic home. But at the same time small-scale firewood residential heating appliances have been identified as major source of air pollution in Europe (i.e. Kappos et al. 2004: Health effects of particles in ambient air; Directive on Ambient Air Quality and Cleaner Air For Europe 2005). As the thresholds for ambient levels of harmful particulate matter (PM10 and PM2.5) are exceeded in many regions, the public authorities are forced to implement effective emission reduction measures. Prohibition as the most effective measure, however, is clearly in conflict with Europe’s renewable energy targets. Therefore it is essential to understand the reasons for high emissions of residential wood combustion (RWC) appliances particularly in real life operation to be able to improve the situation on both sides - technology and regulation.

Due to long lifetimes of RWC technology a significant share of existing combustions systems is far beyond state of the art technology. Even currently sold systems are often not optimized for field operation. It is well known that real life operating conditions significantly differ from the standard type testing methods. Many of today’s RWC systems are mainly optimized for the standard type test and operation safety. Therefore real life emissions and efficiency from biomass combustion units differ significantly to standard type test results.

The user behavior has a significant influence on the emission level of heating appliances. Especially the use of unsuited fuels (e.g. high water content) and improper operation (e.g. air supply settings) can lead to poor combustion conditions and consequently high emissions (Mudgal et al. 2009: Lot 15 Solid fuel small combustion installations. Task 3: Consumer behavior and local infrastructure)

Currently it is not clear which of these reasons contribute to what extend of emissions in real life operation. However, to improve the situation, emission limits from small-scale combustion units are continuously tightened. There is a need to identify the reasons of high emissions and implement effective measures for reduction of emissions in order to satisfy future national and current eco-label emission requirements. Finally a general reduction of PM emissions from batch wise fired room heaters and insets/closed fireplaces and an additional reduction of CO and VOC emissions from firewood stoves will be necessary.

Objectives of the BioCAT project.
The BioCAT project aims at a significantly decreasing emissions of CO, VOC and PM from batch wise fired room heating appliances, specifically insets/closed fireplaces and firewood stoves. Therefore an oxidative honeycomb catalyst technology is integrated into combustion units in combination with an optimization of the primary combustion conditions. By these measures the emission release is anticipated
The emission targets to be reached within the BioCAT project are in relation to emissions from currently best available technologies (BAT – according to Lot 15 EuP, Task 6, 2009) as well as the most stringent emission limits in Europe. The most stringent emission thresholds in Europe for insets/closed fireplaces firewood stoves are 1250 mg/Nm³ regarding CO and 40 mg/Nm³ regarding PM emissions, which is reflected in the German BimSchV Tier 2.

The associated most stringent emission limits for firewood stoves are 700 mg/Nm³ regarding CO and 30 mg/Nm³ regarding PM emissions (all values at STP, 13 %O₂). The CO emissions of BAT are 700 mg/Nm³ for insets/closed fireplaces and 600 mg/Nm³ for firewood stoves. The PM emissions of BAT are 40 mg/Nm³ for insets/closed fireplaces and 60 mg/Nm³ for firewood stoves (all values at STP, 13 %O₂).

The emission targets of insets/closed fireplaces BioCAT solutions are 400 mg/Nm³ for CO and 25 mg/Nm³ for PM emissions. Regarding firewood stoves the emission targets of BioCAT solutions are 200 mg/Nm³ for CO and 20 mg/Nm³ for PM emissions (all values at STP, 13 %O₂). This illustrates that the BioCAT project aims at setting a new emission standard for batch wise fired room heating appliances. For this the CO emissions from insets/closed fireplaces had to be reduced to approximately one half of the CO emissions from current BAT and CO emissions from wood stoves had to be even reduced to one third of the current BAT. The requirement is that all BioCAT product combinations will reach the most stringent emission limits in Europe and therefore set a new standard for BAT.

At the end of the BioCAT project five near-to-market product combinations are developed. After an extensive optimization of the primary combustion conditions, all products are equipped with the innovative catalyst technology EnviCat® which was especially developed to meet the needs of batch wise fired room heating appliances. This catalyst is based on a mullite ceramic carrier and is coated with promoted and stabilized alumina and proprietary amounts of platinum and palladium. The catalytic system is also available on a metallic carrier, which allows a lower reduction in cross area section and also an increase in catalytic active surface.

The final objective of the BioCAT project is the positive type testing according to EN 13240 respectively EN 13229 standard of the products at certified testing institutes.

Project Results:
Overview on the BioCAT approach.
Different methods were applied during the BioCAT project to assess the catalyst performance on the one hand, but also the effect of the primary optimisation and finally the overall achievement of the BioCAT solution. The consecutive investigation of the catalyst behaviour allowed its optimal integration into the combustion appliances.

