Joint RTD programme on Small-Scale Combustion

Achieved Results

in the framework of ERA-NET Bioenergy

September 2009

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1 Summary

ERA-NET Bioenergy is a network of national government agencies and ministries responsible for coordinating and funding national research efforts into bioenergy.

In the framework of ERA-NET Bioenergy, a call for proposals on small-scale combustion was launched in March 2006. Universities and research organisations from Austria, Finland, Germany, Sweden and the UK were invited to send their proposals following national eligibility criteria.

The joint RTD programme was initiated by the building of a common framework. Therefore, analyses of the legislation, of the evaluation methods regarding proposals, as well as of the barriers on programme financing were carried out. The participating organisations agreed on a common process for launching the call and evaluating the proposals. The decisions to fund projects were, however, made nationally, and the funding came from national budgets, preferably by incorporating the granted projects into the national research programmes.

Eighteen proposals were received, the total requested funding for which was 7.6 M€. These proposals were evaluated by an international jury who provided recommendations for funding. The final funding decisions were taken nationally after the jury meeting according to each country’s own rules.

The process resulted in five funded projects with a total granted support of 1.7 M€:

- Development of Test Methods for Non Wood Small-Scale Combustion Plants
- Clean Biomass Combustion in Residential Heating: Particulate Measurements, Sampling and Physicochemical and Toxicological Characterization (BIOMASS-PM)
- Evaluation of technology for small scale combustion of pellets from new ash rich biomasses regarding combustion technology and emission reduction in special case particulate matter and Nox (Combustion Characteristics of Ash Rich Pellets)
- Small Scale Biomass-Fired CHP Systems
- Control Potential of Different Operating Methods in Small-Scale Wood Pellet Combustion (COPECOM)

Feedback was gained from the researchers on how they had experienced working in the frame of an ERA-NET Bioenergy joint call. Overall, the experience was very positive. The project leaders stated that there must be a coordinated funding within a specified area to realise cooperation between research groups in different countries.

2 Introduction

ERA-NET Bioenergy is a network of national government agencies and ministries responsible for coordinating and funding national research efforts on bioenergy. The goal of this network is to strengthen national bioenergy research programmes by enhancing cooperation and coordination between national agencies. The aim is that, through collaboration, the individual national programmes produce higher quality results, and through coordination complement each other, avoiding duplication.

To reach these goals the network is pursuing four lines of activity:

- Establishing structures for the systematic exchange of information
- Identifying common strategic issues to form a basis for integrated programmes and projects
- Undertaking joint activities such as common programme monitoring
- Implementing joint research activities

This report will summarise the successful first example of implementing joint research activities: the pilot joint RTD programme on the topic “Small-Scale Combustion”. From the lessons learnt of this first pilot joint programme, a list of recommendations was written that can be used for future joint programmes. In Table 1 all steps from the initiation to the evaluation of the joint RTD programme are listed.

Table 1. The chronological order of all the steps in the call process

2005	Formulating the idea and choosing ERA-NET Bioenergy participants
1 March 2006	Launch of the call for proposals
3 May 2006	Deadline of the call for proposals
16 May 2006	Information exchange on received proposals among the ERA-NET Bioenergy SSC participants
June 2006	Pre-check of proposals by the ERA-NET Bioenergy SSC participants
30 June 2006	Members of international evaluation jury nominated
1 August 2006	Proposals sent to jury members
1 Sept 2006	Jury meeting on evaluating proposals
16 October 2006	National funding decisions made
17 October 2006	Clearing process and contract negotiations
November 2006 – January 2007	Granted projects started
May – August 2008	Granted project ended
December 2008	Evaluation of the SSC RTD programme

3 Background

ERA-NET Bioenergy is an EU project with the objective to establish structural cooperation between national bioenergy research programmes in the member states. The 24 EU countries spent around 220 M€ on bioenergy research and development in 2001, of which 80% came from the six original ERA-NET Bioenergy member states. It was recognised that public funds could be more effective and efficient if strong cooperation and coordination of national research activities were achieved through networking. Therefore, in 2004, six member states initiated ERA-NET Bioenergy in order to strengthen the European research area (ERA) in the field of bioenergy. By 2008, fifteen organisations from ten countries have started to gain experience in joint actions, workshops and joint calls in the area of bioenergy research (see Table 2).

One of the tasks of ERA-NET Bioenergy is to carry out and gain experience from pilots of joint transnational research. The implementation will be done with transparent mechanisms such as evaluations, project co-operation and calls for research proposals (such as the Small-Scale Combustion Programme described in this report).

Table 2. Members of ERA-NET Bioenergy. Members involved in the Small-Scale Combustion Programme are highlighted

Organisation	Country	Acronym	Dates
SenterNovem	The Netherlands	SenterNovem (co-ordinator)	Since start
Ministry of Economic Affairs	The Netherlands	MinEA	Since start
Finnish Funding Agency for Technology and Innovation	Finland	Tekes	Since start
Swedish Energy Agency	Sweden		Since start
Department of Trade and Industry	United Kingdom	DTI / BERR	Till 1-9-2007
Engineering and Physical Sciences Research Council	United Kingdom	EPSRC	Since start
Federal Ministry of Transport, Innovation and Technology	Austria	BMVIT	Since start
The Austrian Research Promotion Agency	Austria	FFG	Since start
Austrian Energy Agency	Austria	AEA	Since start
Fachagentur Nachwachsende Rohstoffe	Germany	FNR	Since start
Federal Ministry of Agriculture, Food and Consumer Protection	Germany	BMELV	Since start
Energinet.dk	Denmark	Energinet.dk	Since 1-4-2006
French Environment and Energy Management Agency	France	ADEME	Since 1-4-2006
The National Centre for Research and Development	Poland	NCBiR	Since 1-12-2008
Sustainable Energy Ireland	Ireland	SEI	Since 1-12-2008

4 Initiating the joint RTD programme

4.1 Choosing the topic

In the first meeting of the ERA-NET Bioenergy partners in early 2005, the process of identifying areas for cooperation started. A long-list of areas was prepared, with inputs from each partner. From this long-list, the subject of small-scale combustion was chosen as an interesting area for cooperation between the members from Austria, Finland, Germany, Sweden and the UK[1] and it was decided to start a call for proposals on this subject.

During a workshop in February 2006, detailed decisions were made on how the joint programme should be executed.

