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Entwicklung von innovativen Biomasse-Klein/Mikro-KWK-Technologien

Development of innovative small(micro)-scale biomass-based CHP technologies

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1 Inhaltsverzeichnis

2 Einleitung/Introduction

Dieses im Rahmen der 4. Ausschreibung des Programms e!Mission.at durchgeführte Projekt ermöglichte die Teilnahme der österreichischen Partner BIOS BIOENERGIESYSTEME GmbH (BIOS) und RIKA Innovative Ofentechnik GmbH (RIKA) am internationalen ERA-NET Bioenergy Projekt „Small-scale BM CHP". An dem vom österreichischen Antragsteller BIOS koordinierten ERA-NET Projekt nahmen insgesamt 12 fachlich hochkompetente Partner aus 4 EU-Ländern (AT, DE, SWE, PL) teil, wodurch ein erheblicher Mehrwert im Vergleich zu einem nationalen Projekt generiert wurde.
Aufgrund der Tatsache, dass die Arbeiten in diesem Projekt zum überwiegenden Teil in englischer Sprache durchgeführt und dokumentiert wurden, ist der nachfolgende publizierbare Endbericht ebenfalls in Englisch verfasst.

This project was carried out within the framework of the 4th edition of the program e!Mission.at and enabled the Austrian project partners BIOS and RIKA the participation in the international ERA-NET Bioenergy project "Small-scale BM CHP". Within the ERA-NET project, coordinated by the Austrian partner BIOS, in total 12 highly qualified partners from four EU countries (AT, DE, SWE, PL) participated, whereby a significant added value compared to a national project could be achieved.
In addition to the Austrian project partners BIOS and RIKA the consortium of the ERA-NET Bioenergy project consisted of the following project partners:
Germany:

- Technology and Support Centre of Renewable Raw Materials (TFZ)
- Orcan Energy AG (ORCAN)

Sweden:

- RISE Research Institutes of Sweden AB (RISE)
- Umeå University, Dept. Applied Physics and Electronics (UmU)
- Luleå University of Technology, Division of Energy Engineering (LTU)
- Chalmers University of Technology, Division of Fluid Dynamics (CHT)
- ENERTECH AB / OSBY PARCA (ENERTECH)
- Ecergy AB (ECERGY)

Poland:

- Institute of Power Engineering (IEn)
- Wektor Marek Gasiorowski (WEKTOR)

Since for the small electric capacity range so far no technologically sound (in terms of efficiency and reliability) and economically affordable biomass CHP technologies were available, the ERA-NET project aimed at the further development and test of new CHP technologies based on small-scale biomass combustion systems in the electric capacity range between some W and 100 kW. The following three CHP concepts were developed within the project:

- Pellet stove with a thermoelectric generator (TEG) (25-50 W_{el})
- Micro-ORC technology (~ 1 kW_{el}) for small biomass boilers

- externally fired micro gas turbine technology (up to 100 kW_{el}) for larger wood chip and pellet boilers

The development was based on basic R&D already performed in the participating countries for promising new technologies and aimed at the achievement of a technological level as well as an economic performance within the project which allows first field tests after project end. The Austrian project partners focused on the further development and optimization of a TEG technology suitable for the integration in pellet stoves.

Within the project 3 new micro-CHP technologies have been developed. Therefore, comprehensive calculations and simulations (e.g. CFD - Computational Fluid Dynamics), experimental research on individual key components as well as the construction and testing of testing plants took place. One work package was focussing on the investigation of ash-related problems (deposit formation, corrosion), which represents a relevant issue for the new CHP technologies especially for the EFGT technology. In addition, techno-economic analyses have been performed for the CHP systems investigated.

In April 2017 after three years of intensive work within the consortium the project has been finalised in time and all milestones and objectives have been achieved according to the work plan. The work within this project was divided into 8 work packages (WPs). Subsequently, an overview regarding the work performed and the results achieved within the WPs is given.

3 Inhaltliche Darstellung / Work Performed

3.1 WP1: Definition of constraints and interfaces

Within WP1 as a first step the specification regarding general parameters, system components and possible applications of the CHP technologies has been performed based on a questionnaire prepared by BIOS for each technology. In addition, for a better understanding of the three technologies a process scheme has been prepared for each technology (see WP3, WP4 and WP5).

Based on the general system specification and the current level of development for the three technologies the specific R&D demand regarding the different components and the methodological approach to solve them has been defined.

As a further consequence, the fields for inter-work-package-cooperation within the project have been identified:

- Experiences regarding ash related problems (deposits, slagging, corrosion) from the test runs within WP3 to 5
- Constraints regarding the performance of CFD simulations (discussion and information exchange regarding relevant calculation models & boundary conditions for the CFD simulations) relevant for WP2 – WP5.
- Intermediate energy storage (e.g. heat storage, battery solutions) relevant for WP3 and WP4.
- Material issues regarding corrosion, strength properties; workability and costs (especially investigated within WP2) relevant for WP3 to 5.
- Methodology/harmonisation of measurements and analyses for the test runs (WP2 - WP5), such as

  - pressure and temperature measurements at high temperatures
  - exchange of experiences regarding the monitoring of slagging and fouling on heat exchanger surfaces
  - calculation methods for the evaluation of the thermal and electrical efficiencies
  - definition of meaningful load cycle tests for pellet stoves and boilers for the test runs
  - definition of comparable flue gas and dust measurements as well as of analyses methods
- Market data and prices for the techno-economic analyses for different countries
- User behaviour (load profiles regarding electricity and heat demand), such as
  - collection and comparison of load profiles for relevant applications and for different user groups
  - definition of representative user behaviours for different user groups (load trends, operation time) comparing heat and electricity consumption
  - specification of representative feed and return temperatures as well as the share of low and high temperature demand in buildings

Regarding these topics, a significant added value has been achieved for all partners by the use of specific expertises available within the international consortium, by intensive discussions at bi-lateral and consortium meetings as well as data exchange between the project partners.

3.2 WP2: Basic R&D on ash related problems with special respect to high temperature heat exchangers

In this WP, different integrated research tasks were combined to gain a better understanding of critical ash related problems of special relevance for the further development of the externally fired gas turbine technology (EFGT - see WP5) based on grate combustion of biomass. Measures for prevention of such problems have also been addressed, including the use of fuel additives, operation principles and material selection.

The overall objectives of WP2 were to

- develop concepts to solve ash problems related to fouling (deposits) and corrosion of high-temperature heat exchangers (HT-HE).
- develop operation strategies for combustion processes which guarantee for high availability and stability in order to improve the operation conditions for the CHP systems.

The work was divided in five specific areas (task 2.1-2.5) each with specific aims and complementary focuses, including experimental lab-studies, model development/validation and full-scale tests, all summarized in the following.

3.2.1 Reduction of alkali release from fuel/bed during fixed bed combustion and recommendations for the use of fuel additives

Authors: UmU: Jonathan Fagerström, Anders Rebbling, Erik Steinvall, Nils Skoglund, Dan Boström, Christoffer Boman; LTU: Joseph Olwa, Marcus Öhman

3.2.1.1 Content and Method

The objectives of this task were to

- quantify the amount of alkali in flue gases as a function of process parameters in a small grate-fired burner using pelletized wood fuels like stemwood-based softwood and woody energy crops (e.g. Willow).
- identify the need for and development of fuel measures for alkali release reduction (e.g. fuel additives), and to define concepts for implementation.

The overall scope of this work was to gain a novel understanding on alkali release behaviour and to develop concepts for reduction of ash related deposit and corrosion problems in biomass fired fixed bed EFGT applications.

The experimental work was performed in two campaigns (Table 1) with combustion tests in two different small scale burners, one moving grate and one underfed burner, and using two different fuels and two additives (kaolin and ammonium sulfate). The use of ammonium sulfate was only for the purpose to introduce “reactive” sulfur and study the potential capture of potassium in stable sulfates in the bed. In the moving grate, also the bed temperature was varied by adjusting the primary- and secondary air, i.e. higher primary air (bed lambda) for colder bed. The fuels used were ordinary stemwood based spruce pellets (ash content 0.4%) and a willow/spruce (60/40) mixture (ash content 0.8%). For the $(NH_4)_2SO_4$ a target and achieved additivation level was defined as 0.4%. Based on previous work, a target value of 1% (based on weight) kaolin addition (as the mineral kaolinite $[Al_2Si_2O_5(OH)_4]$), to the spruce fuel was used, with the aim to reduce the release of gaseous alkali (mainly K). Due to the losses of OH-groups (up to 25% of molar weight) from the kaolinite mineral during drying, and some additional material losses in the additivation process, the ash content of the additivated fuel only increased from 0.40 to 0.96%.

Table 1: Experimental matrix for the two campaigns with small-scale burners

Campaign 1: Moving grate burner (40 kW)				
Fuel (pellets)	**Load (kW_{fuel})**	**Bed temp (°C)**	**Bed lambda**	**Additive**
Spruce (stemwood)	17	~900 (cold)	1.5	+ kaolin + $(NH_4)_2SO_4$
Spruce (stemwood)	36	~1200 (hot)	0.8	+ kaolin + $(NH_4)_2SO_4$
Campaign 2: Underfed burner (20 kW)				
Fuel (pellets)	**Load (kW_{fuel})**	**Bed temp (°C)**		**Additive**
Spruce (stemwood)	15	~1200 (hot)		+ kaolin
Willow (willow/spruce 60/40)	15	~1200 (hot)		

Size-fractionated particle sampling in the flue gases was performed with a 13-stage low-pressure impactor (0.01-10 µm), and the elements (K, Na, Zn, S and Cl) in fine particles (PM_1) were analyzed by ICP-AES and SEM-EDS. The residual ashes in the boilers were analyzed by SEM-EDS and P-XRD. The main combustion gases (CO_2, H_2O, CO, NO/NO_2, SO_2, HCl) were monitored by FTIR (with an O_2 sensor). The release of alkali (K and Na) from the fuel bed was derived from calculations of the fraction of the respective elements that were found in fine PM compared to the concentrations of the elements in the ingoing fuel. The analyses of the fuels and fine PM was done by wet-chemical methods (ICP-MS/AES).

3.2.1.2 Results

There were significant variations seen regarding PM_1 emissions Figure 1 and alkali release Figure 2, between the different fuels, operation cases and additivations applied. As seen in Figure 1, the PM_1 emissions varied overall in the range of 14-50 mg/Nm³ (at 10% O2) for the moving grate and 5-46 mg/Nm³ (at 10% O_2) for the underfed burner. Both the kaolin and ammonium sulfate reduced the PM_1 emissions significantly, and a clear effect of the bed temperature was also seen. The composition of the PM_1 was dominated by K, S and Cl, with minor amounts of Na and Zn.
The release of K and Na is the main governing factor for the deposit formation on the HT-HE, while the chemistry of the aerosols and deposit built-up determines the corrosion potential of the deposits formed. It is well known from literature that alkali salts, especially the chlorides, are detrimental regarding corrosion at steel alloys in superheaters and other heat exchanging devices in traditional biomass fired boilers [1,2]. In Figure 2, the release fractions of K and Na for the two burner set-ups in the studied cases are shown. The significant reduction potential, in accordance with the reduction in PM_1 emissions, is clearly illustrated by these tests, where the effects of both fuel, operation and additivation concepts can be utilized. Overall, these studies have shown great potential for reduction of PM_1 emissions and fine aerosol formation, which is of great importance for the potential built-up of deposits in a HT-HE system.

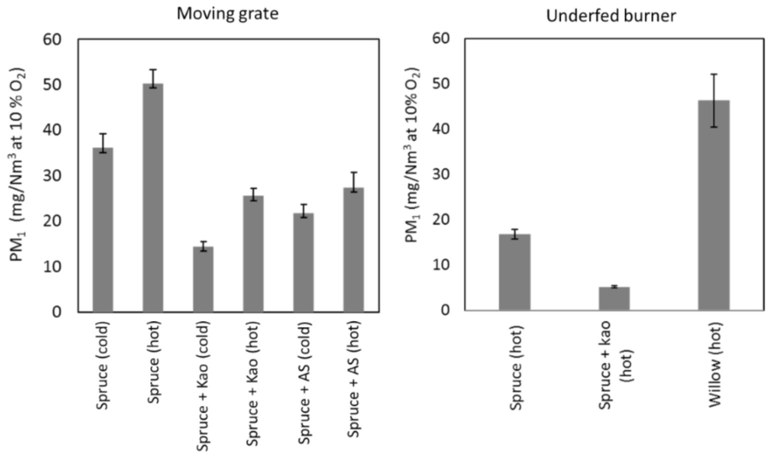

Figure 1: PM_1 emissions for the two combustion systems tested

[1] Nielsen HP, et al. The implications of chlorine-associated corrosion on the operation of biomass-fired boilers. Progress in Energy and Combustion Science 2000;26(3):283-298.
[2] Mudgal D, et al. Corrosion problems in incinerators and biomass-fuel-fired boilers (review article). International Journal of Corrosion 2014, Article ID 505306 (doi.org/10.1155/2014/505306).

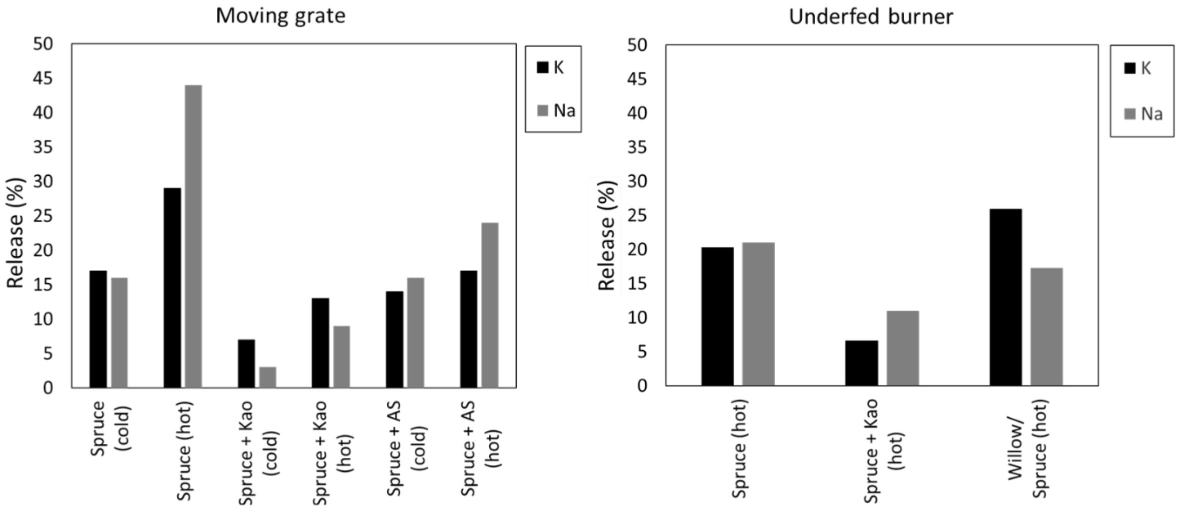

Figure 2: Release fraction of potassium (K) and sodium (Na), i.e. fraction of ingoing K and Na that were found in the PM_1, for the two tested combustion systems applying cold or hot bed temperatures and kaolin (kao) or ammonium sulfate (AS) additivation

3.2.1.3 Conclusions (experimental work)

The following conclusions, based on the experimental work performed, can be defined:

- Similar alkali release behaviour seen in the small-scale moving grate and the underfed burner appliances.
- Considerable potential exists for reduction of PM_1 emissions and alkali release by using additives in woody fuels, with kaolin showing the largest effect (up to 60-70%).
- Controlling the fuel bed temperature is also of great importance for the overall success in alkali reduction measures.
- Highest reduction of alkali release was achieved when combining the process parameters ("cold bed") and the fuel additive kaolin - up to 76% reduction in K release.
- Accurate control of both process parameters and fuel additives are measures to control deposit formation on the HT-HE in EFGT applications for biomass.
- Unfavourable process conditions, e.g. too high bed temperature (>1000°C), can decrease the positive effects of fuel additives.