1) Characterizing the CAT by synthetic flue gas: This test targeted to identify the optimum operation conditions of the catalyst and to assess the required temperature range for integration in a stove system. A synthetic preheated and mixed gas with N₂, CO₂, O₂; CO, NO and C7H8 was used to characterize the catalyst performance as well as to provide information for later integration development steps. The emissions are measured before and after the catalyst.

2) Characterizing the CAT by real flue gas: This testing method allows the characterisation of the catalyst under real gas conditions. Real flue gas of a continuously fed combustion system is conveyed over the catalyst system under defined flow and temperature conditions. The experimental set up consists of two
measurement sections upwards and downwards of the catalyst. For comparison also an uncoated "catalyst dummy element" (with same flow properties as catalyst but without catalytic activity) was used. This setup allowed the direct comparison of the emissions before and after the catalyst.

3) The primary optimisation effect in combustion systems: Each combustion appliance was tested accordingly to the respective EN standards. This allows the documentation and comparison of the development progress.

4) The secondary effect in combustion systems: The integration of a catalyst acts as a throttle in the flue gas path way. Thus it also influences the combustion conditions. To elucidate the catalyst efficiency a distinct method was developed. Because of the integration of the catalyst into the combustion system it is not possible to determine the flue gas before and after the catalyst. Thus, the emissions of the integrated catalyst system is determined at one measuring section downstream the catalyst. For this the tested combustion units were equipped with catalysts in varying designs and carrier materials as well as additionally with “dummys” to determine potential primary and secondary effects of the catalyst implementation. For determination of the significant catalyst reduction a statistical calculation was used respecting the variance of a batch wise combustion process as well as a certain probability for the catalyst reduction potential of a certain flue gas component.

5) BioCAT solutions: The BioCAT solution is the primary optimized combustion system with integrated catalyst. These final BioCAT solutions were type tested according to the respective EN standards at external certified testing institutes.

Characterizing the catalyst by synthetic gas.
For characterization of catalytic material a special test stand was developed and constructed in order to characterize the catalyst performance as well as to provide information for later integration development steps. Figure 1 presents the scheme of the test stand for characterization of the combustion catalyst performance. The test stand consists of a 1990 mm long high-grade steel tube, heated by two heating jackets, with a maximum heating temperature of 900°C. The catalyst is placed 100 mm after the end of the heated tube in a catalyst casing. The gases (N2, CO2, O2; CO, NO and C7H8) are mixed to the desired concentrations by mass flow controllers with the option to produce a wet gas mixture with wanted water content. This adjustable synthetic gas mixture passes the catalyst at a defined temperature. The gaseous emissions, temperatures and differential pressure are measured 100 mm before and 160 mm after the catalyst. A further temperature measuring point is directly integrated in the catalyst bed.

The catalyst in the BioCAT project consists of platinum and palladium and a carrier material. Related to the increasing and decreasing of temperature in a firewood stove, the structure resists to thermal caused tension in respective stoves. Because of the less part of solid particles and the non rapid flue gas stream in small scale combustion systems attrition of the catalyst surface can be neglected.

For the experimental investigation of the thermal stability of the catalyst of the BioCAT project several tests were performed. For this, three catalytic material samples were thermal treated at 700°C, 800°C and 900°C for 24 hours in a muffle oven. After thermal treatment the conversion rate at a certain temperature as well as at certain flue gas composition and flow conditions was determined for each sample. This comparative test showed that there are no significant reductions due to the thermal treatment of the catalyst samples (Figure 2).

The chemical deactivation is also known under the term catalyst poisoning. In this process, certain chemical substances such as sulphur, phosphorus, chlorine or lead in the gas phase are absorbed at the catalytic active. The difference to the normal catalytic reaction, however, is the fact, that the poisonous
substances do not desorb from the surface. This leads to an accumulation of the substances on the catalyst surface and this causes two effects:

- Occupied surface areas are no longer available for the catalytic reaction. A smaller active surface results a weaker catalyst performance.
- Fixed molecules in the catalytic surface can disturbed the mass transfer between gas molecules like carbon monoxide and oxygen. This transfer is prerequisite for the heterogeneous oxidation reaction.

Solid biomass fuels consist only of very little amounts of sulphur and chlorine. Furthermore the release of these elements is mainly in terms of particle emissions, which do not react with the catalytic surface.

According to the manufacturer, the catalyst which was used in the BioCAT project does not show any chemical deactivation during the operation in log wood combustions appliances.

For determination of reduction potential of catalytic material the test stand shown in Figure 1 was used. Comparative tests with the adjusted synthetic gas of 1000 ppm CO, 10 % O2, 11 % CO2 and a velocity of 0.8 m/s at catalyst allows the calculation of the characteristic catalyst temperatures, which describe a certain conversion rate. They are common in product specifications of catalyst manufacturer and in literature (Carnö et al. 1996; Blasin-Aubé et al. 2003; Ferrandon et al. 1999a; Liotta 2010).