4.2 Identifying barriers and cooperation models

To be able to accomplish a joint RTD programme, a cooperation framework had to be established. Each partner in the SSC-team had to perform the actions described in section *5 Accomplishing the programme* independently of each other, yet in a coherent way, so careful cooperation was required during all actions. Therefore, analyses of legislation, of evaluation methods and of barriers on programme financing were carried out. Simultaneously, areas of cooperation other than small-scale combustion were started and the analysis of barriers and cooperation models was used as an input for them as well.

Funding regulations were found to differ between the participating countries. Some countries had specific legislation on research funding while others had only general state aid laws. There were also various funding instruments, such as grants, loans or contracts. Nevertheless, the call on small-scale combustion has proven that this was not a hindrance to cooperation.

The ERA-NET Bioenergy members evaluated three proposals using their national criteria to learn about differences in working methods. In addition, the various evaluation criteria used by the countries were studied. In the analysis of the criteria, one single most important criterion that determined the outcome of the evaluation was not found. However, it was decided that, for the small-scale programme, a common evaluation method would be used.

The establishment of a financial common pot would be a means to prevent proposals from being rejected due to national budget constrains in one country. A common pot would mean that all national funding to the joint programme went into the same pot and all funding decisions were made together, not nationally.

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[1] The ERA-NET Bioenergy members participating in the Small-Scale Combustion RTD Programme are hereafter called the SSC-team.

Regulations for funding foreign scientists and entities vary among the countries. In some countries, it is possible to fund foreign entities if the research is of interest to and relevant for the country. It is also possible that foreign entities participate as subcontractors and thus do not receive direct funding. Typically, grantees must be established and the implementation of results be possible in the country. Therefore, most countries would not have been able to participate in a common pot, and it was thus decided not to use this model, but the following one:

The participating organisations agreed on a common process for launching the call and evaluating the proposals. The funding decisions were, however, made nationally, and funding came from national budgets, preferably by incorporating the granted projects into the national research programmes.

5 Accomplishing the programme

5.1 Opening the call for proposals

In the beginning of March 2006, the first pilot joint call for proposals on the topic "Small-Scale Combustion" was launched. In this coordinated activity, five countries participated with their national programmes: Austria, Finland, Germany, Sweden and the UK.

The following topics were defined for proposals:

1 Combustion control and fuel input/supply in small-scale combustion
2 Clean combustion and emission control
3 Test methods for non-wood small-scale combustion plants
4 Small-scale CHP (combined heat and power production)

Proposals were invited from universities and research organisations following national eligibility criteria. Small and medium companies were also allowed to participate, however, only when acting as research organisations. The proposed projects had to consist of consortia of partners from at least two of the countries involved in the call.

Each partner in the consortium applied separately to the relevant national agency. The proposal had to be submitted in two parts:

- The common proposal –written jointly by the applying researchers of the consortium. The common proposal had to be in English, as it was evaluated by an international jury and formed the basis for the funding decision.
- The national standard application form(s) – following the rules of the agency.

Eighteen proposals were received applying for in total 7.6 M€.

The common proposals could not be altered after the deadline for submitting them.

5.2 Evaluation of proposals

The evaluation of proposals was conducted by an international jury who provided recommendations for funding. The ERA-NET Bioenergy member Tekes, from Finland, was the secretariat of the call, collecting all the inputs from the various evaluation processes. For information exchange, a virtual office was used for sharing the documentation emanating from the evaluation process.

The evaluation process was enclosed by a number of sub-processes, as follows.

5.2.1 Pre-check of proposals

The evaluation of proposals started with a pre-check conducted by the responsible persons at the agencies. The aim of the pre-check was to guarantee that the proposals met all formal and financial requirements and that the projects fit into the participating national programmes. The pre-check dealt only with formal aspects and did not evaluate the scientific quality of the proposals.

5.2.2 Jury evaluation process

The jury was composed of one expert from each country in the SSC-team.

Firstly, the jury experts made pre-judgements of the proposals that had passed the pre-check. The judgements were made using an evaluation form that was adapted to the small-scale combustion call from an Austrian research programme.

Thereafter, the final judgements were made during a meeting lead by a moderator. The members from the ERA-NET Bioenergy countries not participating in the programme were welcome to join the jury meeting as observers. During the jury meeting, the experts had to agree on a common score for each of the evaluation criteria. Total scores resulted in a ranking list of the proposals.

In addition, the jury experts had to formulate recommendations and comments on each proposal to help the SSC-team formulate the rejection and invitation letters. The recommendations stated whether the projects were

- Definitely to be funded if resources were available
- Fundable at the discretion of the ERA-NET Bioenergy members if sufficient funding was available
- Not to be funded even if sufficient fund was available

Finally, a strategic panel, comprised of the SSC-team, held a meeting to analyse how the national budgets would impact grant decisions.

5.2.3 National decisions for granting proposals

The final funding decisions were taken nationally after the jury meeting and according to each country's own rules. It was agreed that in case one country should reject a joint project during the national decision process, this whole project would not be funded. It was also agreed that nothing should be published before the national decisions had been made.

5.2.4 Clearing process

The clearing process was an information exchange between the SSC-team to inform each other on the outcome of the national decision processes. Not until all national decisions were made did the agencies send out the binding feedback.

5.3 Funded projects

5.3.1 Requirements

Contract negotiations started after the clearing process. A consortium agreement had to be signed by all project partners of a joint project within three months after the partners received their grant agreements/contracts. The purpose of the consortium agreement was to agree on intellectual property rights and other relevant issues concerning responsibilities within the project and exploitation of results.

All grant agreements/contracts included the conditional phrase “the project will only be funded if funded by all countries participating in the project”, or similar wording.

In addition to the standard requirements of the individual national funding agency, the SSC-team required that the project partners participate in workshops organised by ERA-NET Bioenergy. A common final report written in English which described the research work and outcomes was also demanded. Research outputs were expected to be publicly available.

For some countries, the national budget was a limiting factor to funding, i.e. not all projects whose scientific quality was evaluated positively by the jury could be financed. For others, budget increases during later stages of the process meant that an additional project could be funded.

The funded projects are listed in Table 3.