3.2.1.4 Recommendations for kaolin additivation

The use of fuel additives can be a cost-effective primary measure for combating both operational problems and emissions of fine ash PM in biomass combustion applications.

The basic principles and function of different additives as well as more applied approaches have been scientifically studied rather extensively and some user related suggestions for implementation have been summarized in the literature and in former ERA-NET projects [3,4,5,6].

[3] Boman C, et al. Fuel additives and blending as primary measures for reduction of fine ash particle emissions – state of the art. Report within the ERA-NET project FutureBioTec, 2012. (http://futurebiotec.bioenergy2020.eu)
[4] Wang L, et al. A critical review on additives to reduce ash related operation problems in biomass combustion applications. Energy Procedia 2012;20:20-29

The measures for alkali release reduction by using fuel additives was in this project focused towards applications with woody fuels in fixed bed boilers, i.e. systems of main relevance for the implementation of the biomass based EFGT technology. Typical fuels in this context are therefore low- and medium ash containing woody fuels of e.g. softwood stemwood, sawdust, cutting residues and energy crops (SRC, e.g. Salix, Poplar). The goal for the application of the kaolin additive is to achieve; ***i)*** maximum reduction of alkali release from the bed/bottom ash, ***ii)*** no/very low levels of alkali chlorides in the aerosols and deposits, and ***iii)*** maintained combustion performance (high efficiency, low slagging).

Prior to implementing the use of fuel additives like kaolin, a number of pre-application considerations need to be addressed, of which some are:

- Define present PM levels, size distribution, and influence by load, etc., to get indications of alkali behaviour in the process and assess potentials for mitigation of deposits.
- Defined target levels for alkali in gas/aerosols for specific EFGT applications.
- Define the potential for process adjustments and optimization, mainly by measures to control the bed temperature (e.g. flue gas recirculation, air distribution).
- Define the fuel ash composition, with respect mainly to K, Na, Ca, Mg, Si, Al, S and P.

The choice of addition level of the kaolin can be defined by different methods, e.g. *empirical data from previous studies, stoichiometric considerations, fuel indices, and/or chemical equilibrium calculations*, together with some special considerations related to both the fuel and the additive.

The overall chemical reactions between kaolinite [$Al_2Si_2O_5(OH)_4$], i.e. the main mineral in the kaolin clay, and gaseous potassium, here KCl, forms the K-Al-silicates kalsilite (I) and leucite (II). Notable is that in reaction II, also SiO_2 is involved. Kaolinite can also react in a similar way with KOH. Overall, this will reduce the amount of K available for reaction with silica (SiO_2), i.e. formation of low temperature melting pure K-silicates, and at the same time also capture K in the coarse bottom ash, thus reducing the release to the gas phase.

I) $Al_2Si_2O_5(OH)_4 + 2KCl \rightarrow 2KAlSiO_4 + H_2O + 2HCl$

II) $Al_2Si_2O_5(OH)_4 + 2KCl + 2SiO_2 \rightarrow 2KAlSi_2O_6 + H_2O + 2HCl$

The base for the additivation of kaolin is the stoichiometric level needed to incorporate all K in the K/Al-silicates. As seen from the reactions I and II, the stoichiometric ratio for K:Al in the formed products is 1:1. Thus, for each mole of potassium in the fuel, one mole of kaolinite should be added. However, upon heating, when the kaolinite is transformed to meta-kaolinite, the mineral loose its OH-groups. Tests showed a weight loss of ~12 wt-% at 550°C. The total fraction of OH-groups corresponds to around 25 wt-% of the kaolinite mineral, and the theoretical stoichiometric additivation level should therefore be adjusted accordingly, somewhere in the range of (+12 to -25 wt-% , most probably at the upper level).

Some additional considerations to address regarding the efficiency of the kaolin additive are:

- At too high process temperatures, i.e. above 950°C in the bed, the meta-kaolinite starts to decompose to other high-temperature forms of Al-silicates and pure SiO_2. This will reduce the

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[5] Sommersacher P, et al. Application of novel and advanced fuel characterization tools for the combustion related characterization of different wood/kaolin and straw/kaolin mixtures. Energy Fuels 2013;27:5192−5206

[6] Brunner T, et al. Additivation Guideline - How to Utilise Inorganic Additives as a Measure to Improve Combustion Related Properties of Agricultural Biomass Fuels. In: Proc. of the 23rd European Biomass Conference and Exhibition, June 2015, Vienna, Austria, ISBN 978-88-89407-516 (ISSN 2282-5819), pp. 508-518, (paper DOI 10.5071/23rdEUBCE2015-2AO.8.4), ETA-Florence Renewable Energies (Ed.), Florence, Italy

alkali capturing capacity and also initiate the risk for slag formation by low-temperature melting K-silicates.

- The high concentrations of Ca in woody fuels may have an effect of the efficiency of the kaolin addition, concerning its capacity to capture alkali (K, Na), since the kaolin can react with Ca, instead of alkali. The formation of Ca/Al-silicates are thermodynamically favoured and have been seen at somewhat elevated temperatures relevant for fixed bed boilers (>900-1000°C), although this effect is not possible to quantify presently.

Two examples with different cases for the application of using kaolin additive are here given with specific recommendations.

Case 1:

High quality standard (class A1) woody (spruce/pine) fuels, with ash content 0.3-0.4 wt-% and K concentration <600 mg/kg d.s.

Theoretical (stoichiometric) adjusted level of kaolin addition is about0.2 wt-%. Previous reported studies have used e.g. 0.2, 1.0 and 3.0 wt-% addition of kaolin. Full reduction potential has not been seen at 0.2% but at 1.0%. *Adjusted suitable level for this kind of fuel should therefore be somewhere around 0.3-0.9 wt-%.*

Case 2:

Traditional SRC (willow, salix, poplar) with ash content around 1%, and K concentration in the range 1000 -3000 mg/kg d.s.

Theoretical (stoichiometric) adjusted level of kaolin addition is 0.5-1.0 wt-%. Very scarce empirical information available. *Adjusted suitable level must be set from case-to-case in the range of around 0.5-1.0 wt-% kaolin, due to significant variations between fuel assortments.*

3.2.2 Deposit formation on the HT-HE – first assessment from lab-tests

Authors: LTU: Joseph Olwa, Marcus Öhman; UmU: Nils Skoglund, Anders Rebbling, Dan Boström, Christoffer Boman

3.2.2.1 Content and method

The objective of this task was to characterize the deposit formation, i.e. build-up rate and composition, in a simulated HT-HE set-up during combustion in a small grate fired burner system.

The experimental and analytical work in this task was based on the work with the underfed burner as already outlined and described for campaign 2 in chapter 3.2.1.1. Thus, the same procedures were applied with the addition of the use of a single-tube HT-HE probe in the upper part of the boiler, shielded from the flames but still at high (relevant) flue gas temperatures. The fuel feed was in the range of 3.8-4-0 kg/h, corresponding to a fuel load of 18-20 kW.

The probe consisted of an air-cooled single-tube with an inner flue gas flow and four exchangeable deposit test rings (inner diameter 25 mm) of the alloy 253MA, placed in series in the probe. Thus, the inlet temperature of the probe was in line with the flue gases with a gradient temperature decrease along the probe. The sample flow in the probe was 70 NL/min and the velocity around 18 m/s. The probe tests were performed during 11 hours sampling per test. The deposits, as well as fine particles and bottom ashes, were subsequently characterized by SEM-EDS and P-XRD.

3.2.2.2 Results

The PM_1 emissions in the three studied cases were shown in chapter 3.2.1.2, where a significant reduction by kaolin addition was seen. In Table 2, the temperatures of the in- and outgoing gas in the probe, as well as the ring surface temperatures, are given. As seen, the inlet temperatures varied in the range of 820-870°C, with a decrease by 300-400°C in the probe. The sharpest decrease in temperature was seen between the first and second ring.

Table 2: Gas and ring surface temperatures for the single-tube deposit probe tests

		Spruce	Spruce + kao	Willow
Gas temperature [°C]	Probe inlet	870	820	850
	Probe outlet	510	490	500
Ring surface temperature [°C]	Ring 1	795	795	795
	Ring 2	510	493	501
	Ring 3	425	405	412
	Ring 4	401	397	395

In general, there were rather small deposits seen in all cases, with more deposits on R1 and R2 compared to R3 and R4. In Figure 3, an image with examples of some rings after sampling is shown for illustration.

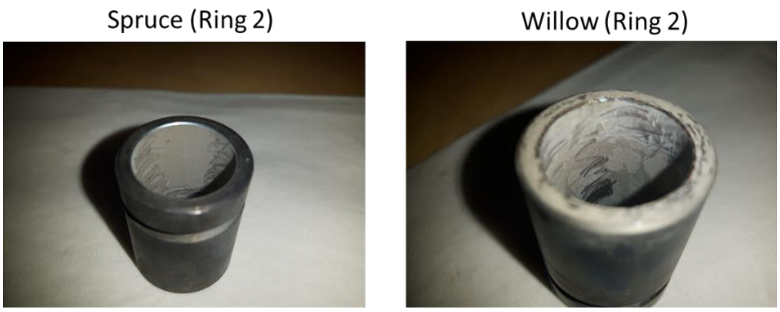


Figure 3: Example of test rings (R2) with deposits after sampling during 11 hours, for spruce (left) and willow (right)

In Figure 4, the deposition rate on the rings are shown. Overall, similar trends were seen between the three cases, although some differences. For example, the deposits on R1 and R2 are more dominant for willow, compared to spruce, with a more continuous decrease from R1 to R4. The observed deposit rates are in average in the range of 1/10 of previously reported typical deposit built-up rates from fixed bed applications with wood fuels.

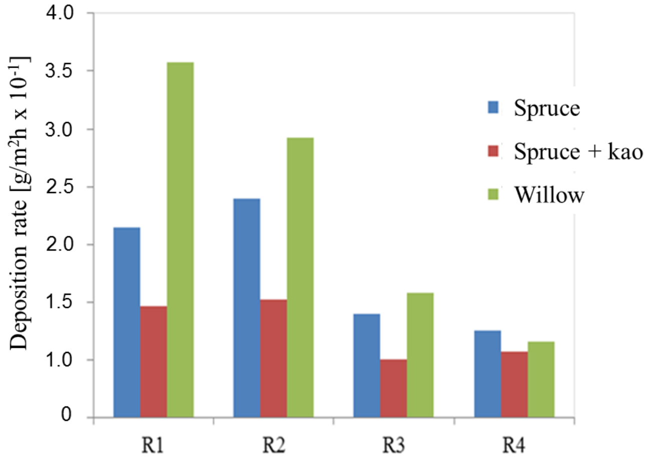


Figure 4: Deposit rates for the three different fuel cases and four rings in the single-tube probe

Based on the SEM-EDS and P-XRD analysis, the chemistry of the deposits was characterized, and the results are shown in Figure 5. For the SEM-EDS, quantitative information on elemental composition is given, while only qualitative information is given (by XRD) for the phase composition of the crystalline matter in the deposits. As seen, the deposits in the test with spruce, were dominated by K and S, with minor amounts of Na, Ca and Zn. In principal no Cl was determined in the deposits. When kaolin was added, the deposit also included Si and Al, thus indicating a slight entrainment of kaolin from the burner zone. For willow, K and S were also the dominating elements, but with somewhat elevated levels of Cl also seen on R3 and R4.

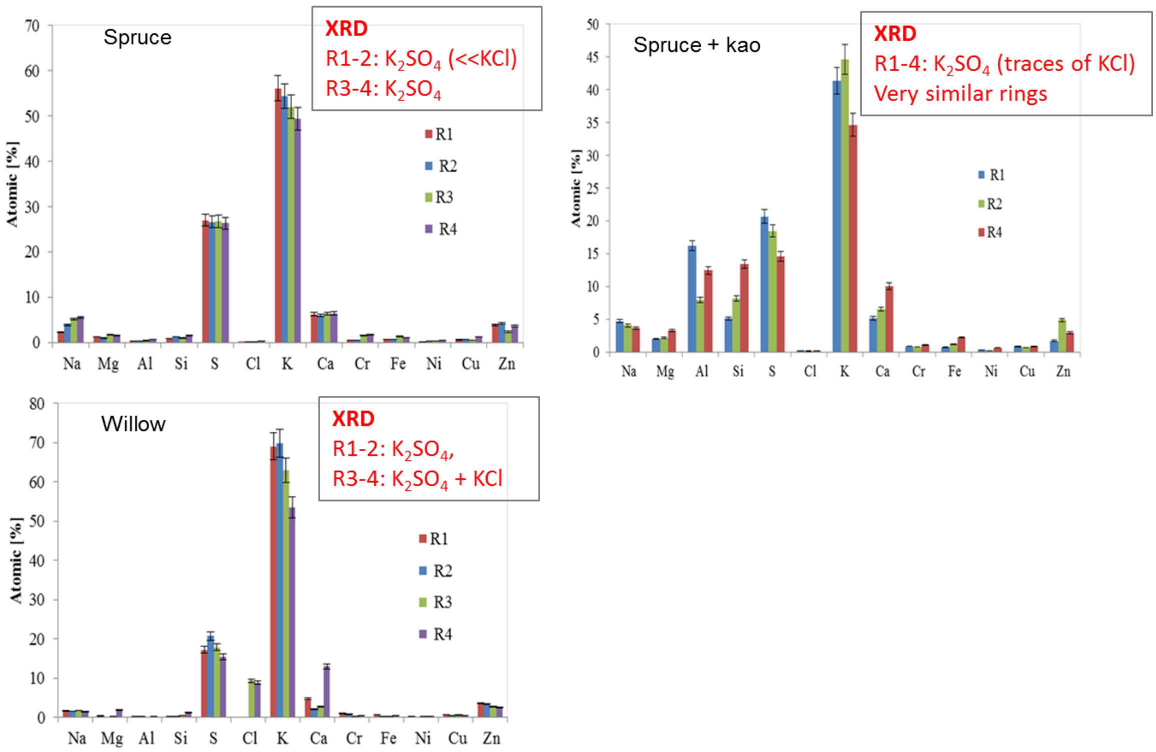


Figure 5: Elemental compositions (from SEM-EDS) of ring deposits on a carbon-free and oxygen free basis, with a qualitative assessment of the phase composition (XRD) included

3.2.2.3 Conclusions

Based on the tests performed within this task, the following final remarks and conclusions can be made:

- Differences in deposit built-up between the fuels; approximately 2 fold increase spruce→willow and 2 fold decrease spruce→spruce+kaolin.
- Symmetrical deposits inside the rings for all the three fuels, where higher ring surface temperatures resulted in higher deposits.
- Main elements in the deposits for woody biomass fuel were K and S with inclusion of low concentrations of Ca, Cl, Na and Zn.
- No/very small amounts of chlorides present in the tested cases for the spruce fuel, only at lower ring temperatures when using willow.
- The temperature profile of the rings influences the condensation behaviour, i.e. separation of K-sulfates and K-chlorides.
- The controlled use of kaolin additive can reduce K release and thereby reduce the deposition load considerably, both the amount AND composition of the deposits are affected.
- Highest deposit rate for willow and in addition also some Cl was found in the deposits at lower ring temperatures.

3.2.3 High temperature corrosion of heat exchanger materials - first experimental assessment

Authors: UmU: Kajsa Persson, Markus Carlborg, Rainer Backman, Christoffer Boman; RISE: Anders Hjörnhede, Sven Hermansson; LTU: Marcus Öhman

3.2.3.1 Content and method

The objective of this task was to experimentally evaluate corrosion resistance and interaction between deposits and different alloys during exposure to synthetic alkali salts at high temperatures of relevance for the EFGT concept.

Four potential HT-HE alloys of various grades were evaluated with respect to corrosion resistance, when exposed to alkali salts and salt mixtures in the KCl-K_2CO_3-K_2SO_4 system. The exposures were done in a tube furnace during 24 h for each experiment at four temperature levels between 700-1000°C.

Three of the alloys tested represent typical HT-steels used in combustion atmospheres at elevated temperatures, these were the austenitic 253 MA, the FeCrAl-alloy Kanthal APMT (pre-oxidized) and the Ni-based super alloy Alloy 600 (Inconel 600). The martensitic stainless steel X20Cr13 (X20) was only included in order to get an estimation of the corrosion on a lower alloyed steej. It is often used in knife blades, cutlery and surgical instruments but also at high temperatures (up to 580°C) applications such as super heater tubes.