Figure 3 shows the conversion rate of CO emission in percentage of the maximum conversion rate of 1000 ppm (100 %) as a function of catalyst temperature. In addition the characteristic temperatures T20, T50 and T90 are marked. These are specific temperatures used for a general characterization of a catalyst and its performance towards a certain component. In Figure 3 T20 represent 20% conversion rate at 190 °C catalyst temperature, T50 represents 50 % conversion rate reached at 238 °C catalyst temperature. 90% of maximum catalyst performance is reached at a catalyst temperature of 381 °C.

Carbon monoxide (CO) is a main component of the emissions from small scale combustion systems. Therefore the reduction potential of catalyst regarding CO was assessed. During the conversion tests the CO concentration was measured simultaneously in the gas stream before and after the catalyst. Figure 4 shows the results of these experiments calculated as conversion of carbon monoxide in percentage as a function of the catalyst temperature.

It is obvious in Figure 4 the optimal CO conversion of the used catalytic material is between 180 °C and 250 °C.

The first part of the graph (up to 170 °C) is characterised by a smooth slope of the CO conversion. At this temperature level the catalytic reaction is most probably limited by the kinetics of the reaction on the surface. This is followed by a significant increase in conversion rate 200 °C and 250 °C. This indicates the starting temperature of the optimum operation conditions of the catalyst. Such a strong increase in the conversion rate in a small temperature window is common for oxidation catalysts in a heterogeneous oxidation reaction. This denotes the temperature range when the limited factor of the catalytic reaction switches to transport phenomena of CO molecules to the catalytic surface.

The curves above 250 °C are again characterised by a slight increase in conversion. This means that the final conversion rate is limited by transportation process to the catalyst surface. The slight increase may be explained in the increase of the CO mobility with increasing temperature. In this temperature phase the most influence on the reduction potential may be the turbulence conditions at the catalytic surface.

The synthetic gas mixture is heated up in a tube before it enters the catalytic material. Reaching 500 °C at the catalyst the surface of the heated tube reactor already reached more than 900 °C. This leads to oxidation of carbon monoxide in the gas stream already before reaching the catalyst. Hence the input concentration of CO to the catalytic system is lower, which finally results in a slightly decreasing
During firewood combustion significant amounts of methane (CH4) emissions occur. Methane also represents has a high share on the emission of non-aromatic hydrocarbons. Furthermore methane has a 20 times higher global warming potential than carbon dioxide (CO2) and is therefore an emission with a huge impact. However, unlike other components of the VOC’s methane is not hazardous to human health. In general methane is used for the characterization of catalysts due to it’s representative of VOC. VOC emissions are known to be a hard to oxidize molecule due to its tetrahedron structure (Saracco, Specchia 2000)

During the methane conversion tests the emissions were measured simultaneously in the gas stream before and after the catalyst using two FIDs. Figure 5 shows the results of these experiments calculated as conversion of methane in percentage. It is illustrated that there is only a little methane conversion at temperatures around 500°C at catalyst surface. The maximum methane conversion was 10% for sample 3. The range of methane conversion of all three tested samples was in maximum between 5% and 10%. The measurement results (see Figure 5) showed that a catalytic oxidation starts at a temperature range above 400°C. Carnö et al. determined similar results with a noble metal coated catalyst. This and other literature sources show that the maximum methane conversion is in a temperature level above 600°C and therefore out of the range of the in the BioCAT project used test stand. For this reason the calculation of the characteristic temperatures (e.g. T20, T50) is not meaningful.

Furthermore the conversion rate of toluene was investigated. Toluene is an aromatic hydrocarbon which represents the tar components in emissions of small scale combustion systems. Aromatic hydrocarbons, especially polycyclic aromatic hydrocarbons (PAH) mainly result from incomplete combustion of carbonaceous fuels like for example firewood.

During the conversion tests of toluene the emissions were measured simultaneously in the gas stream before and after the catalyst using two FIDs. Figure 6 shows the results of these experiments calculated as conversion of toluene in percentage as a function of catalyst temperature. It is illustrated that toluene conversion starts around 250°C and becomes maximum at 350°C. The maximum conversion rate of toluene was found to be between 35% and 49% for the considered catalyst system. Table 2 shows the important temperatures for the characterization of the toluene conversion. The average results of 6 test runs with toluene shows: At 262°C 20% of the maximum conversion rate is reached, at 282°C already 50% and at 322°C the catalyst reaches 90% of its maximum capacity for toluene.