Table 3. Budgets and grants of the approved projects

Project No	Title of project	Project acronym	Participating country	Total budget €	Granted support €
JWP1-5	Development of Test Methods for Non Wood Small-Scale Combustion Plants		AT	119 550	49 828
			DE	128 291	118 118
			FI	49 140	32 635
			SE	50 118	49 140
JWP1-5 Total				**347 099**	**249 720**
JWP1-9	Clean Biomass Combustion in Residential Heating: Particulate Measurements, Sampling and Physicochemical and Toxicological Characterization	BIOMASS-PM	AT	60 000	97 471
			DE	55 350	85 000
			FI	223 333	158 000
			SE	232 421	120 825
JWP1-9 Total				**571 104**	**461 296**
JWP1-11	Evaluation of technology for small scale combustion of pellets from new ash rich biomasses regarding combustion technology and emission reduction in special case particulate matter and Nox	Combustion Characteristics of Ash Rich Pellets	DE	300 404	234 912
			FI	75 000	45 000
			SE	131 912	129 349
JWP1-11 Total				**507 316**	**409 261**
JWP1-12	Small Scale Biomass-Fired CHP Systems		DE	242 553	97 165
			UK	112 600	194 000

JWP1-12 Total				**355 153**	**291 165**
JWP1-15	Control Potential of Different Operating Methods in Small-Scale Wood Pellet Combustion	COPECOM	FI	174 300	157 300
			SE	121 570	100 000
JWP1-15 Total				**295 870**	**257 300**
Total				**2 076 542**	**1 668 742**

5.3.2 Project abstracts

JWP1-5 Development of Test Methods for Non Wood Small-Scale Combustion Plants

The aim was to identify European regulations concerning testing rules, general conditions of the energetic use of non-wood biomass, state of boiler technology, applicable measurement methods, development of adequate test procedures and identification of further R&D required. The results show for example that there are potentials for energy crops and various residues, especially straw from grain production in Austria, Denmark, Finland and Sweden. The most interesting types of biomass for use in small-scale combustion units are straw pellets and pellets from Miscanthus or reed canary grass. The future demand on energy grain will depend very much on market prices for grain. To meet an increased demand for non-wood fuels, there is a need to develop fuel and load flexibility to avoid sintering, fouling, corrosion and high emissions. It is also important to develop technologies that meet the users' demands for convenience. More research is needed on identifying disturbance on dust measurements.

A best practice guideline was prepared as a proposal for an international standard for testing requirements of automatically stoked boilers for non wood solid biomass fuels up to 400 kW. It is strongly recommended that a European standard regulating the requirements for testing small-scale furnaces for biogenic non-wood fuels be established.

JWP1-9 BIOMASS-PM

The use of solid biofuels for heating is expected to increase in the EU as a means to reduce the emissions of greenhouses gases to the atmosphere. However, the combustion of solid biofuels in the residential sector is a significant emission source of fine particles that have significant negative health effects. Therefore, there is a need to harmonise the regulations on emissions from small-scale boilers and stoves.

The aim of this project was to determine feasible methods for particulate emission measurements, sampling and physicochemical characterisation, taking into account not only the combustion process and particulate sampling, but also the physicochemical characterisation of particulate emissions and the evaluation of emission-related health risks.

The following measures for the reduction of particulate emissions from small-scale biomass combustion were proposed: i) financial support for the substitution of old combustion devices, ii) provision of consumer training to ensure appropriate handling of boilers and stoves, iii) support of research on low particulate emission combustion technologies and iv) support of research on cleaning technologies. A best practise guideline for particle measurement was worked out. Common requirements for toxicological studies – aerosol exposure as well as particulate collection methods – were given. Toxicological studies connected to chemical composition of particles can be used to identify incorrect handling of devices.

JWP1-11 Combustion Characteristics of Ash Rich Pellets

Final report from JWP1-11 has not been finished within the timeframe decided on.

JWP1-12 Small Scale Biomass-Fired CHP Systems

The aim of this project was to develop a novel 2 kWe biomass-fired combined heat and power (CHP) system suitable for public and large domestic buildings.

A small-scale biomass-fired CHP with Organic Rankine Cycle (ORC) was developed, modelled and tested. Successful power generation with the experimental system indicated that ORC-based power generation can be applied to 1-10 kWe biomass-fired CHP. Both modelling and laboratory testing indicated that the total efficiency of the CHP system can be 80% or higher. The highest achievable electrical efficiency of the CHP system was within the range of 4.3 – 8.5%, which was similar to the efficiency predicted by modelling. The electrical efficiency of the CHP system achieved with the existing turbine-pulley-alternator set was only about 1.1%.

JWP1-15 COPECOM

In small-scale solid biomass-fired systems the most severe disturbance is the fluctuation of energy content in the fuel feed. So far, no cost-effective feed-forward solution for his disturbance has been presented.

The goal of this project was to compare the control potential of different domestic wood pellet burners (< 20 kW) based on direct combustion and on gasification. The comparison was done both in theory and in practice with respect to cost effectiveness, burning efficiency and emissions.

When combining the two theoretical models developed in the project, a comprehensive monitoring method for small-scale wood-pellet combustion is achieved, which provides upgraded information on how to control the process to achieve higher efficiency with minimised emissions. However, a lot of work is still necessary in order to make such a concept for estimating efficiency, flue gas and air flow based on physical and data-based models commercially available in combustion units.

6 Evaluation of the joint programme

Feedback was gained from the researchers on how they had experienced working in the frame of an ERA-NET Bioenergy joint call. Firstly, the researcher's experience from the call process was evaluated during an initial project workshop and the general impression of the call was positive. However, there was uncertainty raised due to the small scale of both the number of countries involved in ERA-NET Bioenergy and the amount of money available for funding. In addition, a better ERA-NET Bioenergy coordination was requested in respect of, for example, synchronized decisions and synchronized dates for common end reporting.

At the final stage of the projects, a questionnaire was sent out to all national project leaders. The following questions were raised:

- Did you know your partners before?
- Will you continue to work with your partners?
- How did the cooperation with industry partners work?
- Has the cooperation made your own research more effective?
- Has the cooperation enhanced the quality of your research?
- Do you have suggestions for further cooperation topics?
- Has the dissemination been improved?
- Pros and cons?

The overall opinion on the joint call was very positive. The participants stated that the work preformed would never have been carried out if the joint call had not been launched. The vital point was that there must be a coordinated funding within a specified area to realise cooperation between research groups in different countries. When the funding is not coordinated, the research groups will not necessary be funded at the same time and their conditions to start projects will halt.

Many of the partners did not know each other before, but wish to continue their cooperation in the future. The participants considered their newly established networks as an investment and wanted further joint calls to get more use of their networks. The cooperation with industry partners, however, can be improved. Most of the project leaders felt that the cooperation had enhanced the efficiency and quality of the research. The dissemination has been improved, but there are room for even further improvements.