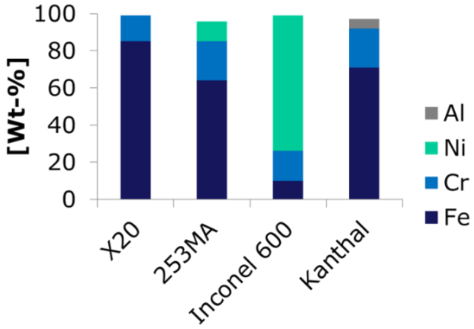
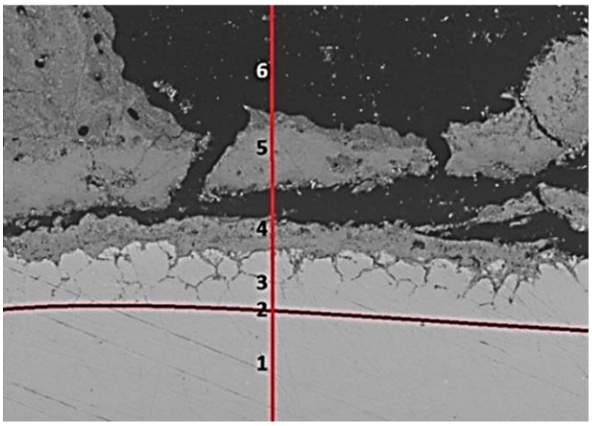


Figure 6: Main composition of the four tested alloys

The five different potassium salts and salt mixtures chosen ([K_2CO_3], [KCl], [K_2SO_4], [$0.8K_2SO_4$ + 0.2KCl], [$0.3K_2CO_3$ + 0.2KCl + $0.5K_2SO_4$]) are all relevant for typical biomass combustion flue gases. The alloys were cut in 2 x 2 cm plates with a metal shear. After the plates where covered with a 3 mm thick layer of salt or salt mixture, three replicates were placed on two ceramic cylinders on the sample holder and exposed at the time. The tube furnace was heated to the desired temperature (700, 800, 900 or 1000°C) before the samples were inserted and exposed iso-thermally for 24 h. A thermocouple was attached under the samples for measuring the temperature. Overall 60 experimental cases were included, with some excluded, e.g. 900 and 1000°C for KCl. Morphological and elemental analysis of the alloy surface and corrosion layers was subsequently performed with SEM-EDS. In Figure 7, an illustration of the evaluation procedure for the materials and corrosion layers with the SEM is shown. In addition, cross-sections of the alloys after exposure were also evaluated by standard optical microscope.



1. Unaffected metal/alloy
2. Corrosion front
3. Inner corrosion
4. Corrosion layer
5. Corrosion scale
6. Epoxy

Figure 7: Illustration of the evaluation procedure and definitions of the different layers identified by the cross-section SEM analysis, here shown for 253MA with 0.2KCl+$0.3K_2CO_3$+$0.5K_2SO_4$ at 900°C, as example

3.2.3.2 Results

Significant differences between the four materials were observed. The presence of KCl in the salt caused the most severe corrosion attacks while the corrosion attacks of the pure sulfate and carbonate were more modest. X20 experienced severe corrosion, with corrosion scale formation in most cases. The KCl-containing salts caused 253MA to form corrosion scales at all temperatures, while the corrosion resistance to other salts was fairly good. Inconel 600 had the second best overall corrosion resistance. However, it should be pointed out that in some cases the alloy was surpassed by 253MA. Kanthal APMT showed the best overall performance, with limited corrosion scale formation and surprisingly high corrosion resistance to the KCl-containing ternary salt mixture at 900°C and 1000°C. In Figure 8, some examples of optical cross-section images taken to illustrate the material interactions and corrosion attacks are shown.

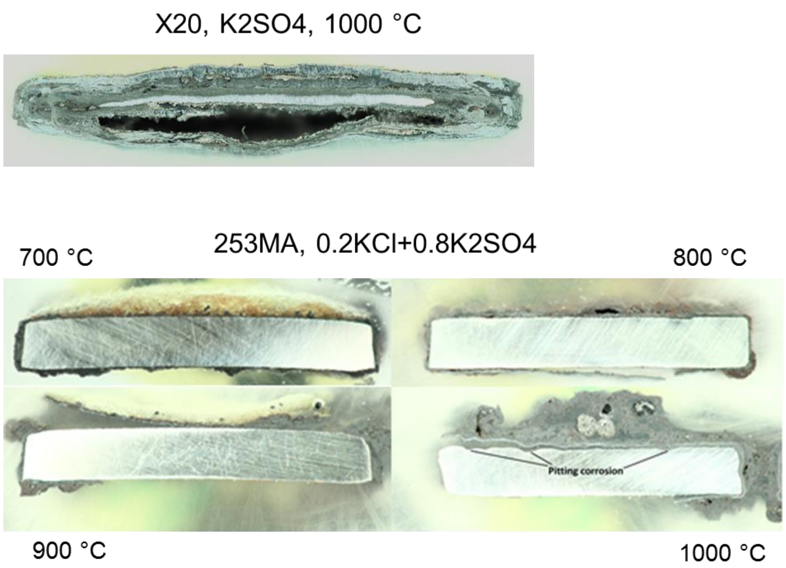


Figure 8: Example of optical cross-section images taken to illustrate the material interactions and corrosion attacks, here with X20 [K_2SO_4] at 1000°C (upper) and 253MA [$0.8K_2SO_4$ + 0.2KCl] at different temperatures (lower)

To summarize the corrosion impact of the samples a 4-grade scale was established, as shown in Figure 9. A more extensive report of all results can be found in a Master thesis from UmU [7].

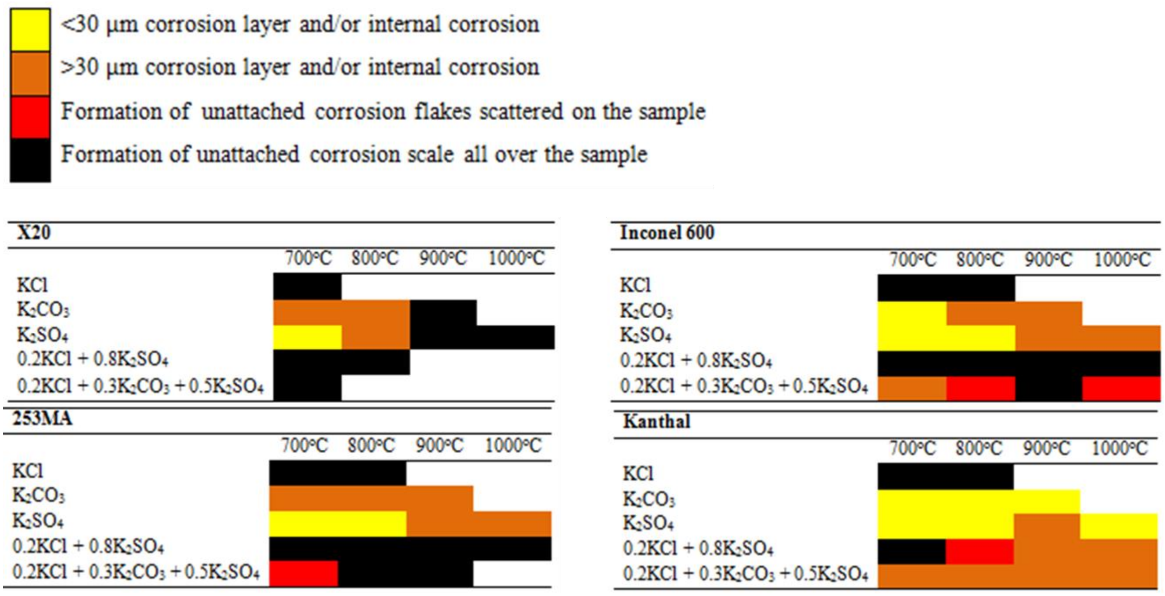


Figure 9: Summary of the corrosion impact for the whole test matrix, divided into a 4-grade scale

[7] Kajsa Persson. High temperature corrosion on heat exchanger material exposed to alkali salt deposits. Master Thesis, Umeå University 2015. (http://umu.diva-portal.org/smash/get/diva2:817823/FULLTEXT01.pdf)

Some aspects to consider for evaluation can be summarized as:

- The results cannot be extrapolated to real life operation and corrosion in a boiler.
- At elevated material temperatures, >800°C, the presence of alkali chlorides in deposits is unlikely.
- The potential formation and presence of chlorides in the deposits in full-scale applications is therefore important to consider. Also details concerning the behaviour of carbonates and sulfates need more attention.
- Aspects regarding boiler operation and intermittent load, fuel variations, flue gas temperatures at the HT-HE, and specific surface temperatures, must be considered to assess the potential real-life corrosion problems. Also alloys may be of interest, and also combined HT-HE material designs.

3.2.3.3 Conclusions

Based on the outcome of this study, regarding the corrosion aspects, the following remarks and conclusions can be made:

- All alloys showed some kind of HT corrosion.
- Exposure to KCl and KCl containing mixtures was clearly the worst (often irrelevant with choice of material).
- Pure K-carbonate gave only modest corrosion, but not likely to be a real situation.
- Exposure to pure K-sulfate was the only case with no/minor corrosion (up to 900°C)
- General order of corrosion resistance; Kanthal APMT > Inconel 600 > 253MA >> X20
- X20 should not to be used in any HT situation
- 253MA and Inconel 600 behaves very similar
- Kanthal APMT performed best (but more expensive and has other mechanical properties)

3.2.4 Advanced modeling of the combustion process in fixed beds to enable a biomass based EFGT concept with high combustion stability and low alkali related deposit problems

Authors: CTH: Henrik Ström; RISE: Fredrik Niklasson, Sven Hermansson

3.2.4.1 Method

The objective of this task was to further develop computational modelling of small-scale fixed-bed combustion by including the effects of ash transformations on the combustion stability for fuels with challenging ash chemistry. The model development was accompanied by a comprehensive experimental campaign to support the development as well as to assess the applicability of the final version of the model.

The experiments were performed in an insulated 60 L bench-scale stationary-bed reactor. For each experiment, approximately 25 kg of pellets were loaded in the reactor. The bed was ignited from the top while primary air was injected from below. Two fuels (stem wood pellets and forest residue pellets) were evaluated at three different air-flow rates. The temperature in the reactor was measured at four heights (in the bed, above the bed and in the walls). The reactor was also placed on a scale to record the mass loss. Gas concentrations were measured with a micro-GC and an FTIR-instrument by extraction of gas samples from the fuel bed. Finally, the remaining ash was analyzed (by weighing and assessing the degree of sintering and slagging) after each run. A hood and radiation shields were employed above the reactor setup. The setup is illustrated in Figure 10.

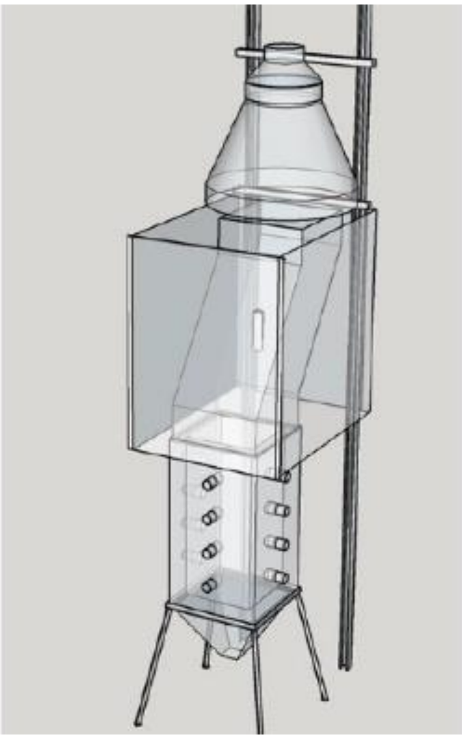


Figure 10: Illustration of the experimental setup

The model framework was a combination of a computational fluid dynamics (CFD) model representing the gas and its interaction with the fuel bed (described as a porous medium), together with sub-models for the conversion on the single-particle scale as well as the bed compaction [8,9,10,11,12]. The ash transformation effects were introduced at the single-particle level, by modifications of the physical properties of the ash in the model (controlled indirectly via the ash porosity). If ash transformations occur, the outcome is a molten and less porous ash that has a higher heat conductivity and a lower mass diffusivity.

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[8] Thunman H, et al. Combustion of wood particles - a particle model for Eulerian calculations. Combustion and Flame 2002;129:30-46.
[9] Hermansson S and Thunman H. CFD modelling of bed shrinkage and channeling in fixed-bed combustion. Combustion and Flame 2011;58:988-999
[10] Ström H and Thunman H. CFD simulations of biofuel bed conversion: A submodel for the drying and devolatilization of thermally thick wood particles. Combustion and Flame 2013;160:417-431
[11] Ström H and Thunman H. A computationally efficient particle submodel for CFD-simulations of fixed-bed conversion. Applied Energy 2013;112:808-817
[12] Johansson R, et al. Influence of intraparticle gradients in modelling of fixed bed combustion. Combustion and Flame 2007;149:49-62

3.2.4.2 Results

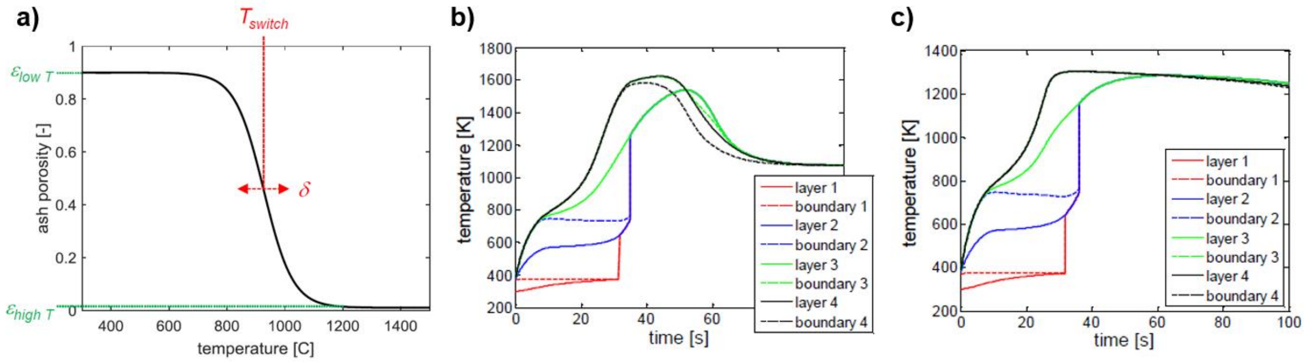


Figure 11: Illustrations of the developed model for ash transformations at the single-pellet level

Explanations: a) the sigmoid function used for the ash porosity, b) temperature evolution in a reference combustion case for a moist fuel particle, c) temperature evolution for the same moist fuel particle with ash transformations taken into account. The legends in (b) and (c) refer to the four particle layers (moist fuel = 1, dry fuel = 2, char = 3, ash = 4)

A sigmoid function approach was found to offer most flexibility to describe the ash transformations at the single-particle level. The final model has four parameters: two limiting porosities, a temperature at which the transitions occur, and the width of the temperature interval around the transition point. It can thus be envisaged as mimicking the melting of the ash layer around a pre-defined temperature (Figure 11).

In the fixed-bed experiments, the temperatures in the reactor were below 1000°C at the lowest air-flow rate (0.1 kg/m²,s) and increased with air-flow rate to roughly 1400°C at the highest rate (0.5 kg/m²,s). It was found that a char layer was formed on top of the conversion front in the case of low air flow, whereas the char layer became thin and difficult to separate from the ignition front at higher air flow. The same phenomenon was also captured by the simulations.