Characterizing the catalyst by real flue gas

The efficiency of the catalyst system is determined using two measuring sections up- and downstream of the catalytic converter after the combustion unit (Figure 7). Using two measuring points for parallel and simultaneous measuring operation eliminates the variance of the combustion. At all times the gas composition upstream and downstream of the catalyst is known. Only short evaluation periods are necessary to determine the elimination rate of the catalyst system. For calculating the conversion rate from a two-point-measurement Equation 1 is used. The conversion rate (%) is calculated by the difference of mass flow of upstream and downstream flue gas multiplied by hundred and finally divided by the upstream mass flow of flue gas. The mass flow (m) of a given component is averaged over periods with constant test conditions. The operational conditions for a certain elimination rate (emission load, gas flow rate, temperature) shall be recorded and reported.

The set up for catalyst testing under real combustion gas conditions consists of the combustion unit, two measuring sections with the catalytic converter and a adjustable catalyst bypass for controlling the
volumetric flow (Figure 8). The measuring sections are equipped with sampling points before and after the catalytic converter. Each sampling point close to the catalyst is connected to an FID as well as to a FTIR for the determination of gaseous pollutant concentrations. To achieve undisturbed flow profiles, the sampling point for particulate matter before the catalyst entrance is placed at a distance of 6 x D, (D is the diameter of the flue gas pipe). Downstream the catalyst a distance of 4 x D is required. The volumetric flow is measured with an impeller anemometer. The reduced pipe diameter leads to a higher flue gas velocity. This increases the accuracy of the flow rate measurement and reduces the necessary length of flue pipes for accurate velocity measurement.

Temperature and pressure are measured just after the combustion unit and additionally at the anemometer. Further temperature sensors are located at the sampling points for the gas analysis. The adjustable catalyst bypass allows the easy variation of the volumetric flow. The flue gas source (combustion unit) is an automatically charged pre-furnace, which is applicable for a wide range of fuels and thus allows modifying the flue gas quality within a wide range. Via a boiler (external heat exchanger) and a boiler bypass, the flue gases can be partly or fully cooled. Target temperatures can be achieved by controlled mixing of uncooled flue gases from the bypass with cooled flue gas from the external heat exchanger (Figure 9). These different temperature levels provide a high flexibility to achieve the desired thermal properties of the raw gas entering the catalyst.

The experiments were performed with a nominal power of the combustion unit between 8 to 9 kWtherm and a flue gas temperature at catalyst of 340 – 380 °C. The used fuel was commercially available wood chips with a water content of 30 %. The dimensions of the investigated honeycomb catalyst are round shaped with a diameter of 144 mm and a height of 51 mm. This catalyst consisted of a mullite ceramic carrier and is coated with platinum and palladium. For comparison also an uncoated carrier “catalyst dummy element” (with same flow properties as catalyst but without catalytic activity) is used. Cumulated masses ahead and past the catalyst are used to calculate the gas-specific conversion rates.

The CO-concentration is not affected by the catalyst-dummy because the cumulated CO-mass ahead and past catalyst is identical; the reduction is close to zero. Furthermore the inactive catalyst-dummy element did not show an effect on the VOC or PM concentration.

The catalyst reduces the CO-concentration in the flue gas and the peaks are flattened. The catalyst-induced drop of the CO-concentration results in a conversion rate of 80 %. The efficiency of the catalyst to oxidise VOC is lower than for CO. The comparison of the cumulated mass of VOC past and ahead the catalyst shows a conversion rate of 48 %. With catalyst the concentration of particulate matter is reduced for three repetitions. However, the conversion rates vary largely, between 10 and 37 % (mean: 27 %)

The primary optimisation effect in combustion systems.

Improving the combustion in log wood combustion by primary measures is meaningful to reach current threshold limits. In the BioCAT project a variety of different primary measures were implemented. All measures target for a decrease of emission release (particulate matter, carbon monoxide and other volatile organic carbon species) and an increase of energy efficiency. This is reached by improving the well-known 3-T criteria for a good combustion: time, temperature and turbulence.

- Each combustible needs a certain time to completely react with oxygen to the combustion products.
- The higher the temperature the faster is the reaction
- A high turbulence guarantees that the oxygen finds its path to the combustible

As a first prerequisite for the implementation of any primary measure the tightness of the combustion device needs to be guaranteed. Within this context tightness describes the constructive implementation to
supply all combustion air only at the foreseen inlet positions. In particular an improper sealing of the door and the pane was found to be a key factor. Such an uncontrolled air supply leads to a chain of effects: the air distribution on the grate is changed, the excess oxygen in the flue gas is increased and currents of cold air can be formed. All effects can significantly increase the emission and decrease the energy efficiency. Thus, to be able to introduce the air supply at the target position a complete tightness of the combustion appliance is required.