The project time was considered to short and the funding to low, especially regarding that the initial networking was time consuming. There were requests for a template for the consortium agreement. The meetings were thought to be very useful, with some comments that the travelling required a lot of resources.

The ERA-NET Bioenergy team used the feedback for improving subsequent calls.

In addition to the questions raised by the ERA-NET Bioenergy team to the researchers, an external evaluation of the joint call has been made. The aim of that evaluation was to assess whether any added value has resulted from the joint work programme. The target group of the evaluation were the ERA-NET Bioenergy members. The results of the evaluation will be a valuable decision support tool for the member countries with regard to continuing their participation in ERA-NET Bioenergy beyond the end of the EU-funded project. The results could also serve as an input to a guideline on how to monitor joint calls efficiently.

7 Project summaries

The following summaries are copied from the end reports of the projects.

7.1 JWP1-5 Development of Test Methods for Non Wood Small-Scale Combustion Plants

7.1.1 Participants

- Austrian Bioenergy Centre (ABC), Austria
- Institut für Umwelt GmbH (IE), Germany
- SP – Technical Research Institute of Sweden, Sweden
- Technologie- und Förderzentrum Nachwachsende Rohstoffe (TFZ), Germany
- HBLFA – Francisco Josephinum Biomass Logistics Technology (FJ BLT), Austria
- Technical Research Centre of Finland (VTT), Finland

7.1.2 Summary

In several European countries increasing efforts are recently made to use non-wood biomass (cereal crops and their residues, energy crops like miscanthus, etc.) as solid biofuel in small-scale furnaces. New technological approaches regarding the appropriate combustion technologies are on the way, but the verification of any such development is difficult and there is a large uncertainty about testing procedures and equipment. While for wood combustion standardized European measuring regulations are available and broadly applied, the testing of non-wood biomass fuel combustion installations is generally not following a commonly accepted procedure. Consequently, the results of such measurements are not fully comparable.

Initially, a study of the driving forces and barriers for the use of non-wood fuels was done in order to evaluate and choose the most promising fuels for small-scale boilers. Furthermore, information on regulations of the authorities in the participating countries relevant for the project as well as other related European documents were gathered. In parallel an overview and further compilation of the current state of technology for small-scale non-wood fuels appliances in Europe, with focus on the participating countries, was done.

Measurement equipment and methods were analyzed and evaluated experimentally at three test stands. The validation was done by applying statistical methods on the experimentally derived results. The overall results are the basis for a proposal (best practice guideline) for a Europe-wide standard for testing non-wood fuels in small-scale boilers.

Finally, a round-robin test was planned and the further R&D required for the development of uniform and comparable tests methods was identified in two joint workshops of the project partners.

There is a wide range of biomass sources which is relevant for the application in small-scale combustion plants and which is classified in the European pre-directive CEN/TS 14961. In the project partner countries in general there are potentials for energy crops and several residues, especially straw from grain production. A potential increase can be expected for energy crops. Most interesting biomasses for use in small-scale combustion units are straw-pellets as well as pellets from miscanthus or reed canary grass. The demand on energy grain will depend very much on market prices for grain.

To meet an increased use of non-wood fuels, there is a need of technical development and of increased knowledge to improve the performance. Development is needed with respect to improved fuel and load flexibility to avoid sintering, fouling, corrosion and high emissions.

The granting of a license for the fuels is handled differently in the partner countries. Regulations reach from no licence for non-wood fuels over a dependence to the plant size up to no licence necessary.

Boiler testing is orientated on EN 303-5 in the partner countries, but there is no valid regulation concerning boilers for non-wood fuels in most cases. Some voluntary labelling systems are implemented.

Depending on future emission limits in the different countries, primary and/or secondary means will need to reduce emissions. Beside combustion and emission performance, it is important that future technique will meet also the users' demands for convenience (e.g. effort for operating combustion plant).

Regarding dust measurements numerous sources of error and a high number of influencing factors and interactions (filter treatment, filter preparation, type of equipment, isokinetics, sampling positions in the exhaust pipe, volume flow determination, asymmetrical particle distribution, etc.) are given. An isolated consideration of a single influence is difficult, particularly as the repeatability of dust determinations is generally relatively low. Further R&D must attach importance on that topic.

For the best practice guideline the European Standard EN 303-5 was used as basis. In order to ensure a wide-spread acceptance of this guideline, changes and amendments to the existing EN 303-5 were kept as low as possible. The work has focussed on derivation and evaluation of measurement principles and procedures.

Six laboratories have expressed interest to participate in a following round-robin test. Two fuels will be chosen (e.g. miscanthus pellets/briquettes and wheat straw pellets/briquettes) and combusted in a max. 100 kW boiler according to the proposed guideline. Further adaptations of the guideline will be done on the basis of the round-robin results where appropriate.

For further R&D research activities on measurement methods for non-wood small-scale combustion plants should be continued categorically. Next step is to start a round-robin project within the ERA-net programme to evaluate compiled results and improve the best practice guideline.

In the course of the round-robin test measurement methods regarding dust measurements have to be evaluated again and experience of participating laboratories should be unified to common European wide dust measurement method.

The consortium of the ERA-net project “Development of test methods for non-wood small-scale combustion plants” strongly recommends the establishment of a European standard regulating the requirements for testing small-scale furnaces for biogenic non-wood fuels.

7.2 JWP1-9 Clean Biomass Combustion in Residential Heating: Particulate Measurements, Sampling and Physicochemical and Toxicological Characterization (BIOMASS-PM)

7.2.1 Participants

- Jorma Jokiniemi, Jarkko Tissari and Timo Turrek, University of Kuopio, Department of Environmental Sciences, Fine Particle and Aerosol Technology Laboratory, Kuopio, Finland
- Raimo O. Salonen, Maija-Riitta Hirvonen, Arto Pennanen and Pasi Jalava, National Public Health Institute, Department of Environmental Health, Kuopio, Finland
- Risto Hillamo, Aki Virkkula, Sanna Saarikoski and Anna Frey, Finnish Meteorological Institute, Air Quality Research, Helsinki, Finland
- Ingwald Obenberger, Thomas Brunner and Joachim Friesenbichler, Graz University of Technology, Institute for Resource Efficient and Sustainable Systems, Graz, Austria
- Hans Hartmann, Peter Turowski and Frank Ellner, Technologie- und Förderzentrum Straubing (TFZ), Straubing, Germany
- Bernd Bellmann, Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.V (FHG), Institute of Toxicology and Experimental Medicine, Hannover, Germany
- Christoffer Boman and Anders Nodin, Umeå University, Energy Technology and Thermal Process Chemistry (UUE), Umeå, Sweden