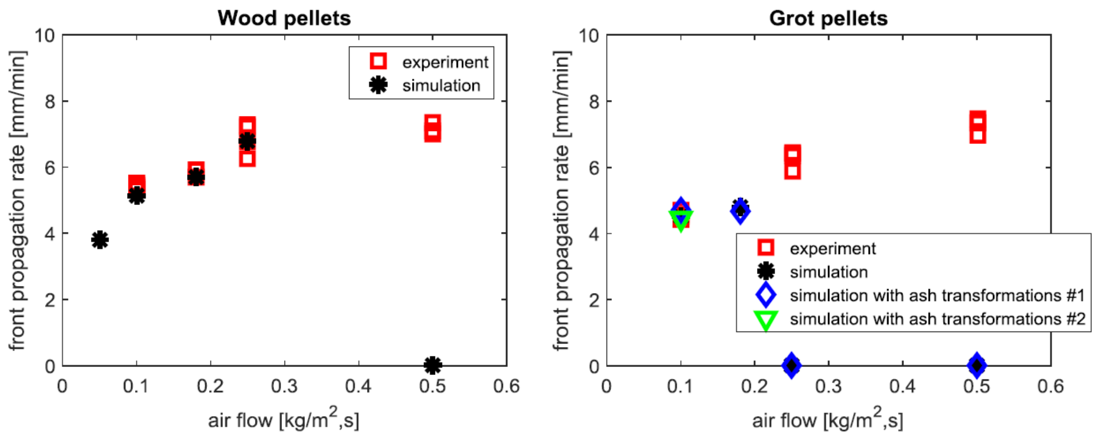


Figure 12: Comparison of experimental and computational front propagation rates for the fixed-bed combustion of wood pellets and forest residue pellets.

Explanations: grot … forest residue; two different parameter sets were evaluated for the ash transformation model (#1 and #2)

The front-propagation rates were found to correlate very well with the mass conversion rate of the bed (i.e. the combustion rate). The agreement between the model and the experiments was very good for low air-flow velocities, but deteriorates as the stoichiometric limit is approached (Figure 12) where the model erroneously predicts too early extinction (due to the fact that an insufficient space above the bed is included in the computational domain). However, at the low air-flow rates the agreement is satisfactory for both front-propagation rates and temperature history in the bed, and the predicted gas compositions are also in fair agreement with the measured data.

It was found in both experiments and simulations that much more ash remains in the reactor when burning forest residue pellets compared to stem wood pellets. Furthermore, both the ash category and the slag fraction increase (i.e. more sintering and slag) with the air flow. The slag fraction also seems to be higher for the forest residues than for stem wood, at least at high air flow. There was no catastrophic slagging observed in the current experiments, but the capabilities of the model to describe effects of such slagging, down to only slightly reduced combustion rates due to milder ash transformations, were confirmed in computational explorations. Further model development is necessary to address medium-to-high air-flow rates with higher accuracy, and to better link the model parameters to specific fuel properties.

3.2.4.3 Conclusions

The main conclusions from this task are:

- To achieve a good combustion stability and high fuel flexibility for the EFGT technology, a fixed-bed boiler should be operated in the low air-flow regime, where a proper balance between combustion rate and maximum temperature can be found.
- At medium-to-high air-flow rates, the combustion rate levels out while the maximum temperature continues to increase. Such operating conditions will increase ash sintering in the bed, and also increase the risk for coarse ash-particle entrainment.

3.2.5 Long-term testing of heat exchanger material in full-scale combustion plants

Authors: RISE: Daniel Ryde, Anders Hjörnhede, Sven Hermansson; UmU: Markus Broström, Christoffer Boman; Osby Parca: Dennis Eliasson

The objective of this task was to test different heat exchanger materials in a full-scale (medium-sized) biomass fired boiler regarding the potential corrosion and material effects. In the first phase, temperature measurements were performed in the flue gas in the vertical shaft in an Osby Parca 3 MW boiler. The measurements showed that the temperature range was 800-950°C, (results shown elsewhere) which is a suitable temperature range for the high temperature heat exchanger.

Given the elevated service temperature of the superheater, i.e. 800-900°C in a combustion atmosphere, the number of candidate materials available for production of superheaters is limited. Despite the elevated material temperature compared to superheater temperature for conventional combustion in boilers, the pressure on the inside of the tubes is relatively low, only 4 bars. The low pressure does not only enable the use of similar materials than normally used for conventional combustion, it also reduces the high demand on the mechanical properties of the material. However, even though it is not shown in this study, one may presume the lower pressure also leads to a lower corrosion rate.

In order to select suitable alloys for superheater material, four different alloys were then exposed in a wood chips (forest residues) fired full scale utility boiler (63 MW_{th}) for almost 420 h. The rationale for the selection of a utility boiler is the more stable operation conditions and the more extensive monitoring of emissions.

Of the four different alloys tested, three are representing different types of materials which are frequently being used in combustion atmospheres at elevated temperatures. The austenitic 253 MA, the FeCrAl-alloy Kanthal APMT and the Ni-based super alloy Alloy 625 were included. The martensitic high temperature stainless steel X22CrMoV12-1 was only included in order to get an estimation of the corrosion on a low alloyed material, guaranteed to corrode in this atmosphere. Some of the four materials used here were also included in the lab-tests reported previously in 2.3. The chemical composition of the alloys are shown within Table 3.

Table 3: Chemical composition of the alloys investigated

Trade name	EN standard	Chemical composition
253 MA	EN 1.4835	Fe21Cr11Ni1.6Si0.17N0.05Ce
Kanthal APMT	-	Fe21Cr4Al3Mo
Alloy (Inconel) 625	EN 2.4856	Ni21.5Cr9Mo3.75Nb+Ta
X22CrMoV12-1	EN 1.4923	Fe12Cr1Mo0.5Ni

The sample test rings were mounted on an internally cooled probe, but no forced cooling of the probe, by cooling media was done. The probe temperature was kept at a slightly lower temperature than the surrounding flue gas due to natural cooling of the probe. The surface metal temperatures on the test rings were about 850°C and 760°C depending on the boiler load. The average temperature during the full exposure was 798°C. The flue gas temperature was estimated to 10 -20°C above the metal temperature. The oxygen concentration in the flue gases was on an average 4.4% during the exposure.

Figure 13 shows the rings on the corrosion probes after a few days of exposure. It can be seen that the deposit formation was extensive. Figure 14 shows grinded and polished cross-sections with the formed corrosion product in the centre.

Figure 13: Probe with the four test rings after a few days of exposure

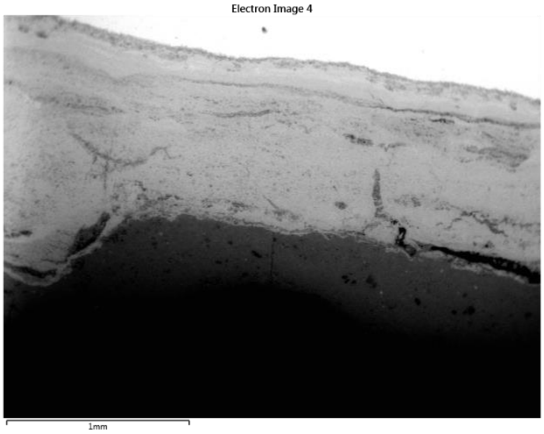
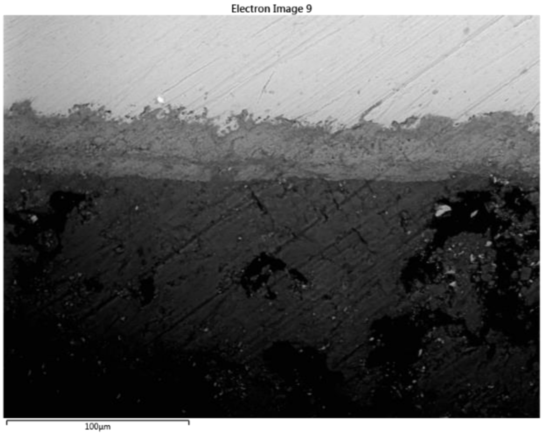
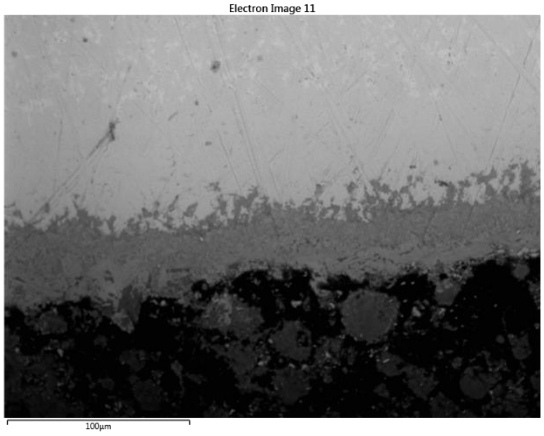
	
Cross-section, showing the corrosion product on the martensitic stainless steel X22CrMoV12-1 after 420 h at 800°C. The top white area is the un-corroded steel, followed by the corrosion product, grey area. The thickness of the corrosion product is over 1 mm.	Cross-section, showing the corrosion product on the FeCrAl - steel Kanthal APMT after 420 h at 800°C. The top grey/white area is the un-corroded steel, followed by a dark area which is the resin in which the sample is mounted. The formed corrosion product cannot be seen in the micrograph, indicating very limited corrosion.
	
Cross-section, showing the corrosion product on the austenitic stainless steel 253 MA after 420 h at 800°C. The top bright area is the un-corroded steel, followed by the corrosion product, grey area. The thickness of the corrosion product is about 40 – 50 µm.	Cross-section, showing the corrosion product on the Ni-based superalloy Inconel 625 after 420 h at 800°C. The top brighter area is the un-corroded alloy, followed by the corrosion product, grey area. The thickness of the corrosion product is somewhat less than 50 µm.

Figure 14: Grinded and polished cross-sections with the formed corrosion product in the center

In Figure 15 the thickness of the corrosion product and the corrosion rates are given. The two leftmost figures show the thicknesses of the corrosion product or oxide scale formed on the samples after the exposure given in the above figures. The centre figure has been scaled in order to give a more adequate appearance of the thicknesses on the alloys of interest in this study. The right figure shows calculated extrapolated corrosion rates, given in mm/year. The corrosion rates are about 1 mm/year for 253 MA and Alloy 625. The estimated corrosion rate for APMT is 20 µm/year. The estimated corrosion rate for the X22-steel is 27 mm/year, which is not shown in the figure.

The different corrosion mechanisms for the alloys have not been investigated in detail. However, a major difference between the tested alloys was the strong presence of Al in addition to Cr in the oxide scale / corrosion product for APMT. It can be presumed that aluminum oxide was formed, which is regarded to be very protective against corrosion in the studied temperature range. The other alloys do not contain Al

as alloying element therefore Cr was the major constituent in the corrosion product, although not shown here.
Given the results presented above, the FeCrAl-steel Kanthal APMT appears to be the obvious first choice amongst the tested alloys.

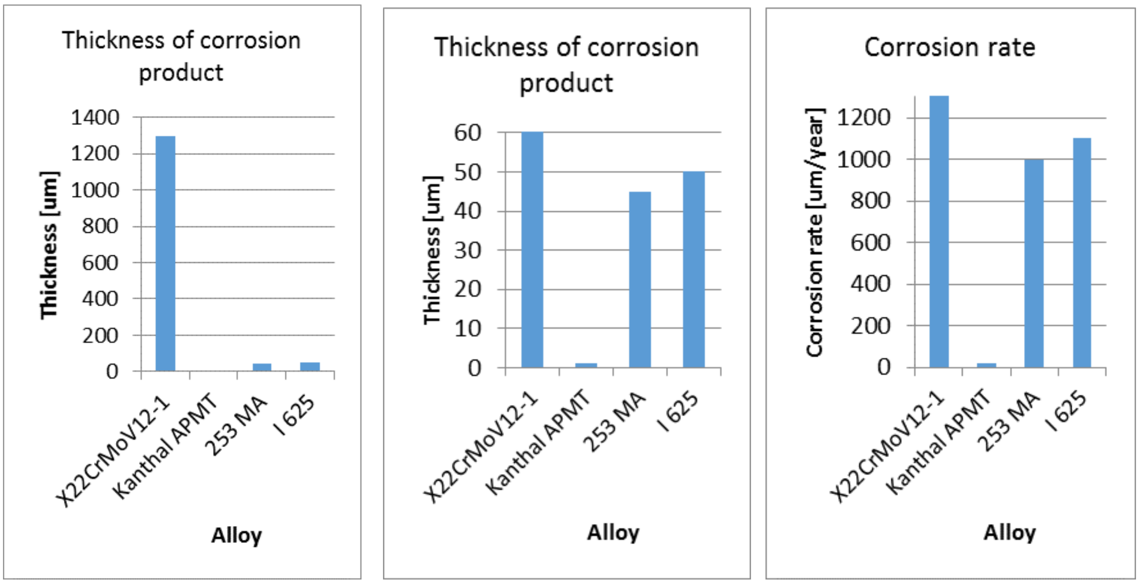


Figure 15: Thickness of corrosion product or oxide scale (two leftmost) and corrosion rate (left), with scaled axis in the centre and left figures to better show the results for the alloys of interest for the HT-HE application

However, attention must also be paid to the extensive deposit formation. It will affect the tube pitch in the HT-HE and its cleaning procedure. Finally, also other considerations will most probably be relevant for the overall assessment of suitable steel materials for the HT-HE. These are further discussed in WP5.

3.3 WP3: Development and test of the TEG technology

Authors: BIOS: Ingwald Obernberger, Gerhard Weiß

3.3.1 Description of the technology

Biomass based room heating systems are very common for space heating throughout Europe. In the recent 15 years especially pellet stoves became more and more popular due to their advantages regarding automatic control, user friendliness (automated ignition, easy and clean fuel handling) and low emissions in comparison to logwood stoves. However, the need of an external electric power supply to provide electricity for ignition and stove operation is a disadvantage of pellet stoves especially with regard to fail-proof and independent heating systems. In order to enable the operation of a modern pellet stove without electric grid connection, a new micro CHP technology based on a selected basic pellet stove design of RIKA and a thermoelectric generator has been developed.
With thermoelectric generators (TEG) maintenance-free electric power can be silently produced from heat. Thus, this technology is particularly suitable to realise a grid-independent operation of stoves, which are usually used in residential areas (e.g. for heating of the living room). The principle of the TEG

is based on the Seebeck effect, in which heat is directly converted into electricity by two connected and differently doped semiconductors placed at different temperatures (Figure 16).

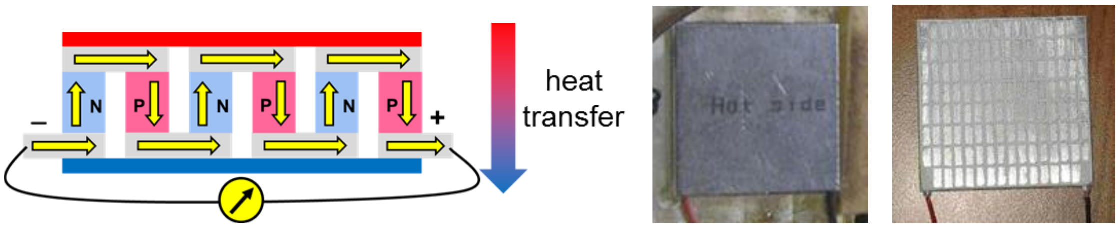


Figure 16: General scheme of a TEG as well as pictures of the thermoelectric modules used in the pellet stove with and without ceramic substrate

The electric output of the TEG is influenced by the type of the TEG, the number of thermoelectric modules used, the temperature difference between the cold and hot side of the TEG (with rising temperature difference the electric output is increasing) and the cold side temperature of the TEG (with a rising cold side temperature of the TEG the efficiency is decreasing). Thus, a high temperature difference at a low cold side temperature of the TEG is the aim for the implementation in a pellet stove. A pre-selection of thermoelectric modules for stoves took already place in former projects by RIKA. Based on these framework conditions and a pellet stove design of RIKA with a thermal stove capacity of 10.5 kW, the general approach for the new pellet stove technology with TEG has been defined (see Figure 17)

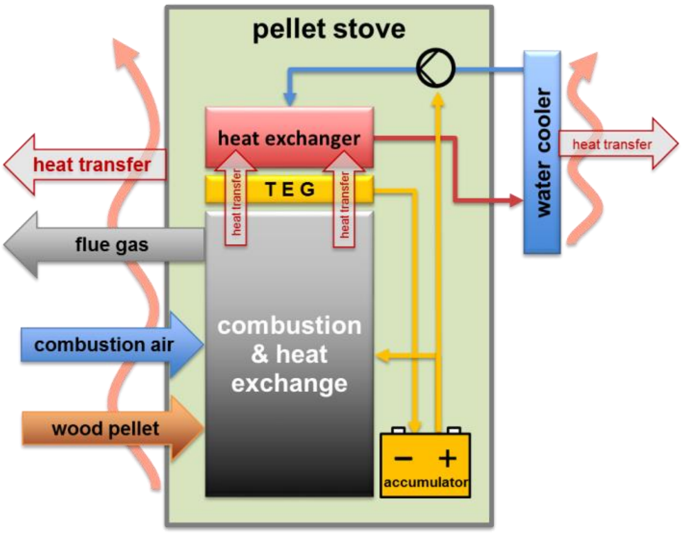


Figure 17: General approach of the new pellet stove technology with TEG

During operation of the pellet stove electricity is produced by the TEG to operate the stove and to charge an accumulator. The accumulator supplies electricity during the next start-up for the ignition and other power consumers (fan, fuel feeding and control system) until the TEG starts electricity production. The TEG is cooled by an appropriate water circuit supplying room heaters.