With the given requirement of air tightness a variety of subsequent primary measures can be implemented:

- Adapting air supply volume. The total air supply needs to be optimised for the mass of a fuel batch.
- Implementing air staging. Distribution of primary, secondary air supply and pane ventilation.
- Optimisation of pane ventilation. Optimisation of air inlet cross sections and nozzles for uniform pane ventilation, which must guarantee cleanness of pane at a low air intake.
- Insulation of combustion chamber. Measures to increase the temperature of the combustion chamber by e.g. refractory material or insulating pane glasses
- Implementation of post combustion chamber. Increase the pathway of gases under high temperature conditions
- Optimise energy management of firebed. Implementation of insulating or energy dissipation measures to handle the ignition phase
- Increase turbulence by baffles. Introduction of baffles in high temperature zones to utilize full capacity of post combustion chamber.
- Avoidance of short-cuts and unintended bypasses to ensure dedicated pathways of air supply and also flue gas

The highest outcome with lowest efforts was given by ensuring a high air tightness of the heating appliance. This can be achieved by only minor adaptions to the construction and by improved quality assurance instructions. They enable significant improvements of emission behaviour and efficiency. Also a very high outcome is achieved by improving the air supply. Implementation of air staging, adaption of air supply funnels to the necessary air supply and the optimisation of pane ventilation is easily conducted and shows a significant improvement in emissions and efficiency.

Apart from the technology also the fuel has a high impact on emissions and efficiency. In particular four different parameters need to be predefined for the operation of a log wood combustion appliance, in order to utilise the potential of the primary measures to a full amount:

- Fuel total mass
- Shape and number of logs
- Fuel moisture content
- Fuel species (i.e. hard or soft wood)

The combination of a detailed specification for the utilized fuel and an optimised combustion appliance has the potential for minimal emission release and maximum efficiency, which comply with national and international thresholds.

Table 3 shows the improvement regarding emissions and energy efficiency in various investigated combustion appliances of the BioCAT project. All improvements were achieved by applying different primary measures without basic constructional design changes. Significant decrease of the carbon monoxide (between -44 % to -74 %) and volatile organic carbon (between -40 % to 78 %) was achieved. Depending on the technology also the energy efficiency was significantly increased (up to 59 %).
The secondary effect in combustion systems.

The efficiency of the catalyst system is determined at one measuring section downstream the catalytic converter (Figure 10). The position of the catalytic converter inside the combustion unit prevents measuring upstream of the catalytic converter. By evaluating an integrated catalyst with one measuring section downstream the combustion unit, the variance caused by the combustion system itself becomes part of the total variance. It is therefore the goal to run the combustion system with a low variance between batches in order to contribute to a low variance of the elimination rate of the catalyst system. The tests include two phases. In the first phase a number of tests are conducted with an uncoated dummy material with the same shape and dimensions as the catalyst. Using this catalyst-dummy represents the reference case. The second test series was conducted with a catalyst instead of the dummy material. Doing so it is avoided that potential primary effects of the catalyst implementation (e.g. extended retention time of flue gas in combustion chamber) are interpreted as a catalytic effect. The dummy material as well as the catalyst has to be mounted identically according to the specifications identified by the catalyst integration development. Figure 11 shows an example of a catalyst-dummy and a catalyst used in one of the stoves.

All primary optimisation measures aim at an efficient combustion during the main combustion phase. However, these measures have only minor effect during the transient phases at the beginning and at the end of a batch combustion. For improvements in these phases the implementation of a catalyst is a feasible and attractive measure to further decrease emissions.

The effect of a catalyst is dependent on the temperature level and the intensity of the contact of catalytic elements with the agents. This denotes that by the introduction of a catalyst in particular two points need to be considered:

- The positioning of the catalyst downstream of the flue gas needs to reflect the operating conditions of the catalyst. Depending on the type of catalytic material the reduction of CO starts already at 100°C. But to burn off also soot from the surface of the catalyst, it is necessary to reach a temperature level of 300 to 500°C at least for a short duration.
- The reduction potential increases with the available catalytic surface and the turbulent contact with the surface. However, both criteria also increase the pressure drop over the catalyst, which is a key parameter for log wood combustion. Thus an optimum of pressure drop and contact area with catalyst needs to be found. Honey comb catalysts show the highest potential to resolve this trade-off (Figure 13). The available shapes of the honey comb catalyst are either round or rectangular. The carrier material differ between mullite- ceramic and metallic.

The final integration of the catalyst needs to be conducted following a certain procedure to achieve the optimum operation of the overall combustion appliance. In a first step the temperature profile downstream of the flue gas pathway needs to be surveyed. This gives a first indication of the positioning of the catalyst. The position shall also allow an easy and comfortable maintenance of the catalyst. Secondly a non-catalytic dummy is integrated at this position. A dummy is a flue gas element having exactly the same size, geometry and flow properties as the catalyst. It creates the same pressure drop in the flue gas path as the catalyst and allows a consecutive optimisation of the primary combustion conditions. Finally the catalyst is reintegrated and a final BioCAT solution is retrieved.