- Esbjörn Petterson and Henrik Wiinikka, Energy Technology Centre (ETC), Piteå, Sweden
- Thomas Sandström, Anders Blomberg and Maria Sehlstedt, Umeå University Hospital, Department of Respiratory Medicine and Allergy, Umeå, Sweden
- Bertil Forsberg, Umeå University, Department of Public Health and Clinical Medicine, Umeå, Sweden

7.2.2 Summary

Background

Residential biomass combustion has a substantial contribution to the total fine particulate ($PM_{2.5}$; particle diameter < 2.5 µm) emissions in most European countries. This is mainly due to a widespread use of old, un-optimised small-scale biomass combustion systems for woody biomass in residential heating. Because of extensive adverse health effects associated with current ambient air $PM_{2.5}$ concentrations, there is pressure in the EU and many European countries to start or strengthen the regulation of combustion emissions in this sector. It has been recently estimated by the Clean Air for Europe (CAFE) Programme of the European Commission that in the year 2000, mainly due to long-term health effects of $PM_{2.5}$, there were nearly 350,000 premature deaths annually due to cardiovascular and respiratory diseases and cancer in the 450-million populations of the 25 EU member states. Moreover, tens of millions of elderly subjects with chronic lung and heart disease, asthmatic subjects of all ages and young children were estimated to frequently have an increased need for rescue medication and restricted daily activity due to health impairment provoked by $PM_{2.5}$. The total economical losses due to the health damage in 2000 were estimated at 268-781 billion Euros (European Commission, 2005).

The present multidisciplinary project consortium consisted of ten internationally well-established research teams from four countries. The purpose of the BIOMASS-PM project was to strengthen the interdisciplinary scientific evidence on the advantages of new combustion technologies and emission after-treatment in small-scale biomass heating systems. Due to intensive research and development work carried out during the last decade, small-scale biomass combustion units have already reached a high technological standard in terms of thermal efficiency and low emissions. However, concerning the reduction of particulate emissions, still further work has to be done.

Summing up the results and conclusions from the country reports (Austria, Finland, Germany, Sweden), it can be outlined, that in all four countries small-scale biomass combustion technologies play a relevant role by providing 10% - 30% of the total energy demand for residential heating and hot water supply. Moreover, small-scale biomass combustion technologies are the dominating renewable energy source for residential heating. It is also similar for all four countries, that logwood is the most common biomass fuel used in stoves and boilers. However, wood pellets have gained rising interest as fuel for residential

heating systems since their market introduction, and this trend is expected to continue.

In all four countries, old biomass combustion technologies (stoves and boilers) dominate the current stock of applications. Since these systems show significantly higher particulate emissions than modern small-scale combustion systems, residential biomass heating has often a relatively high contribution to the total national thoracic particle (PM_{10}; particle diameter <10 µm) and $PM_{2.5}$ emissions and is, therefore, facing increasing criticism. Comprehensive R&D work on the optimisation of small-scale biomass combustion devices has been performed during the last decade and, as a result of this, advanced residential biomass combustion technologies, operating at significantly lower particulate emissions than the old technologies, are already available. The lower particulate emissions have been achieved by improving the combustion conditions in ways that reduce the formation of organic aerosols and soot. However, the changeover from old to new residential biomass combustion systems has, so far, not taken place. Also the development of secondary measures for particulate emission reduction is in all four countries just in the initial phase. Therefore, the same measures for the reduction of particulate emissions from small-scale biomass combustion can be proposed for Austria, Finland, Germany and Sweden:

- Financial support for the substitution of old combustion devices by modern systems.
- Provision of appropriate “user training” for non-automatically fed systems.
- Support of the R&D of low-particulate-emission combustion technologies.
- Support of the R&D and application of appropriate secondary particulate emission reduction technologies for residential biomass combustion systems.

There were significant differences between the four countries with regard to the existence of particulate emission limits for small-scale biomass combustion appliances. In Finland, no emission limits exist so far, and in Sweden particulate emission limits are fulfilled on a voluntary basis. In Austria, there are particulate emission limits, and it is expected that they will become more stringent within the coming years. The most ambitious emission limits in Europe with regard to particulate matter are soon expected to get into force in Germany (2015 target: 20 mg/Nm³, dry flue gas, 13 vol% O_2). A major problem is that different units and different O_2 reference levels are applied in different countries. Therefore, a harmonisation on a European level is recommended.

One of the main objectives of the project was a determination of feasible methods for particulate emission measurements, sampling and physicochemical characterisation. An appropriate best practise procedure was worked out. One of the most relevant aspects of this best practice procedure should be that it covers the evaluation of the whole process chain, starting from the combustion process (combustion quality, performance of the furnace) followed by particulate sampling, the physicochemical characterisation of particulate emissions, and the evaluation of emission-related health risks. A future aim should be to link the information gained from the physicochemical characterisation of particulate emissions with the results of toxicological studies in order to estimate the health risk potential of the emissions in relation to technologically and economically feasible small-scale biomass combustion systems. Consequently, the approach taken in the BIOMASS-PM project deviates from the commonly applied particulate sampling and measurement techniques, since in these procedures the interface with the toxicological evaluation of particulate emissions has not been taken into account.

Measurement of particulate emissions

The present best practise recommendations must apply to bad burnout conditions as they represent the most important challenge for future R&D of technologies as well as for health protection. As the first step of the procedure, due to presence of the condensable organic species at stove/boiler outlet, a dilution of the flue gas with clean air is recommended. Only clean air (filtered air) should be used for dilution. The dilution ratio has to be monitored continuously by parallel CO_2 or NO_x measurements in the diluted and undiluted flue gas.

The dilution ratio should be high enough to keep the temperature of the diluted flue gas <52°C in order to ensure a full yield of condensable species in particulate phase. The dilution ratio should be in a range of 20 for the full potential of particle formation by condensation of organic vapours. However, higher dilution ratios can be applied, e.g. in connection to toxicological health studies.