3.3.2 Methodology of test runs and accompanying R+D

For the development of the new technology the following methodology has been considered in order to ensure an efficient and target oriented approach during the project:

- Development of a model and subsequent performance of **transient system calculations** for the definition of the meaningful number of thermoelectric modules and to evaluate different cooling options for the TEG. With transient system calculations a realistic overall dynamic system modeling based on the given boundary conditions regarding pellet stove operation, TEG and ambient was possible. Thereby, cooling options based on air cooling, water storage with convection air cooling and a water circuit with convection air cooling have been modelled and evaluated (see Figure 18). Due to the low and stable TEG cold side temperatures achievable, the water circuit has been identified as the most suitable cooling option for the TEG. Furthermore, this cooling option offers the possibility to heat an additional living room. In addition, the calculations pointed out that 10 – 12 thermoelectric modules are required to ensure a sufficient power production of the TEG at nominal as well as at partial load down to 30%.

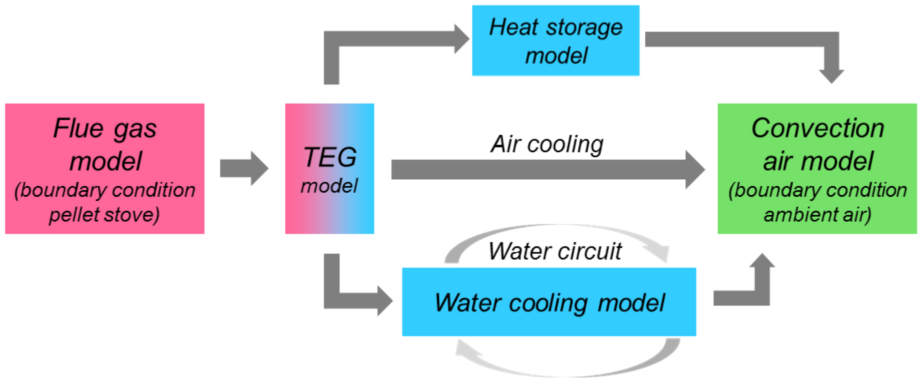


Figure 18: Structure of the transient system calculations for the tree cooling options investigated

- Definition of **optimised system components** enabling high efficiency, low electricity demand and low investment costs. A main focus of the development work was put on the selection of appropriate low voltage system components (ignitor, flue gas fan, fuel feeding system and water pump) to reduce the electricity demand of the pellet stove at start-up and during operation. Furthermore, the interaction of TEG, accumulator and power electrionics has been fine-tuned and is controlled in order to maximize the electricity production during operation.
- **CFD (Computational Fluid Dynamics) based design of a pellet stove with integrated TEMs.** By the CFD simulations very good burnout conditions at full and part load have been achieved for the testing plants with a complete burnout before the flue gas passes the TEG area (important to prevent soot or tar deposit formation on the hot surfaces of the TEG module). Based on the CFD simulations an optimised positioning of the 12 thermoelectric modules with rather uniform surface temperatures has been achieved and the maximum temperatures of the new components water pump, electronics and accumulator have been evaluated and reduced by increasing convection air openings and metal sheets for radiation protection. Furthermore, the air staging and window flushing has been optimized to ensure a clean window and low O2 content in the flue gas (high thermal efficiencies). In Figure 19 exemplary the resulting temperatures of the flue gas, the convection air and the stove are shown.

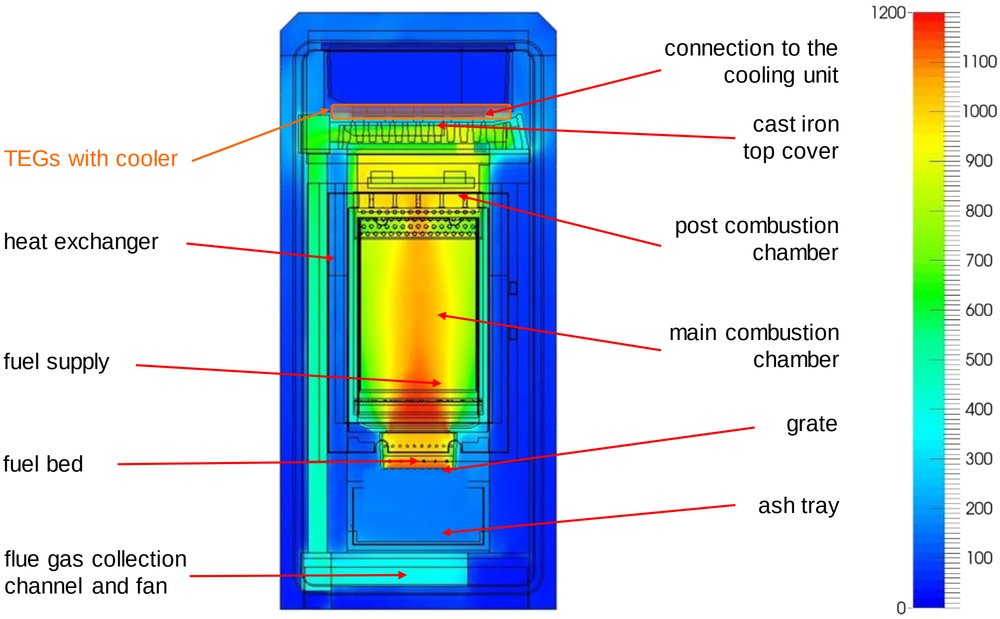


Figure 19: Gross section of the pellet stove with iso-surfaces of flue gas-, convection air- and stove temperatures [°C]

- **Construction of testing plants** (2-stage approach): Based on the development work a pre-optimised prototype of the micro CHP system was constructed (1st testing plant) and comprehensive test runs have been performed to evaluate the performance of the pellet stove, the TEG as well as the cooling system. In addition to the pellet stove a cooling system (water circuit) was designed, constructed and tested. Based on the data and experiences gained from the test runs the system has been stepwisely optimized and a second - near to the product - testing plant was constructed and tested. In Figure 20 pictures of the two testing plants investigated are shown.

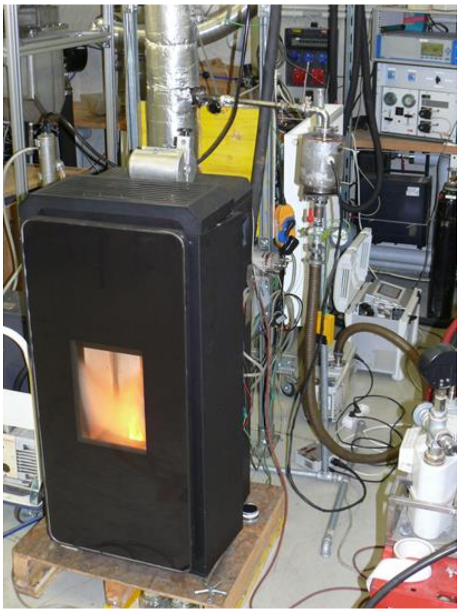


Figure 20: 1st testing plant (left) and 2nd (right) on the test stand at BIOS

- **Performance of test runs**, evaluation and stepwise optimisation of the technology: With both testing plants comprehensive test runs at different loads (30%, 50%, 65% and 100% of nominal load) as well as load cycle tests (for the 2nd testing plant) have been performed to evaluate the new technology. Thereby, temperatures of the flue gas, combustion air and water system as well as of the cold and hot side of the TEG have been measured. In addition the volume flow of the flue gas, combustion air and water system as well as all relevant gaseous emissions (O_2, CO_2, CO, OGC, NO_x) in the flue gas have been measured continuously. Furthermore, for dedicated test runs the total and fine particulate emissions have been detected. In addition selected fuel and ash samples have been analysed by BIOS. The test runs have been evaluated and energy balances as well as carbon balances have been made for plausibility checks.

3.3.3 Results achieved and comparison with the project targets

Already with the first testing plant very promising results regarding thermal efficiency, gaseous emissions and electricity output of the TEG have been achieved. With the second testing plant which already represents a near to the product system including the power electronics the performance could be further improved. In the following an overview regarding the final results with the 2nd testing plant are presented.

Due to the efforts taken to implement components with low electricity demand and due to the optimised control system a very low electricity demand for the new pellet stove micro CHP technology has been achieved for nominal load (9 W) and part load (5 W at 30% part load) operation. Within this electricity demand the power consumption of the water pump for the water circuit is already considered (see Figure 21).

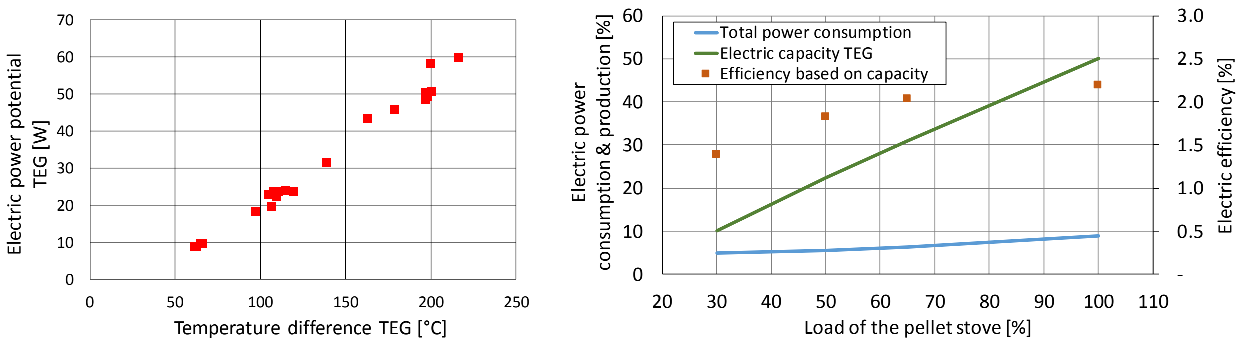


Figure 21: Electric power potential of the TEG in dependence of the temperature difference between cold and hot side of the TEG (left); electric power consumption and production as well as electric efficiency of the TEG during stable load operation (right)

Depending on the temperature difference between cold and hot side of the TEG (which is directly correlated to the power of the pellet stove) the potential electric power is 10 W at 60°C temperature difference (representing 30% part load) to 50 W at 200°C temperature difference (representing nominal load operation). Thus, over the whole load range of the pellet stove the electricity demand can be covered by the TEG. Furthermore, the surplus electricity produced in the range of 5 to 40 W is used to charge the internal accumulator for the next re-start of the pellet stove. If the accumulator is again fully charged the electricity produced can be used to charge external devices (e.g. mobile phones) via USB-port.

The electric efficiency of the TEG related to the thermal input is in the range of 1.4 to 2.2% (see Figure 21). Based on the test run results, the overall efficiency at nominal load amounts to 91% and rises at 30% part load up to 97%. At nominal load 8.4 kW of the useful heat is released by the pellet stove itself (by radiation and convection air) and about 2.3 kW (21% of total heat output) by the two radiators of the water system (suitable to heat a second living room).

Since in real life pellet stoves are operating at different loads and most of the time not at stable conditions, the practical suitability of the new micro CHP technology has also been evaluated based on a load cycle test especially developed for pellet stoves (see www.bereal-project.eu). The load cycle includes three different load phases (nominal load, 30% part load and 65% part load), three starts of the pellet stove and lasts for 8 h (see Figure 22).

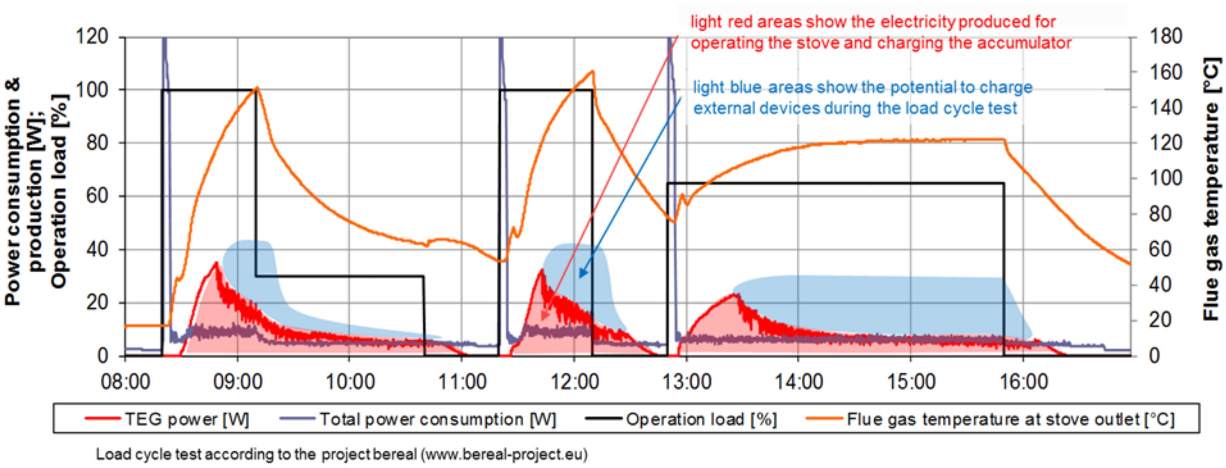


Figure 22: Load cycle tests performed with the new pellet stove with TEG

The load cycle tests with the new micro CHP pellet stove technology have shown that after each start-up of the stove the accumulator can be re-charged within the given time of operation. Thus, at the end of the load cycle test run the accumulator is again fully charged. In addition a potential of about 50 Wh to charge external devices is given during a load cycle test (represented by the light blue areas in Figure 22). For the load cycle tests [13] an overall efficiency (including the cooldown phases between the operation phases and at the end of the load cycle test) of 92.6% has been achieved which is a very good result.

Summing up, with the 2nd testing plant the project targets regarding reduction of the electricity consumption and electricity production as well as the electronics system integration has been completed and the practical suitability has been proven.

3.3.4 Highlights and outlook:

With the new micro CHP technology based on a pellet stove and a TEG system, a renewable CO_2-neutral room heating technology which can operate off-grid has been developed. The TEG system is a wear- and maintenance-free as well as noiseless technology and thus ideally suitable for applications in living rooms.

[13] Reichert G., et al. 2016: Definition of Suitable Measurement Methods and Advanced Type Testing Procedure for Real Life Conditions; Final Report of the “beReal” project, funded by the FP7-SME-2013-2, Research for SME associations within the 7th Framework Programme of the EU, http://www.bereal-project.eu/

The electricity produced by the TEG system covers the energy demand for operation and start-up of the pellet stove. The surplus electricity produced can be used to charge external devices, such as mobile phones or other small consumers. The practical suitability of the new micro CHP technology has been proven by the successful performance of load cycle tests with the 2nd testing plant.
Due to the water cooling system, a second living room can be heated by the new pellet stove technology. Furthermore, the economic calculations within WP6 pointed out, that the new technology is also from an economic point of view an interesting solution. The final design and long-term testing of the new components is currently ongoing. Its market introduction is planned by RIKA within the next two years.