To simulate a real life use the combustion units were operated at non-optimal conditions. For three
combustion unit spruce was used to do the testing. One of the combustion units used briquettes as fuel. The stoves were operated at low excess air ratios. For these reasons emissions in the reference case (with catalyst-dummy) tended to be higher compared to type-testing results. The emissions were measured during six batches with catalyst-dummy and six batches with active catalyst.

- Homogeneous test fuel has to be selected and be prepared carefully in order to avoid high measuring variations by variable fuel properties.
- For high repeatability of measurements per batch the (re)charging shall be performed always in the same way.
- Before starting the measurement the furnace is operated over two batches (cold start + 1 batch).
- Phases with open door shall not be considered in the measurement or sampling.
- The emissions were measured at least during six batches (subsequent to the two pre-heating batches).
- One repetition coincides with one refilling interval / batch.
- Stove settings must be kept unchanged after the second refill with wood logs.
- For testing the stove with or without catalyst (reference measurement) identical refilling criteria apply.
- All continuously measured variables shall be measured in intervals not exceeding 20 seconds and recorded as the mean of less than one minute. The length of the intervals should allow to detect data fluctuations.

Nevertheless, even with constant settings the emissions of combustion units for log wood vary to some extent from batch to batch. To separate this “natural” effect from the catalytic effect it is necessary not only to calculate the difference of the means but also to analyse the statistically significant difference. Significant difference at a confidence level of 85 % means that with a probability of 85 % this calculated difference is an effect of the catalyst integration and cannot be explained by coincidence. The reduction calculated from the simple difference of the means only corresponds to a confidence level of 50 %. At a probability of only 50 % the conversion rate (calculated from the difference of the means) is caused by catalyst integration.

Regarding the difference of arithmetic mean values as calculated from the series of performed batches, the CO-concentration could be reduced by 74 to 97 % when using the catalyst. The high variation of the combustion from one batch to another leads to a largely reduced significant difference (at confidence level of 85 %), ranging from 64 to 77 %.

Looking at the arithmetic means of the batches the OGC-concentration could be reduced by 32 to 73 % when using the active catalyst. The significant difference (confidence level: 85 %) range from a non-significant reduction to 32 %.

Methane (CH4) is part of the OGC-emissions. The arithmetic means of the methane-concentration could be reduced up to 46 % by using the catalyst. At combustion unit 4 the level of residual oxygen was lower for the tests with catalyst than with catalyst-dummy. This lead to an increase of methane emissions compared to the tests with catalyst-dummy. In this case the methane conversion at the catalyst could not be identified (0 % conversion). The significant difference (confidence level: 85 %) ranges from a non-significant reduction to 8 %. Due to the high variation of the mean values of the methane concentration the significant differences differ widely from the differences of the arithmetic means.

In three out of four combustion units the arithmetic means of the PM-concentration could be reduced by 17 to 59 % by using the catalyst. At the combustion unit 1, the means of the PM concentrations were slightly increased with catalyst (Figure 31). The significant difference (confidence level: 85 %) range from a non-significant reduction to 21 %. Due to the high variation of the mean values of the PM concentration the
significant differences differ widely from the differences of the arithmetic means.

The BioCAT solutions
The technical development process was finished with an evaluation of BioCAT-integrated combustion systems at accredited bodies. The stove manufacturers did the type-testing (EN13240 and EN13229 respectively) to show performance at test bench conditions. A successful type-test is a prerequisite for the market launch of the products.

All of the developed combustion systems, with exception of the Staffieri “tunnel mega largo”, were type tested by external accredited testing institutes. The results are summarized in Table 4. The testing reports are presented in the appendix of this report. The names of both stoves of the manufacturer Stuv changed while development progress. The Stove Stuv16/68-V changed into Stuv16-78, the stove StuvX was a completely new prototype development while project with final name Stuv 30.3-IN.

The type test results of the primary optimized and catalyst integrated stoves and fireplace inserts are summarized in the following sentences:
The Hapero briquette stove, was tested according to the EN 13240 standard. The test results according respective standard are 836 mg/Nm3 for CO emissions, 8 mg/Nm3 for VOC emissions and 63 mg/Nm3 for PM emissions (all data at STP, 13% O2). Thedetermined efficiency is 79 %.
The Rika catalyst integrated firewood stove, was also tested according to the EN 13240 standard. The measured CO emissions are 209 mg/Nm3, the VOC emissions are 45 mg/Nm3 and the PM emissions are 19 mg/Nm3 (all data at STP, 13% O2) The efficiency was stated at 75 %.
The STUV 16-78 fireplace insert, was tested according to the EN 13229 standard. The results are 117 mg/Nm3 for CO emissions, 32 mg/Nm3 for VOC emissions and 27 mg/Nm3 for PM emissions (all data at STP, 13% O2). The determined efficiency is 79 %.
The STUV 30.3-IN firewood stove was tested according to the EN 13240 standard. The results are 391 mg/Nm3 for CO emissions, 78 mg/Nm3 for VOC emissions and 29 mg/Nm3 for PM emissions (all data at STP, 13% O2). The determined efficiency is 79 %.
The type testing of STAFFIERI Tunel Mega Largo is still in progress.
All type-tested combustion systems passed the thresholds for the German BimSchV tier 2 and in accordance to the Austrian 15a agreement. The BioCAT solutions of Rika and Stuv set a new state-of-the-art, since the emissions undergo the targeted values of the proposal.