A second important step of the best practise procedure is the determination of the gas phase composition (O_2, CO, CO_2, NO_x, OGC) with conventional flue gas analysers. These gas phase measurements should be performed in the undiluted flue gas at boiler/stove outlet, since conventional flue gas analysers are usually not designed for measurements in diluted flue gas flows.

The total emission of particulate matter should also be determined in undiluted gas due to two reasons. First, this procedure enables a comparison of the results from small-scale biomass combustion installations with those obtained from boiler tests that are usually performed without dilution. Second, losses of coarse fly ash particles occur during dilution, which means that a measurement in diluted flue gas would lead to an underestimation of the total particulate matter emission. The measurements should always be performed according to the respective test standards.

A stepwise chemical analysis procedure is recommended, so that the level of characterisation can be adjusted to different purposes. A basic fractionation into soot, organic and inorganic matter is currently highly relevant. There can be also fractionation of the carbonaceous matter into elemental (EC) and organic (OC) carbon. Further fractionation and speciation of the organic and inorganic matter can be performed, especially in scientific studies. The concentrations of known genotoxic PAHs in particulate phase emissions are of great interest.

Concerning all analysis methods mentioned above, it is important to adjust the pre-treatment, conditioning, handling and storage of the sampling substrates to the demands of the respective analysis method. As the dilution ratio applied during sampling may influence the chemical composition of particulate emissions, it should always be reported in connection to the results of chemical characterisation.

For automated furnaces in continuous operation, it is recommended to perform the measurements and particulate sampling at stable full-load and minimum load operations. For automated furnaces in on/off operation (especially relevant for Sweden), the tests should be done according to the Swedish P-marking regulations. Concerning batch combustion systems, also the first full batch or kindling wood ignition should be included in the test. Sampling during this first batch should start as soon as the CO_2 concentration exceeds 1 vol%. For all subsequent batches sampling should start at the beginning of the batch and should end as soon as the CO_2 concentrations decrease below 4 vol%.

When applying the present best practise procedure, the chemical and physical characterisation of particulate emissions from biomass combustion can be adjusted to the level of information needs for different purposes.

Investigation of health effects of particulate emissions

Aerosol exposure systems with on-line diluted flue gas from combustion installation are used in experimental human and animal studies. Also re-aerosolization of combustion emission particles collected in advance with, e.g. electrostatic precipitator, has been used in animal studies. Alternatively, one may collect size-segregated emission particles from diluted exhaust and instill them in aqueous medium directly to cell culture or under visual control to the lower airways of experimental animals e.g. mice or rats.

Common requirements for both the aerosol exposure and the particulate collection method are:

- Evaluate the characteristics of the exposure system in advance using standard aerosol monitoring and sampling methods as reference.
- Avoid carefully any external contamination of the combustion emission particles and use methodologically similar sham exposure to filtered air or blank samples that control all stages of particulate sample handling.
- Report always the combustion technology, fuel and condition as well as the dilution ratio, temperature and the results from gaseous and particulate monitoring and chemical speciation as background information in the toxicological study report.
- The most important size range to be investigated in toxicological studies is PM_1. However, investigation of the coarse (> 1 μm) particles, mostly fly ash, or separation of the ultrafine particles (< 0.1/0.2 μm) from other submicron

fine particles may be motivated in connection to some technologies or biofuels, or special health issues of interest.

- The non-toxicity of particulate sampling substrate needs to be confirmed in cell tests made in advance. The substrates should be pre-cleaned before sampling using the same solvent and cleaning protocol as in the actual particulate extraction. Blank substrates are processed similarly to the ones used in particulate sampling.
- Particulate collection needs to be done with dilution and cooling the flue gas <52 °C to include condensable material in particulate phase emission.
- After particulate sampling, collection substrates must be protected from sunlight and removed as quickly as possible for storage at -20 °C. For subsequent weighing and extraction, the frozen substrates and particulate material need be conditioned at room temperature for 4 hours in closed containers, followed by 16–18 hours in open containers before weighing.

Toxicological cell and animal studies need at least tens of milligrams of biomass combustion particles per size range and test condition, so that the same particulate material can be used for testing several different end-points as well as making chemical analyses of interest (e.g. ions, total and water-soluble elements, PAHs). Tens to hundreds of milligrams of size-segregated particulate mass have been recently collected from wood combustion experiments using a high-volume cascade impactor (HVCI). It collects particles at high volume (850 litres/min) in four size ranges ($PM_{0.2}$, $PM_{1-0.2}$, $PM_{2.5-1}$, $PM_{10-2.5}$), and the collected particulate mass can also be extracted from the sampling substrate, i.e. porous polyurethane foam, with a high 80-90% efficiency.

One of the main motivations for toxicological studies is to provide scientific evidence on the biological plausibility of adverse health effects reported in epidemiological studies. Experimental human and animal studies can be conducted on a limited number of research questions on biomass combustion aerosol due to ethical reasons and elaborate study setups, but toxicological cell studies can be utilized more flexibly to reveal the toxicity profiles of multiple combustion conditions. It can be stated that the traditional test of mutagenic activity in bacterial cell cultures (Ames′ test) should be mostly replaced by modern test batteries in cultured mammalian cells like macrophages and respiratory epithelial cells. In all toxicological setups, the dose-dependency and time-dependency of the different kind of response endpoints to biomass combustion particulate samples need to be known to avoid false negative findings.

The inflammatory activity of air particles has been linked for a long time to exacerbation of pulmonary diseases like asthma and chronic bronchitis, but more recently it has been suggested to contribute to atherosclerosis and acute vascular events such as cardiac infarction and stroke. Tissue damage induced in the lungs and other organs by combustion-derived particles can be also mediated, at least partly, by direct cytotoxicity, i.e. via increased apoptotic, i.e. programmed, cell death or un-programmed necrotic cell death, or via inhibition of DNA synthesis in the cells.

Genotoxicity is primarily regarded as the mechanism leading to increased carcinogenic risk. In connection to research on biomass combustion-derived particles, Comet assay can be used as a relatively easy and quick screening test of DNA damage. Its information can be complemented, e.g. by the more elaborate micronucleus test and PAH-DNA adduct test.