3.4 WP4: Development of the micro-scale ORC technology

Authors: TFZ: Paul Rossmann; Hans Hartmann; Orcan: Jürgen Fernengel

3.4.1 Description of the technology:

The Organic Rankine Cycle (ORC) technology itself is already state-of-the-art. In principle it applies an "ordinary" thermal power plant process (see Figure 23), but uses an organic fluid for evaporation instead of water. As every thermal process, the ORC operates between two temperature levels, or, to be more specific, between two pressure levels which are depending on the chosen type of fluid and its evaporation and condensation temperature. The advantage of the ORC process is the possibility to use lower temperatures for the evaporation of the fluid for the generation of electricity compared to a water-based rankine cycle. While choosing the suitable fluid, this could theoretically even mean that the hot side of the thermal process is at ambient temperature and the cold side is a fluid which has a temperature significantly lower than the ambient temperature, e.g. a compressed gas after expansion to normal pressure. The thermodynamic process is shown in Figure 23.

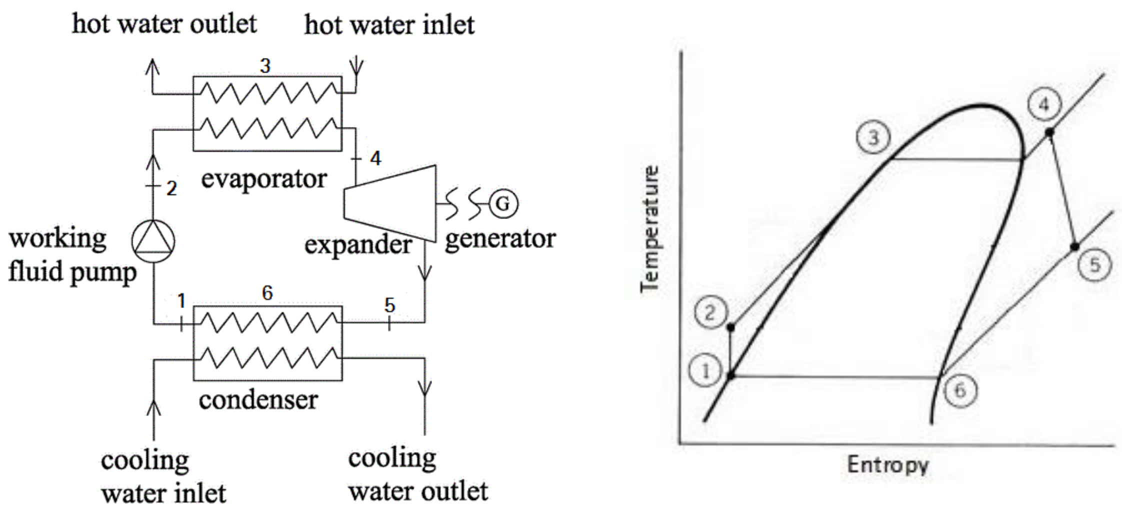


Figure 23: Rankine Cycle – main components (left), ORC-process – T-S-diagram (right)
Explanations: 1 → 2 : pressure rise caused by the fluid pump; 2 → 4 : preheating, evaporation and overheating in the evaporator; 4 → 5 : energy conversion in the expansion machine; 5 → 1 : cooling and condensation of the fluid in the condenser

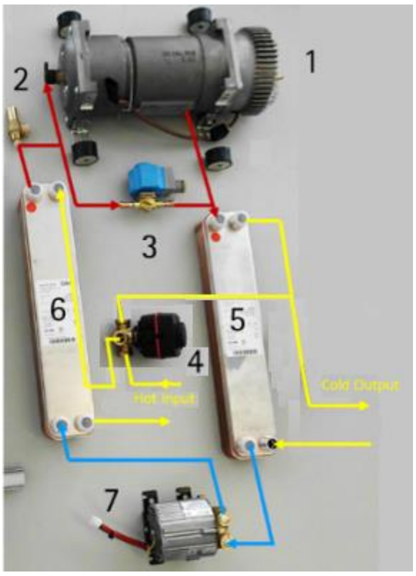
For the capacity range from 200 kW_{el} to 2,500 kW_{el} the ORC process itself is state-of-the-art. Small and micro CHP systems, however, face yet unsolved problems. Scaling down to around 1 kW_{el} deteriorates both, low investment costs and electric efficiencies, which would be high enough to cover the basic electricity demand of an ordinary single household.

Micro-CHP systems are usually operated in a heat controlled mode, taking the building's heat demand as a reference. To optimise the control strategy by considering the power demand, the electricity production and the availability for the building was not possible so far because of missing information about the heat transfer from the boiler to the ORC system, the load curve and the fluctuations of the power demand of the user.

The main obstacles for market success of current micro-ORC systems are initial investment costs and payback periods. Furthermore, there is almost no experience on the durability of the components used in the ORC.

The thermal and electric output of small-scale ORC systems currently available on the market are still far too high for most domestic applications. Therefore, ORCAN developed an ORC module with a standardised interface which optimises the heat transfer from the biomass boiler to the ORC based on a pressurised hot water cycle. It should be suitable for integration in new and secondly be also applicable as retrofit unit (add-on) for existing boilers.

As mentioned before, this module has to meet low investment costs and low maintenance costs on the one hand and an electrical output, which allows acceptable payback periods, on the other hand. To acquire low investment and low maintenance costs, ORCAN uses as few components as possible to run the ORC (see Figure 24) and only such components which are derived from mass production. These components are already available at low costs and are tested for adequate lifetime. For this reason the electrical output is not maximized, as it would be if components perfectly fitting to the micro ORC were constructed. But the low costs make it possible to achieve acceptable payback periods (see therefore WP6) and the use of standard components to achieve a high product lifetime. To receive an impression of the main components see Figure 24.



1: Expansion machine
2: Safety valve
3: Fluid-bypass valve
4: Internal water-bypass valve
5: condenser (plate heat exchanger)
6: evaporator (plate heat exchanger)
7: pump

Figure 24: Main components of the ORC-module

3.4.2 Methodology of test runs and accompanying R+D:

A pilot plant was constructed and an appropriate hydraulic scheme was developed for coupling the micro-ORC system with small-scale biomass boilers. The aim was to achieve an universally applicable retrofit solution.

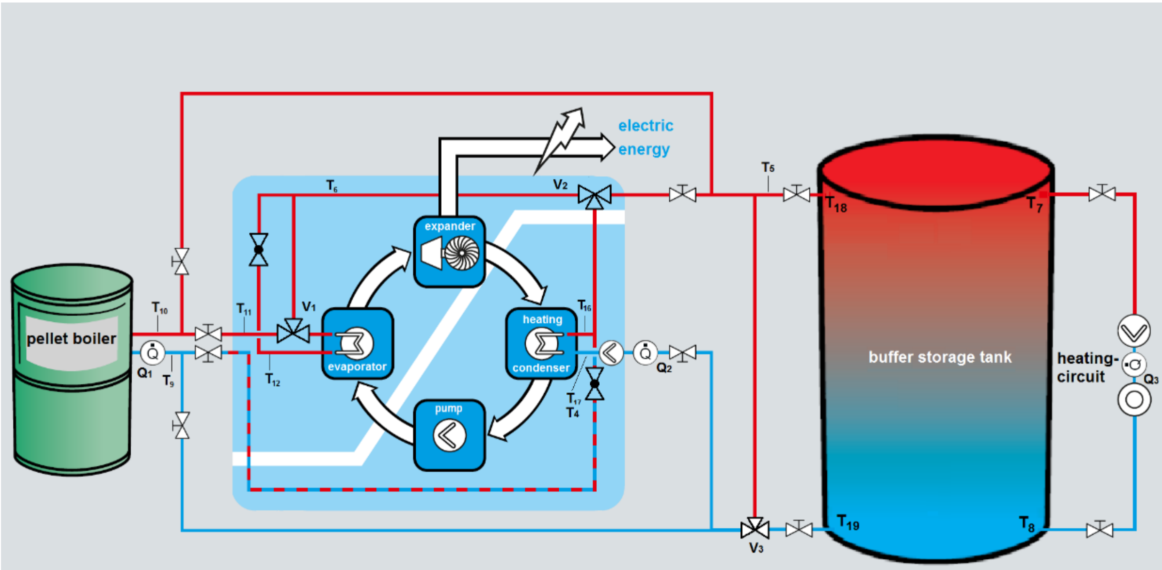


Figure 25: Hydraulic scheme for coupling the micro-ORC system with an existing small-scale biomass boiler

New options regarding control strategy for micro ORC systems in residential buildings were tested. Therefore, the interfaces between boiler and ORC at feed temperatures from 95°C to 120°C without additional heat exchanger were evaluated. The design, positioning and integration of this heat transfer concept were optimized by ORCAN and TFZ, in order to achieve a hot water cycle with low cost and reliable “off the shelf” components.

In order to be able to estimate the power potential and also the efficiency potential of the ORC with different boundary parameters, a semi-empirical thermodynamic simulation was performed by ORCAN in addition to the tests carried out by TFZ. The simulations predicted a net electrical efficiency of 3% based on the total heat transferred to the evaporator and a net electrical power output of 300 W at an average temperature difference of 40 K between the hot water inlet temperature at the evaporator (85°C) and the cold water inlet temperature at the condenser (45°C). The amount of heat transferred to the evaporator was 10 kW_{th}. After implementation of improvements identified, the CHP system was tested under defined load cycles in order to validate the optimised control strategies.

A modified small-scale pellet boiler (24 kW nominal heat output) without additional heat exchanger was installed at the test stand of TFZ and was tested under reproducible conditions. On the basis of the results of these experiments, the optimum conditions for the operation of the boiler and the ORC module were determined in order to achieve the highest possible electrical and total efficiency as well as an improved economic performance.

The following parameters were varied during the test runs:

- Temperature of the hot water circuit
- Operating modes of the boiler (full load / partial load)

- Relevant settings of the control strategy

During the test stand tests these parameters were continuously recorded:

- Boiler efficiency at different flow temperatures or boiler temperatures
- Gaseous and total PM emissions, fuel consumption of the pellet boiler
- Heat losses of the ORC
- Generated electric power of the ORC at various boundary conditions of the assessed boiler load conditions
- Required electric power for pellet boiler and ORC system (auxiliary energy demand)

By means of model calculations an optimum control strategy for the ORC system for residential energy supply was developed. This strategy considers economically relevant variables such as annual operating hours, dynamics of the daily heat and power demand, costs for electricity and efficiency impacts of variable boiler loads. Due to this control strategy the direct utilisation of the electricity produced by the ORC in the user's building was increased (without electricity storage).

In order to gain a sufficient data base for the model calculations, typical patterns of heat and electricity consumption data were recorded in various private households over one year by TFZ. Based on this, correlations between heat and electricity demand were defined for different types of users as a basis for a heat-operated control of the system which also takes the electricity consumption into account.

With dynamic process simulations using the software TRNSYS (performed by BIOS) based on the data recorded in private households by TFZ and the measurements performed at the TFZ test stand, different control strategies, including different boiler operation modes, electricity and fuel prices as well as energy storage options (buffer tanks, batteries) were evaluated. These simulations were done with the priority to optimise the electricity production.

3.4.3 Results achieved and comparison with the project targets:

In various tests carried out by TFZ, a generated electrical net power output of about 300 to 330 W was measured at a hot water inlet temperature into the evaporator of about 93°C / 105°C and a cold water inlet temperature into the condenser of 35°C (see Figure 26). The amount of heat transferred to the evaporator was about 9 kW. This corresponds to a maximum electric efficiency of about 3.5% in continuous operation.

As a result of the data collection regarding electricity and heat demand of typical residential buildings over a whole year a base load electricity demand of 250 to 400 W for all households can be identified. This basic electricity demand can be covered to a certain extent by the ORC system and thus, the target to increase the direct utilisation of the electricity produced by the ORC in the user's building has been achieved.

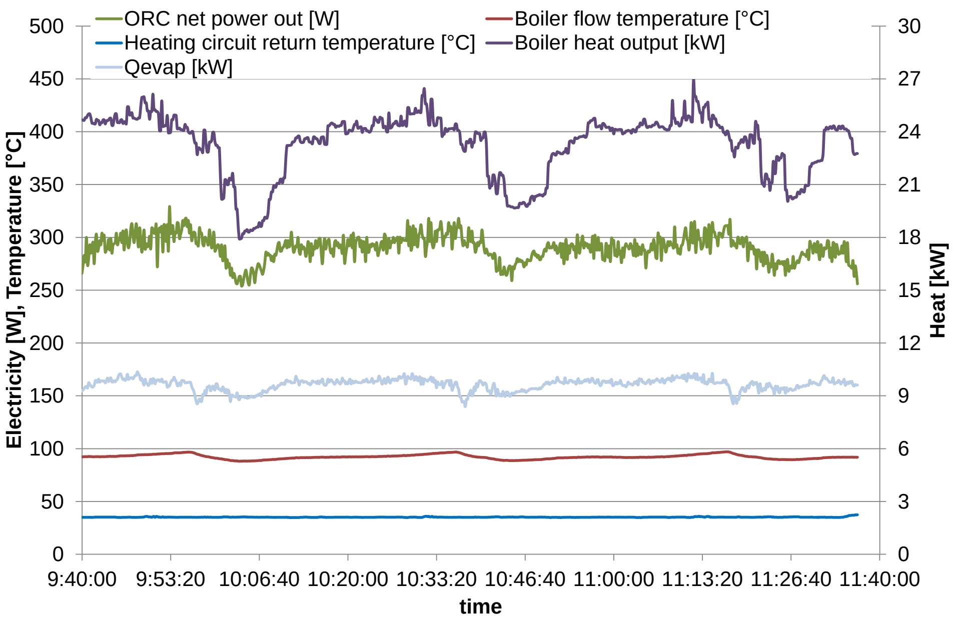


Figure 26: Test run results of the ORC at a hot water inlet temperature of about 93°C and a cold water inlet temperature of 35°C

Based on the data from one representative building of the field monitoring, an upscale of the load profile was performed by BIOS in such a way that the ORC can be operated for more than 2.000 hours at full load for the first step of simulations. TRNSYS simulations (simulation of the heating system, including buffer storage and hydraulics) based on heat and electricity load curves of typical residential buildings measured within the project were then performed by BIOS to support the work regarding the optimised system integration and system control of ORCAN and TFZ.

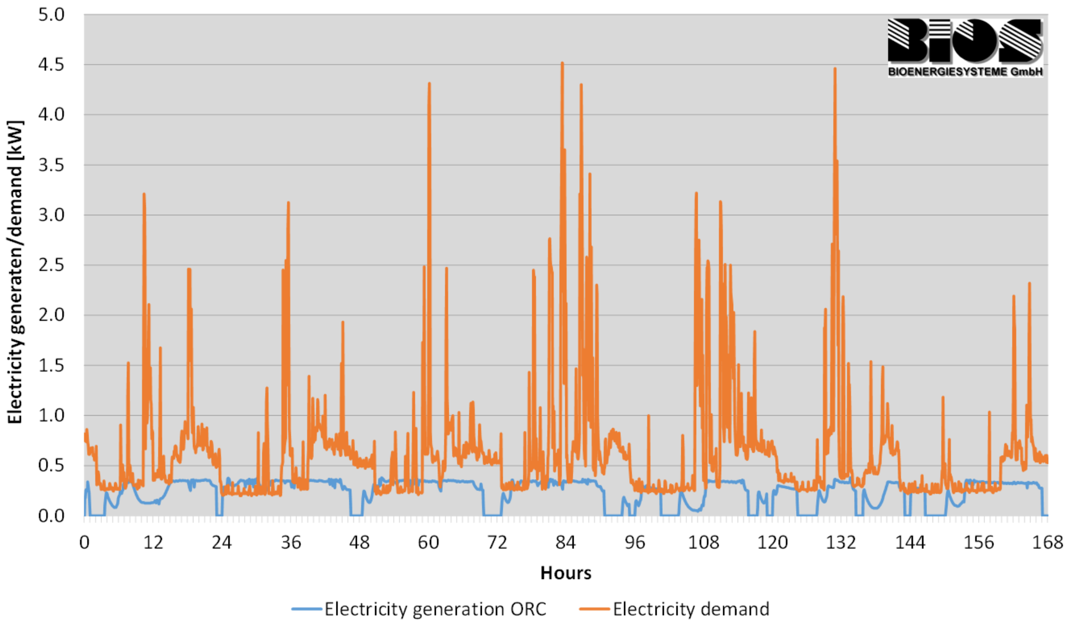


Figure 27: TRNSYS simulation results regarding electricity generation of the ORC vs. electricity demand of the residential building over a typical week in winter

These simulations resulted in a maximum thermal load of about 21 kW (for the dimensioning of the boiler) and an annual heat demand of about 42,000 kWh for the heat consumers. A low temperature heat demand (35°C return temperature) and a 2,000 l buffer storage capacity (i.e. about 100 l/kW) were assumed for the simulations.