Potential Impact:
Socio –economic impact.

The technological findings of the BioCAT projects lead to five innovative near to market products with integrated honeycomb catalyst systems. The emission and efficiency performance of each BioCAT solution were evaluated by standard type tests at accredited testing institutes. The results demonstrate a significant reduction of CO, VOC and PM emissions. Additionally significant lower emissions are reached during non optimal operating conditions and maloperation by the user. Due to the results of BioCAT project verified the high optimization potential of primary optimized and catalyst integrated batch wise fired room heating appliances particularly in real life operation.
The SME partners got comprehensive knowledge about effective primary optimization measures as well as about the implementation of the primary measures in different products. By this the SME partners will be able to transform the BioCAT knowledge to other products of them. This will lead to a multiplying effect...
and a overall optimization of their current range of products as well as for a improved approach regarding
further developed emission reduced and high efficient products. In addition SME partners got
comprehensive information about catalyst performance as well as knowledge of essential aspects for
integration of catalysts into batch wise fired room heating appliances. This will enable the SME partners to
adapt and develop their products towards further tightened emission thresholds in short time. Based on
the findings of the BioCAT project a competitive advantage of SME is guaranteed. The used catalyst is
specifically adapted to firewood combustion and reduces gaseous as well as particulate emissions
significantly particularly under maloperation conditions. Although there is a generally high market potential
of BioCAT solutions not all SME partners, however, decided to bring the final BioCAT solutions into the
market as long as their current products meet the legal requirements. Additionally the increased costs of
the product in comparison to not catalyst equipped combustion appliance is not accepted in the markets
yet. Consequently the legislative body and the market do not force them to bring the BioCAT solutions into
market. Therefore Rika and Stûv will only adapt their products with the primary optimization measures.
Stafferi, however, will use the BioCAT solution to meet the legal requirements and to get their product into
market. The BioCAT solution of Stafferi enables the company to extend its product into the German and
into the Austrian market. Hapero decided to use the outcomes of the BioCAT project for revision of their
briquette combustion concept and finally for development of a new product without automatic fuel supply.
For this a follow-up project of Bioenergy2020+ and Hapero is planned. Generally the SME partners of
BioCAT projects are able to react quickly on strengthened emission limits. Further the BioCAT solutions
guarantee the SME partners a stable or increasing market share in near future.
The developments made in the BioCAT project strengthen the market positions of the participating SME
partners. The BioCAT products and already the primary optimized combustion systems reach the
emission levels of the currently best available technology. Therefore the project will have a direct impact
on their volume of sales. The know-how transfer also enables the SME partners to multiply the results
gained in the BioCAT project. By this impact on the volume of sales, also employment is safeguarded and
possibly enhanced.

Wider societal implications.

The technological optimization applied by the two step BioCAT approach (combination of primary and
secondary measures in one product) lead to a significant emission reduction regarding operation of batch
wise fired room heating appliances. In compare to the initial system analysis of all combustion appliances
of BioCAT project the CO and VOC emissions were reduced up to 90 %. Due to the toxic as well as the
carcinogenic impact of CO and VOC this is a significant improvement regarding human health. VOC
emissions contain many compounds that cause displeasing odor. Because of this issue public authorities
often are concerned with complaints of neighbors of firewood room heating users. By reduction of VOC
also the aromatic compounds could be reduced leading subsequently to a reduction of odor trouble. This
will reduce complaints and thus raise the public acceptation respecting firewood room heating appliances
particularly. Therefore it would be possible to increase the use of firewood room heating appliances
particularly in urban areas leading to a reduction of fossil resources for room heating purposes.
Batch wise fired firewood room heating appliances are a major source for air pollution. Due to this, the
emission thresholds for operation for this kind of residential wood combustion appliances become more
and more stringent. PM emissions can seriously affect human health and they are claimed to be
responsible for bronchial asthma as well as for allergic disease of the respiratory path. The PM emissions
of BioCAT solutions are around 20 to 30 mg/Nm³. This is only half of the BAT according to Lot 15 EuP (Task 6, 2009). Consequently BioCAT solutions enable a significant reduction of PM emissions and therefore a improvement of pollution of ambient air. However, the results of BioCAT project illustrates that significant emission reductions are also reached at maloperation (i.e. uncertain fuels, overload, poor air conditions, wrong user behavior). Concluding to that it will be confident that emissions in real life will be reduced also if the appliance is not operated at optimal conditions. Further the BioCAT solutions show a trend towards higher efficiencies in comparison to the initial system analysis particularly under field operating conditions. This will have positive effects for the user of BioCAT solution as well as positive economic effects. A raised efficiency leads to a lower fuel consumption at a certain thermal heat output. This will enforce a further reduction of emissions. Additionally a minor fuel demand of the user enables a increase of the overall potential for energetic or material use of wood resources.