Future directions

It is obvious that the field of residential biomass combustion would much benefit from a European-wide harmonization of the emission test methods and procedures. Interdisciplinary research involving both the combustion and aerosol scientists as well as toxicologists on several topics is needed:

- More detailed comparison of different sampling and dilution methods is needed to define a standard method for the measurement of fine particle emission from residential biomass combustion installations.
- Further technological R&D is needed to improve both the primary measures (combustion and control systems) and the secondary measures (emission after-treatment) to reduce particulate emissions from small-scale biomass combustion systems.
- More information on the impact of real-life user practices on particulate emissions is needed as well as on the overall impact of small-scale biomass combustion emissions on local and regional air quality.
- More information is needed about the association between different kinds of particulate matter emissions from biomass combustion installations and their adverse health effect potential as assessed by experimental human and animal studies. Cardiovascular endpoints should be investigated in addition to respiratory endpoints. This would increase information about the biological plausibility of adverse health effects reported in epidemiological studies.
- Cell studies should provide a generic concept on the association of inorganic and organic chemical constituents with the inflammatory, cytotoxic and genotoxic activities of particulate emissions from a series of combustion technologies and biofuels. The representativeness of the results should be confirmed in selected experimental animal and human studies. This information would help the regulator to give emission limits to some potentially highly toxic constituents (e.g. PAHs), the industry to direct its product development towards health-wise cleaner and safer combustion installations, and the consumer to adapt for good operational practice.

It would be advantageous also to promote interdisciplinary research between the aerosol scientists and epidemiologists:

- New short-term panel studies with personal exposure monitoring and source-specific exposure modelling are needed. Contributions of biomass combustion

source-specific outdoor $PM_{2.5}$ to indoor $PM_{2.5}$ should be assessed as well as lung dosimetry in relation to the physico-chemical properties of the particles (e.g. fresh emission nearby vs. aged regional emissions).
- GIS-based cohort studies on chronic respiratory and cardiovascular diseases and cancer are needed. Data on household heating appliances and relevant particulate emission factors need to be up-to-date, because they are in constant change due to altered appliance types and improvement of technologies.

The topics suggested for future research collaboration between the present research partners of the BIOMASS-PM project should be considered for funding in the 7th Framework Programme of the European Commission or ERANET-type collaboration of national funders.

7.3 JWP1-11 Evaluation of technology for small scale combustion of pellets from new ash rich biomasses regarding combustion technology and emission reduction in special case particulate matter and Nox (Combustion Characteristics of Ash Rich Pellets)

7.3.1 Participants

- Håkan Örberg and Jan Burvall, Swedish University of Agricultural Sciences (SLU BTK), Umeå, Sweden
- Claes Tullin, Swedish National Testing and Research Institute (SP), Borås, Sweden
- Heikki Oravainen, Technical Research Centre of Finland (VTT) Jyväskylä, Finland
- Peter Quicker and Ralph Berger ATZ Entwicklungszentrum, Sulzbach-Rosenberg, Germany
- Stefan Beer and Ralph Berger University of applied sciences Amberg-Weiden, Amberg, Germany
- Stefan Hajek, Herding GmbH Filtertechnik, Amberg, Germany
- Alfons Fellner, A.P. Bioenergietechnik GmbH, Hirschau, Germany
- Fritz Grimm, Fritz Grimm GmbH & Co. KG, Amberg, Germany

7.3.2 Summary

Final report from JWP1-11 has not been finished within the timeframe decided on.

7.4 JWP1-12
Small Scale Biomass-Fired CHP Systems

7.4.1 Participants

- Hao Liu, School of the Built Environment (SBE), University of Nottingham, Nottingham, United Kingdom
- Ingo Romey, Institute of Technology of Energy Supply and Energy Conversion Systems (TEE), Department of Mechanical Engineering, University of Essen, Essen, Germany

7.4.2 Summary

With the financial supports of UK EPSRC and German FNR via ERA-NET Bioenergy, School of the Built Environment, University of Nottingham (UK) and Institute of Technology of Energy Supply and Energy Conversion Systems, Department of Mechanical Engineering, University of Essen (Germany) joined forces to develop a novel 2 kWe biomass-fired Combined Heat and Power (CHP) system suitable for public and large domestic buildings' application. The specific objectives of the project were:

- To prove the applicability of biomass-fired CHP with Organic Rankine Cycle (ORC) in a small-scale system of 1-10kWe
- To design, construct and evaluate a 2kWe biomass-fired CHP system
- To develop a computer model for the 2kWe biomass-fired CHP system

The following conclusions had been obtained from the project modelling and experimental activities:

- A small-scale biomass-fired CHP with ORC has been developed, modelled and tested.
- Successful power generation with the experimental system indicates that ORC-based power generation can be applied to 1-10 kWe biomass-fired CHP
- Both modelling and laboratory testing indicate that the total CHP efficiency of the CHP system can be 80% or higher.
- With a thermal input of 20 kW to the boiler, the power output of the CHP system was predicted to be within the range of 1.5 to 2.71 kWe, depending on the ORC working fluid, the maximum and the minimum ORC fluid temperatures. This corresponds to an electrical efficiency of 7.5 – 13.5% for the CHP system.
- The highest achievable electrical efficiency of the CHP system which was calculated from the experimental results (obtained with the maximum ORC fluid temperature of 100 ºC) on the ORC flow rate, ORC working fluid pressures and temperatures at the inlet and outlet of the turbine, and the thermal input of the boiler was within the range of 4.3 – 8.5%, depending on other

experimental conditions such as ORC fluid, which was similar to those predicted by modelling.

- The electrical efficiency of the CHP system achieved with the existing turbine-pulley-alternator set was only about 1.1%. Three factors resulted in a lower electrical efficiency than those predicted by the modelling and calculated from the measured data at the turbine: (1) the turbines investigated were modified from compressors and hence had low efficiency; (2) the alternators were designed to run at high RPM but under the tested conditions, the alternators were running at low RPM which was just over their minimum RPM to generate any power; (3) the efficiency of the alternators was only in the region of 50 – 60%.

7.5 JWP1-15 Control Potential of Different Operating Methods in Small-Scale Wood Pellet Combustion (COPECOM)

7.5.1 Participants

- Pentti Lautala, Tomas Björkqvist and Timo Korpela, Tampere University of Technology, Tampere, Finland
- Kauko Leiviskä and Mika Ruusunen. University of Oulu, Oulu, Finland
- Björn Zethræus, Växjö University, Växjö, Sweden
- Ilkka Uusi-Maahi, HT Enerco Oy, Haapamäki, Finland
- Jörgen Bech, MBIO Energieteknik AB, Gemla, Sweden

7.5.2 Summary

COPECOM – *Control potential of different operating methods in small-scale wood pellet combustion* was a research project funded by ERA-NET Bioenergy. The project consortium consisted of Tampere University of Technology (Finland), University of Oulu (Finland), Växjö University (Sweden), HT Enerco Oy (Finland) and MBIO Energiteknik Ab (Sweden). The duration of the project was 1.4.2007–30.9.2008, and the budgets of Finnish and Swedish partners were 146 900 € and 950 000 SEK, respectively.