As a result of TRNSYS simulations, the ORC reaches about 3,300 annual full load operating hours based on the heat output (annual electricity generated by the ORC divided by the nominal electric capacity of the ORC). The usable electrical energy of the ORC over one year amounts to 980 kWh and the average electric efficiency of the ORC is close to 3% over the whole year, based on the heat input into the ORC of 33,000 kWh. In terms of the optimal economic use of the generated electricity, however, the electrical efficiency is not the decisive parameter, but the quantity of electrical energy that can be used directly in the household. The increase of the return temperature of the heat consumers by 15°C (50°C instead of 35°C) would result in a decrease of the average electric efficiency by 1% down to 2% and the annually usable electrical energy generated by the ORC would decrease to 690 kWh. More than 90% of the electricity can be produced from October till April. Thus, the operation of the ORC during warmer seasons with low heat demand is not recommended.

The impact of the improvements on emissions (CO, OGC, PM) and efficiency of the small-scale pellet boiler were investigated by TFZ and compared to a reference case (conventional hot water boiler). There was no impact on gaseous and particulate matter emissions at different boiler flow temperatures (standard operation: 70°C flow temperature, high temperature operation: 105°C flow temperature). But the flue gas temperature rose proportionally to the boiler flow temperature from 106 to 132°C and thus the combustion efficiency decreased from 95.6% to 93.6% (see Table 4). The fuel demand of the pellet boiler increased due to the high flow temperatures in the order of about 2% compared to the standard mode of operation. This slight decrease of the overall efficiency due to the CHP operation mode seems acceptable under consideration of the additional electricity production possible.

Table 4: Gaseous and particulate matter emissions at different boiler flow temperatures

	T flue gas [°C]	water flow [l/h]	T flow [°C]	T return [°C]	air ratio [-]	O_2 [%]	CO [mg/ Nm³]	NO_2 [mg/ Nm³]	PM [mg/ Nm³]	boiler output [kW]	exhaust losses [%]	combustion efficiency [%]
Standard operation mode, 55 °C return temperature, full load	106	1,443	67	51	1.5	7.2	44	172	27	23	4.3	95.6
95 °C boiler temperature, 80 °C return temperature, full load	121	1,428	93	79	1.5	7.1	72	178	23	24	5.3	94.6
105 °C boiler temperature, 90 °C return temperature, full load	132	1,426	104	89	1.6	8.3	13	190	24	24	6.4	93.6

3.4.4 Highlights and outlook:

The further developed and improved micro-CHP-system in the capacity range of 1 kW_{el} will be available in the near future in the market and the electricity production can be almost completely used to cover the own electricity demand of private households. The use of standard components from technologically similar fields resulted in a reduction of the investment costs and an increase of the electric efficiency (=

net electric output / fuel power input (NCV) * 100) and thereby makes biomass based micro-scale ORC systems market competitive.

But, of course, the development is not finalized with the end of this project. There are several points, which are already in progress at other test benches or may become part of the development. They are listed in the following.

Already in progress:

- Optimized hot water circuit control
- Rotation speed control of the expansion machine
- New model design (more compact)

Further development:

- Heat transfer control
- Replacement of solenoid valve at bypass
- General reduction of power consumption

Optimized hot water circuit control:

The control of the hot water circuit will be a two temperature control (evaporator inlet temperature and evaporator outlet temperature), instead of a single temperature control (only evaporator inlet). This was already in another product version tested. The benefits are the possibility to return a definite temperature to the boiler and a better control of the heat used by the ORC. An adapted hydraulic scheme for coupling the micro-ORC system with an existing small-scale biomass boiler is also required (see Figure 25). Currently the ORC uses as much heat from the system as possible (independently from the heat production of the boiler). A consequence may be to introduce an oscillating ORC operation when the boiler operates at part load (i.e. the boiler heats up the hot water until the ORC starts -> the ORC takes as much heat out of the system, as needed for the hot water temperature to drop beneath the ORC operation temperature -> the ORC stops -> the boiler heats the water temperature up again, until the ORC starts, and so on). It shall be noted that this oscillating operation would cause no noise problems for the user, as the ORC is equipped with a very efficient noise insulation.

Rotation speed control for the expansion machine:

The expansion machine has an optimal operational rotation speed depending on the live-steam pressure and density and the condensation pressure. Experiments took place to determine the correlation between the rotation speed and these parameters. With the possibility to control the rotation speed of the expansion machine the ORC could achieve a slightly higher electrical efficiency over a broad band of variable heat input and temperature levels.

New model design:

Besides technical and economical requirements the ORC has to match also comfort and lifestyle necessities. This addresses mainly noise insulation, but also a compact design, as available space is scarce in many households. This is particularly true for ORC modules which are applied as add-on solutions to already existing installations. The noise insulation was already implemented in the test rig used in this project. A more compact construction and an attractive surrounding shell design have also been realized at another test rig (see Figure 28) within the project.

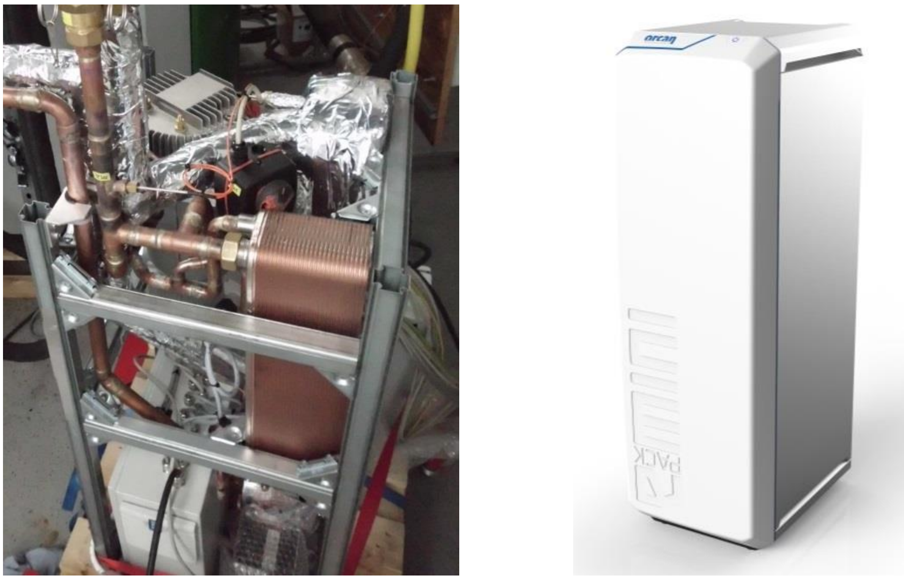


Figure 28: Compact construction and new compact design of the ORC unit

Further development:

Apart from the points, which are already in development, there are at least three more, which should be considered in future development. The first, the heat transfer control, aims at an even more optimized hot water circuit control. While adding a flow meter it should be possible to control an even more exact transition of heat from the hot water to the working fluid. The other two points are the replacement of the solenoid valve in the organic fluid circuit (which permanently consumes electric power during operation of the ORC) and the general reduction of the power consumption. Both aim at a lower internal electricity consumption, which reduces the net electricity output. Especially the solenoid valve, having a 20 W internal power demand, represents a rather large individual consumer.

3.5 WP5: Development of the HT-HE for gas turbine applications

Authors: TFZ: Paul Rossmann; Hans Hartmann; Orcan: Jürgen Fernengel

3.5.1 Description of the technology:

The concept of externally fired gas-turbine (EFGT) means, simplified, that pressurized air is heated to high temperatures by flue gas from a biomass boiler and afterwards expanded through a turbine system for electricity production. A schematic view of the EFGT system is given in Figure 29.

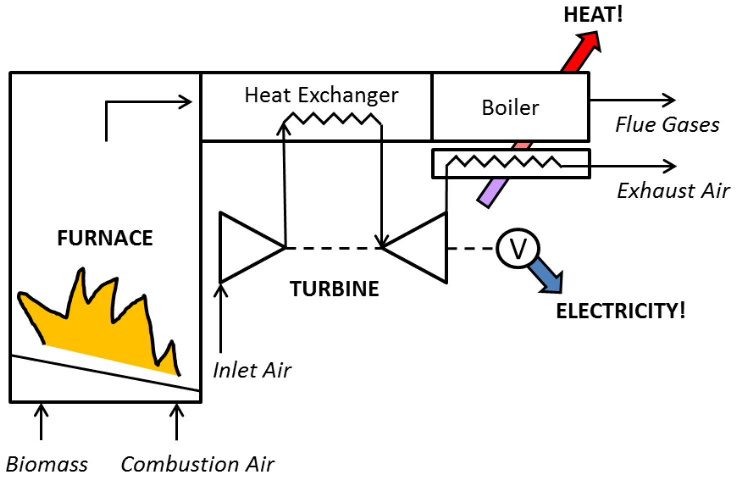


Figure 29: Schematic view of a biomass fired externally fired gas-turbine system (EFGT)

An important upside of EFGT system is, that since the flue gas is not in contact with the gas turbine, which allows one to omit complex gas cleaning system. Which opens for combustion of fuels with troublesome ash forming properties. Furthermore, the specific investment of the EFGT is foreseen to be relatively low while the potential power-to-heat ratio is relatively high, as compared to other small-scale technologies [14]. The commercialization of EFGT systems has, however, been held back by technological challenges. A dedicated micro turbine is now under development by the project partner Ecergy AB. Still, a robust heat exchanger for the aimed high temperatures and elevated pressure (regarding thermal stresses) and the dust loaded hot flue gases (regarding ash deposit formation and high temperature corrosion) needs to be developed. To achieve a reasonable electricity efficiency, air temperatures of 800 – 1,000°C at turbine inlet are required. Overall, the following technological goals have been addressed within this project:

- Design and technological validation of a high-temperature heat-exchanger (HT-HE)
- Optimization of the system configuration for maximized efficiency
- Presenting guidelines for the HT-HE and system design

System optimization for EFGT:

To maximize the benefit of the EFGT application, a thermodynamic model of an EFGT system was built and several operational cases were investigated. The flow sheet of the model is given in Figure 29. The system modelling and simulations were performed within a Swedish national project [15]. The simulations were done with the software EBSILON®Professional, which is a thermodynamic cycle process program that is used for engineering, designing and optimization of plants. The software is widely used to simulate a wide variety of thermodynamic cycle processes and on different scale levels, such as feasibility studies on plant scale including detailed studies and dimensioning of plant parts. EBSILON

[14] Kjellström, B. Cost of electricity from small scale co-generation of electricity and heat (Kostnad för el från småskalig kraftvärme), Värmeforskrapport 1237, 2012.
[15] Sven Hermansson, Anders Hjörnhede, Daniel Ryde, Per-Olof Sjögren, Christoffer Boman, Jonathan Fager-ström, Anders Rebbling, Joseph Olwa, Marcus Öhman, Per Nockhammar, Mattias Svensson, Small scale CHP using externally fired hot air turbines - system integration, heat exchanging and turbine control, SP Report 2015:64, ISBN 978-91-88001-90-0, ISSN 0284-5172, Borås, 2015

includes an extensive and well validated library for thermodynamic properties of fluids and solids including also fuels. Additionally, parameters for components and conditions can be custom-specified for specific conditions or if relevant material data is missing.

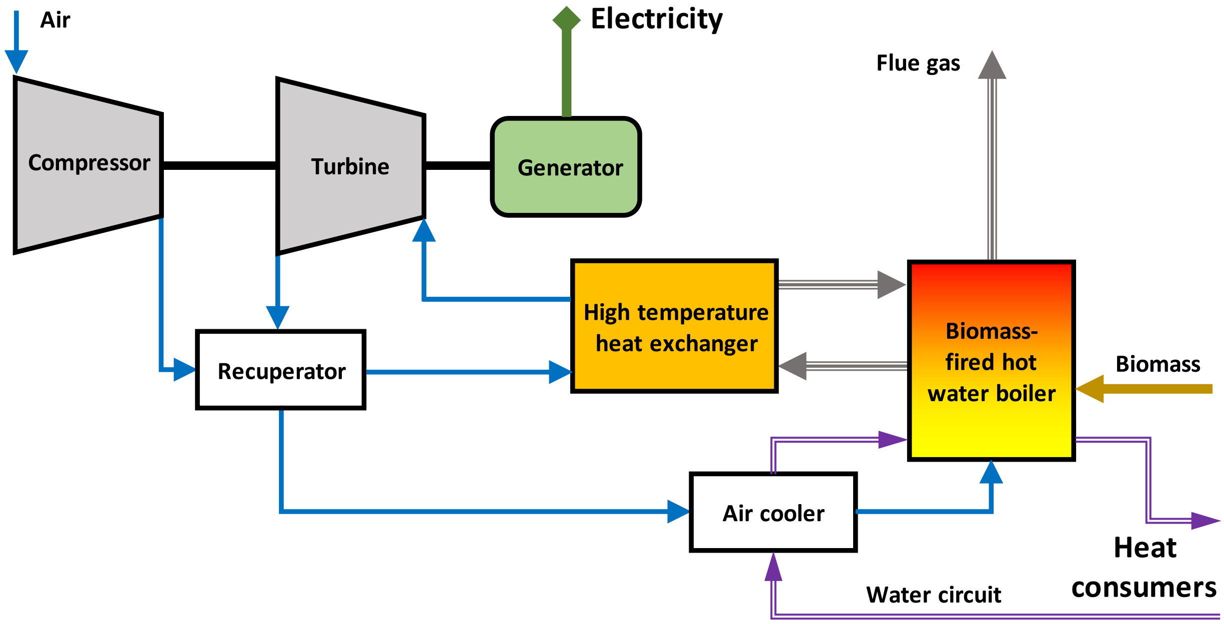


Figure 30: Flow sheet of the thermodynamic simulation of the EFGT system

Explanations: The baseline of the simulation is the case when the turbine exhaust air is used as pre-heating source for the water cycle (3. Return water) before emitted to ambient air

The baseline case for the simulations was chosen as the case when the exhaust air of the 74 kW (gross) turbine is used as pre-heating source for the boiler water cycle, illustrated as baseline in Table 5 and Table 6. The furnace system was fed with 3 MW standard softwood pellets (based on LHV) and efficiencies of the combustion and turbine systems for full and partial loads were taken into account using data provided by the technology suppliers. Ambient heat losses and auxiliary power needed were taken into account in the simulations. Beside the baseline case, five potential constraints have been considered to improve the efficiencies of the system, as listed in Table 5.

In Case 1, the exhaust air was recycled to replace some of the combustion air for the biomass furnace, instead of being heat exchanged to the water cycle. Additionally, in Case 2 and 3, the turbine air was humidified after the compressor by adding of 7.2 wt.% H_2O, with the aim of increasing the mass flow of the fluid and hence the power output from the turbine. In Case 4, the size of the boiler was re-designed to match the air supply from the turbine, i.e. fully covering the supply of combustion air. Finally, in Case 5, moist fuel was used in the biomass furnace. This adjustment results in a higher flue gas flow in the HT-HE and thus increase the power to heat ratio. Furthermore, the increased flue gas humidity makes flue gas condensation feasible. The moist fuel was simulated simply by using the same fuel properties as in the other cases (softwood pellets), except for the increased moisture content.