The BioCAT solutions do not need any electricity for correct function. Therefore BioCAT solutions also meet the requirement of user respecting a guaranteed security of energy supply. Therefore the acceptance for this secondary abatement technology will be much higher compared to secondary abatement technologies with electricity demand.

Main dissemination activities

Within the BioCAT project several dissemination activities were done to bring in the knowledge as well as technology of BioCAT integrated solutions into the market of firewood stoves. Therefore much scientific as well as popular information was disseminated to all relevant stakeholders such as retailers, contractors, end customer, public stakeholders, legal authorities, linked industry, topic related associations and scientific community in the field of small scale biomass combustion. Following the main dissemination activities are listed and described:

BioCAT Website
A website for the project BioCAT is hosted under www.biocat.bioenergy2020.eu The website is continuously provided with newest information on the project BioCAT. Therefore following substructure was provided containing a general description of BioCAT project, information about relevant events concerning the BioCAT project and publications such as public reports or scientific publications or presentations. Further relevant links and contacts about involved people are given.

Wikipedia entry
An entry on the BioCAT project was made at www.wikipedia.org. The entry reflects the main outcome of the project and acknowledges the funding of the EC under FP7 – Research for the benefit of SMEs.

Video Clip on BioCAT Project
A video clip of the BioCAT project was produced. The video clip lasts 7 minutes and 54 seconds. The projects background, objectives and approach are explained in interviews with employees of BIOENERGY2020+, which were involved in the BioCAT project. The video clip was disseminated and distributed via the following websites:
- www.energiefernsehen.de
- www.bioenergy2020.eu
Marketing Booklet
Dissemination of main outcomes and foregrounds to all relevant stakeholders with a marketing booklet.
The marketing booklet provides all relevant topics of the BioCAT project.

Dissemination of results in standardization groups
The standardization results of the BioCAT project are disseminated to take influence in ongoing
standardization work. For this the methodology of testing secondary abatement technologies and the
procedure of testing of stoves and insets under practical conditions were used. The results are presented
on the Advisory Board meetings, where closely related international and national stakeholders get together
as well as at national and international standardisation groups (VDI 33999, EN 13240 & EN 13229)

Dissemination of technology outcome of the project
The near-to-market products were achieved at the end of the project. However the technology outcome of
the respective products will be done after the project. The planned dissemination measures are:
■ Presentation of Stove/Inset systems on Fares & Expos
■ Presentation of a catalyst demonstrator (“DemoCAT”) on Fares & Expos
■ Visual & Oral presentation of an overview on near-to-market product outcome of the BioCAT project at
  industrial conferences
■ Newsletter & marketing booklets as material for retailer information campaign

Dissemination of scientific results
The dissemination of scientific project results were done continuously during the whole project duration.
They were disseminated at scientific & industrial conferences (already at the early state of the project), at
a BioCAT Advisory Board meetings where closely related national and international stakeholders get
together. Further the scientific outcomes will be disseminated as scientific articles that will be published in
national and international scientific journals

Exploitation of results

Technology exploitation:
The technology exploitation of the BioCAT project results will be done by the SME partners. Each SME
partner will use the knowledge of the primary optimization as well as the basic primary approach used for
all developed and optimized products. Further each SME partner has the opportunity to bring the catalyst
integrated products (BioCAT solutions) into the market.

Scientific exploitation
The scientific results were exploited continuously over the project duration. For this different scientific
presentations as well as publications were performed. Further the final results will be used for scientific
exploitation at national and international scientific conferences. For each publication the scientific partners
cooperate with the respective SME partner.

Exploitation of results for standardization
The BioCAT project results were used and will be used for standardization purposes. In detail the results will be exploited for following standardization groups. The methodical results are used for development of the new VDI-Guideline 33999. This guideline will provide test measurements as well as test procedures about testing of secondary abatement technologies. Further the methods and procedures used in the BioCAT project are represented in the revision group of EN 13240 & EN 13229 for development of testing procedures and measurement methods for standard type test of respective products.

List of Websites:
A website for the project BioCAT is hosted under www.biocat.bioenergy2020.eu

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Documents connexes

- final1-figures.pdf

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