The background for the project was that in small scale solid biomass fired systems the most fatal disturbance is the fluctuation of energy content in the fuel feed. So far no cost effective feed forward solution for this disturbance has been presented. The remaining solution is then to manage the combustion by active feedback control. The potential for a fast and exact feedback control is highly determined by the possibilities for adequate observation and impact of the process.

The goal of the project was to compare control potential of domestic wood pellet burners (<20 kW) based on direct combustion and gasification and to develop cost effective control solutions for them by means of data based and physical modelling. The comparison was done both in theory and in practice with use of state of the art feedback control. The possible benefits were defined in perspective of cost effectiveness, burning efficiency and emissions. A minor objective was to clear out in theory if the small-scale gasification could be utilized also for minor power production.

The role of Finnish partners was to investigate the operation and control potential of the different types of combustion systems by extensive measurement procedure and modelling. It was observed that parameters affecting the cleanliness and efficiency of combustion were draught, fuel feeding period and both the amounts of fuel and air feeds. It was noticed, however, that the combustion properties and parameter values vary significantly between the two burners. It was confirmed that by active control the variations in combustion conditions can be compensated to some extent, but a controllable process and proper instrumentation are required. Finally, the emission and efficiency requirements determine the required automation level.

The role of Växjö University was to develop a statistic on-line mixing model, which gives a connection from design and process parameters of burner and combustion chamber geometry to emissions. The model was developed and tested in comparison with experimental data. In spite of the fact that both burners operated far outside the normal combustion interval, the model seems to be able to predict reasonably well the variations in CO-emissions. The experiments fully support the fundamental model assumption – that it is the imperfect mixing in the gas phase that is responsible for the high emissions of unburnt hydrocarbons and unburnt fuel as measured by CO, not the overall residence time in the combustion chambers in commercial, domestic scale boilers. As a result, automatic control measures to improve the combustion behaviour should concentrate on the addition of burnout air with respect to its momentum and its direction. The model generated seems to be able to support such a control system.

At the beginning, reference tests according to EN 303-5 standard were performed with both systems and analysed also by mathematical modelling. The generated model based on physical and chemical phenomena gave useful results, when the measurements were used as inputs. The goal of the model was to calculate the efficiency losses due to sensible heat (flue gas, excess air and steam) and due to unburnt particles (solid char, CO, CH_4 and H_2) based on O_2, CO, flue gas and indoor temperature measurements, fuel properties and unburnt char estimate. Additionally, the air and flue gas flows were determined indirectly. The model gave good results when compared to reference test, so the model is a useful tool for small scale combustion.

Analytical redundancy was utilised in this project by modelling important quantities of the combustion, namely O_2 and CO. The analysis procedure for data-based modelling was based on finding the most valid temperature sensor that is dependent on the O_2 and CO levels in case of both burners. Based on the analysis, the flame temperature was found to have the most potential dependency on carbon monoxide and oxygen. This way, CO and oxygen values can be produced inferentially, giving the real-time information about combustion quality and acting as inputs for the mixing model.

The mixing model and data-based models generated during the project can be integrated with a model based on physical behaviour of subprocesses in wood combustion. The dynamical combustion model then provides e.g. dynamic connections between fuel feed, primary and secondary air feeds, temperature of primary zone and total power generated in combustion. Together with the combination of the mixing model and data-based inferential models, a comprehensive monitoring method for small scale wood pellet combustion is achieved.

Combustion optimisation based on design of experiments (DOE) results was studied to explore optimal combination of the four control factor values. The optimised factors were fuel power, fuel feeding period, draught and combustion air flow. The results were compared to reference tests with both burners. It can be concluded that the boiler output was decreased as the air and fuel feeds were cut down. As a result of changed operation point, the oxygen level lowered a bit and the CO emission level was reduced significantly to a very low level. Moreover, the fact that the efficiency optimum is not reached at nominal power can be considered as a benefit. Then, the burner can operate close emission optimum most of the time, so the operation periods of the burner become long. By this, the unclean start-ups and shut downs can be reduced, and the total emission levels remain low. After the optimised control environment was achieved, the combustion control was applied. With burners equipped with a combustion air fan and fixed primary/secondary air feed ratio, the excess air stabilization does not work as desired. Therefore, power stabilization is suitable control strategy for Biona and Velmax burners. Several control methods, including oxygen trim fuel feed control were implemented and tested during the project. It was shown that with active control combined with optimised control environment variables, more stable operating conditions can be reached. If the primary and secondary air feeds were separated, there would be more degrees of freedom when designing control strategy for the system.

Altogether, a future control framework was developed, which is based on the research work done by the project partners. The foundation of the control framework is the temperature measurement information enriched by mathematical modelling. The enriched information can be used to determine emissions and efficiency of the system. This information can also be used with statistic mixing model to gain information, in which direction the process should be driven. As a result, there is a combination of models, which provides upgraded information on how to control the process to achieve higher efficiency with minimised emissions.

In general, one should note that the combustion properties vary with different systems. Therefore, constructing a control system the entire system must be considered. Hence, system design must be done in a way that the process is controllable. Additionally, proper instrumentation is required. Also the operation point of the system can be changed to a more suitable one. Ultimately, the emission and efficiency requirements determine the disposable automation level, which in turn determines the sensors, actuators and hence control strategies that can and must be applied. The automation level that is required to meet the emission limits will increase in the future.

As a conclusion, the requirement for cost-effectiveness is dominant in small scale applications, which sets hard limits to on-line measurement and control instrumentation in sold applications. A comprehensive solution is to enrich data of simple measurements. This enriching of sensor information can be done by a combination of physical and data based models. Such models were developed in this project. By the generated models, the oxygen and CO levels could be determined based on temperature measurements. By these estimates, efficiency, flue gas and air flow estimates can be calculated. Using the same input information, the mixing model describes the direction in which the combustion should be headed. As a result, there is a combination of models that require and support each others. The sensor information and model based knowledge forms the foundation for control. Still, a lot of work is undone in order to use such a concept in commercial combustion units, but this project served as a needed step for that direction.