Table 5: Simulated cases in the thermodynamic modelling of the EFTG system

Baseline	"Pre-heat"	Turbine exhaust air pre-heats the water cycle for the furnace boiler
Case 1	"Comb air"	Turbine exhaust air is used as biomass combustion air
Case 2	"Humid & pre-heat"	Turbine air is humidified to maximize power output (Baseline)
Case 3	"Humid & comb air"	Turbine air is humidified to maximize power output (on Case 1)
Case 4	"Opt size"	Furnace size optimized to match turbine exhaust air (on Case 1)
Case 5	"Opt size & moist fuel"	Moist fuel + flue gas condenser (on Case 4)

The results from the thermodynamic simulations of the EFGT system are presented as net heat and net power output, as well as corresponding efficiencies, in Table 6. This means that the convective and radiative thermal losses to ambient environment are subtracted, as well as the additional internal electrical losses due increased load of fans. The efficiencies are defined as:

Total net efficiency: $\frac{P_{th} + P_e - P_{losses,th} - P_{losses,e}}{P_{fuel}}$

Electrical net efficiency: $\frac{P_e - P_{losses,e}}{P_{fuel}}$

Net marginal electrical efficiency: $\frac{P_e - P_{losses,e}}{P_{fuel} - P_{fuel,sep}}$

Where P_{th} is the thermal power, P_e is electrical power, $P_{th,losses}$ are the thermal losses, $P_{losses,e}$ are the electrical losses, including internal power consumption, P_{fuel} is the input fuel power based on lower heating value (LHV) and $P_{fuel,sep}$ is the fuel power that would be needed for the production of the heat only. The net marginal electrical efficiency (NME) is the efficiency of the extra fuel that has to be supplied to the system in order to produce the resulting amount of electricity, as compared to producing only the heat. The NME is hence a more relevant measure for the electrical efficiency, when using an oversized heat production unit, than the normal electricity efficiency or alpha value, since the system is not optimized for maximized power production.

Table 6: Modelled net heat and power efficiencies for a 74 kW gross turbine on a 3 MW_{LHV} biomass boiler

Explanations: Marginal losses included: flue gas fan work, internal power consumers and system convective heat losses

EFGT configuration (3 MW_{LHV} fuel input)	**Heat output**	**Heat losses**	**Power output**	**El.eff**	**Tot. eff.**	**Marginal el. eff. (NME)**
	kW	kW	kW	%	%	%
Baseline "Pre-heat"	2528	178	59	2.0	86	30
Case 1 "Comb air"	2588	118	59	2.0	88	45
Case 2 "Humid & pre-heat"	2346	360	84	2.8	81	21
Case 3 "Humid & comb air"	2402	304	84	2.8	83	25
Case 4 "Opt size"	1414	111	63	3.7	87	52
Case 5 "Opt size & moist fuel"	1131	111	63	4.4	83	51

The results, presented in Table 6, reveal that a compatible level of 45-52% NME could be reached when using the turbine exhaust air to replace some of the combustion air in the biomass furnace (Cases 1, 4 and 5). This should be compared to the inferior result of the Baseline case of 30% NME due to higher heat losses via the turbine exhaust air. The results also show that the power output can be maximized by humidification of the turbine cycle (Case 2 and 3). However, due to the loss of condensation heat to exhaust air or flue gases, both NME and the total efficiency are reduced. This loss could, however, be diminished if the system already includes a flue gas condenser. Moreover, by reducing the biomass furnace size to make fully use of the turbine exhaust air supply (Case 4), a further efficiency improvement can be achieved, partly due to better heat economy, but especially due to the reduced flue gas fan work.

The conclusions of the system optimization using thermodynamic modelling and simulations are that the turbine exhaust air should be used as combustion air in the biomass furnace and that the furnace should be designed to match the air supply from the turbine exhaust. This option gives the best results both concerning NME and thermal efficiency, of which the latter is of great importance for this kind of application. To temporarily boost the power output from the system, humidification could however be used, if the increased thermal losses could be accepted. Should the system already fire wet fuels and be equipped with a flue gas condenser, such losses will be significantly reduced.

General prerequisites regarding the integration of the HT-HE:

For the positioning of the HT-HE, two main paths could be followed:

- Complete integration of HT-HE into the furnace
- Add-on HT-HE as an external device connected to the furnace system

Pros and cons - Complete integration of HT-HE into furnace:

+ low heat losses to ambient
- complete redesign of furnace and/or boiler system
- complex security and emergency shutdown

Pros and cons - add-on HT-HE as an external device connected to the furnace system:

+ standard biomass furnace
+ possibility to stream line production of turbine add-on system
+ less complex emergency shutdown
- Additional tubes and insulation
- Increased heat losses

With the main objective to provide a solution for power generation in an already well established biomass heating system, the option of complete integration into the furnace becomes unrealistic. Therefore, the add-on option should primary be considered for this kind of system solution.

Position of extraction of flue-gas to the HT-HE:

The design parameters of the heat exchangers summarize the most important guidelines for the choice of flue gas extraction to the heat exchanger:

- Flue gas temperature should be 850-900°C and reasonably stable (850°C into HT-HE)
- Combustion reactions should be completed, to minimize material wear.
- Position should preferably be protected from flame radiation

From these guidelines, an extraction position should be chosen and validated. Here, the procedure was illustrated using the same Osby Parca 3 MW furnace as for the system optimization. The approximate position of extraction is indicated in Figure 31 as a red dot in the cooled vertical shaft connecting the horizontal post-combustion zone with the boiler part. To validate the position, the flue-gas temperature was measured using a purpose-designed water cooled suction pyrometer (see Figure 31 and Figure 32).

The temperature was simultaneously measured in four different levels along the vertical shaft, from the top of the shaft to about half of the shaft height, during three different operational loads: nominal load (3.0 MW_{th}), elevated load (3.2 MW_{th}) and partial load (2.0 MW_{th}). Furthermore, in each level and for each load, the core temperature and the wall boundary temperature was registered by sliding the pyrometer across the shaft.

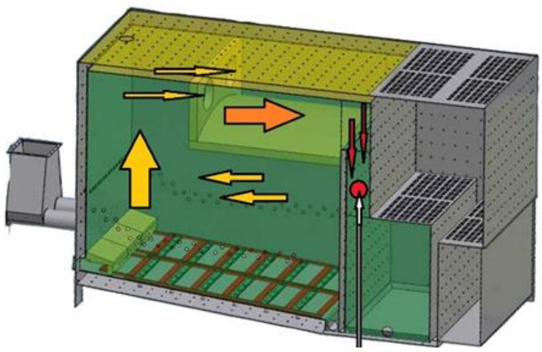


Figure 31: Point of flue gas extraction for high temperature heat exchange, indicated as a red dot in the shaft connecting the post-combustion chamber with the boiler

Figure 32: Suction pyrometer is used for the temperature measurements at four levels of the vertical shaft in the biomass furnace. The highest probe corresponds to the highest temperature, i.e. the first measuring point meeting the gas stream

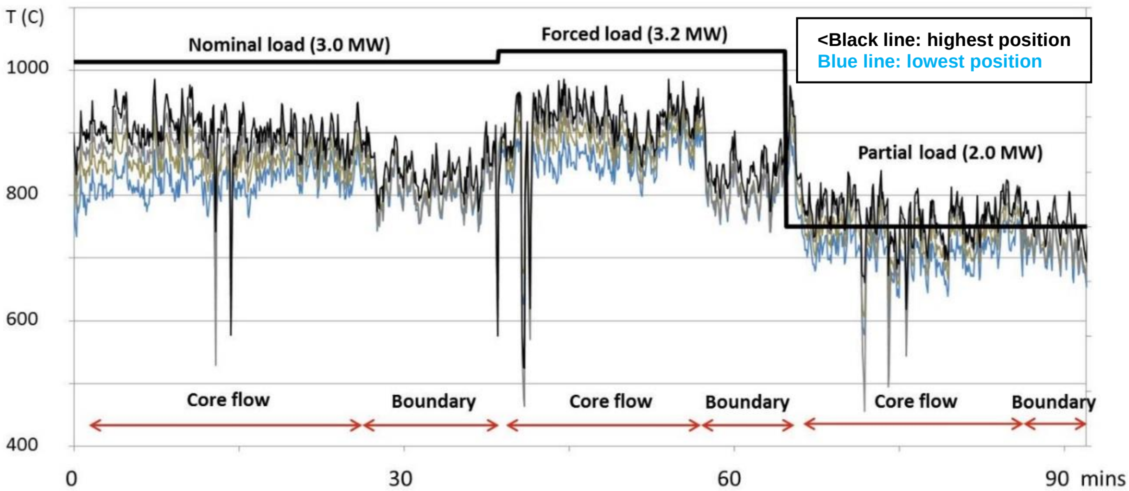


Figure 33: Measured temperatures in the vertical shaft of the biomass furnace.

Explanations: The black line represents the first measurement position (i.e. most upstream) and the blue line is the last measurement point (i.e. most downstream); “Core flow” measured in the middle of the flue gas duct; “Boundary” measured near the wall of the flue gas duct.

Some typical results from the validation of the extraction points are presented in Figure 33, as measured temperatures along the shaft. The temperature levels reveal that the target temperature (>850°C) can be reached in the up-stream parts of the vertical shaft, during nominal or forced load. However, downstream the shaft, along the wall boundary as well as during reduced load, the temperatures fall below 800°C disqualifying these positions for flue gas extraction. Recommended guidelines for this particular furnace would, hence, be to position the flue gas extraction in the upper part of the vertical shaft, while operating on maximum load as long as possible. Additional recommendations for investigations would be to reduce the flue gas cooling by adding brickwork to the cooled walls.

Method of guiding the flue gas through the HT-HE and back to the boiler:

Two methods of extracting the flue gas and passing them through the HT-HE are plausible:

- Additional flue-gas fan positioned between HT-HE outlet and boiler inlet
- Throttling of the flue gas stream between furnace and the boiler (after the flue gas for the HT-HE is extracted)

Pros and cons - Additional flue-gas fan positioned between HT-HE outlet and boiler inlet:

+ Direct control of the flue gas flow through the HT-HE
- Extreme working temperatures for the fan
- More costly with two separate fan installations
- Possible control conflict with primary air fan

Pros and cons - Throttling of the flue gas stream between furnace and the boiler (after the flue gas for the HT-HE is extracted):

+ The downstream flue-gas fan is used to drive the flue gas through the HT-HE
- Over dimensioned fan needs to be installed
- Extra power consumption du to flanging

The throttling option is recommended. The throttle/flap should be positioned downstream the extraction of the flue gases for the HT-HE and before the cooled flue gases from the HT-HE are fed into the boiler. An extra flue gas fan is unrealistic, primarily due to the elevated temperature that still occurs downstream the HT-HE (approx. 600°C). Moreover, it would be difficult to combine two actively controlled flue gas fans by means of achieving a stable system. By using the throttle/flap, the flow through the HT-HE is completely driven by the flue gas fan downstream the boiler. The downside of an add-on HT-HE and a throttle is the extra work that is required from the (over-dimensioned) flue gas fan. This loss is however included in the net efficiencies considered in the system analysis.

3.5.2 Description of the HT-HE:

The HT-HE was designed using a CAD software. The selected materials used for the construction were investigated in WP2 and proposed by the Swedish partners UmU and RISE. The choice for the laboratory construction was a compromise between quality, weldability, machining and price and finally the Sandvik 253MA (EN 1.4835) steel was chosen. The good mechanical properties at high temperatures were satisfying to use it in the HT-HE construction. The model of the heat exchanger is made with 14 rows of meander shaped bended steel pipes. The pipes at the ends are connected with common inlet and outlet collectors. The outlet collector with the hot air is recommended to be directly connected with the inlet of the air turbine. The short distance between the two components enables to minimize the possible heat loses. Figure 34 shows a general view on the internal pipes of the HT-HE. The figure shows also the finite elements calculations and the equivalent stress in the heated pipes. Figure 35 shows the side view of the heat exchanger and the CFD calculation results with temperature profiles of the compressed air as well as the flue gases. The figure shows the results of the heat exchange process and the temperature increase at the air side and temperature drop on the flue gas side.

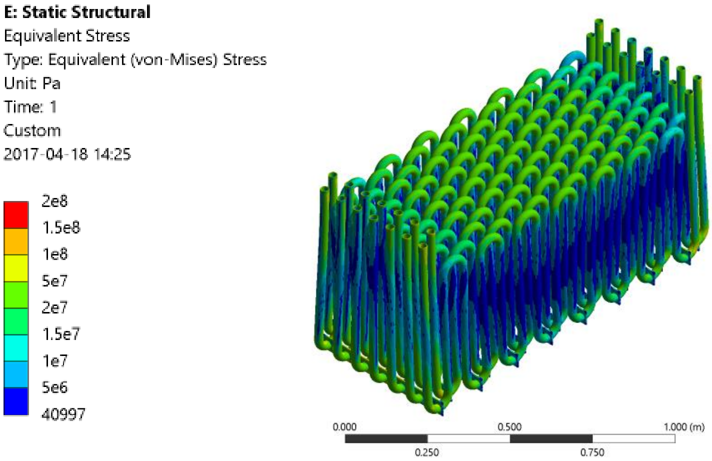


Figure 34: Front view of the internal part of the HT-HE – finite elements calculations and the equivalent stress

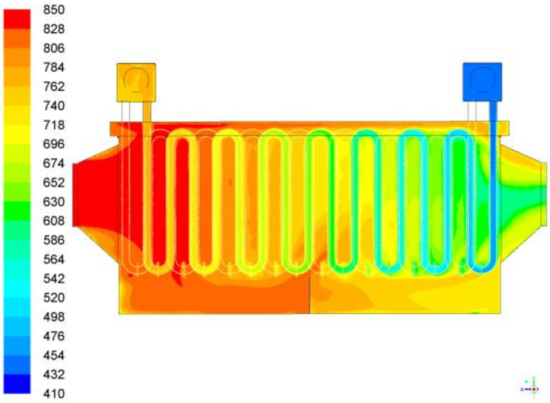


Figure 35: Side view of the HT-HE – temperature profiles (in °C) based on CFD simuilations

3.5.3 Methodology of test runs and accompanying R+D – brief overview

The test runs of the HT-HE model were performed at a semi-industrial test stand at IEn with a possible thermal power up to 0,5 MW. The combustion chamber was fired with milled wood pellets, as well as milled miscanthus and cereal straw to be able to study the influence of the biomass type on deposit formation and slagging processes on the HE-tubes as well as the necessity to apply a pneumatic or mechanical cleaning system. However the experiments showed that agricultural biomass should not be used in this technology because of severe slagging and corrosion risks.

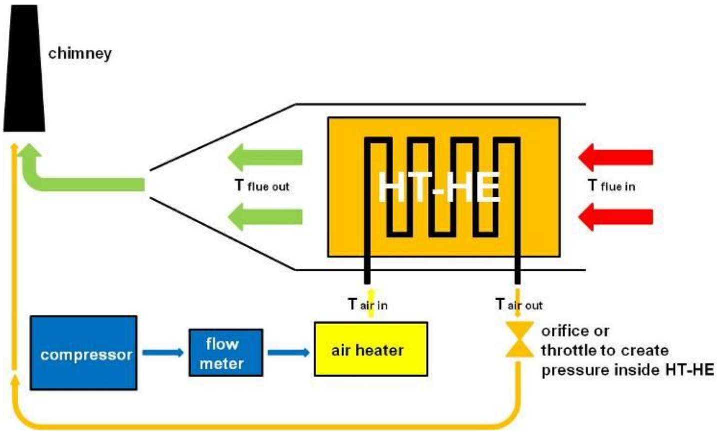


Figure 36: Scheme of the lab-scale test stand at IEn

The simplified scheme of the test stand is presented in Figure 36. During the laboratory tests, the cold compressed air was electrically pre-heated to the initial inlet temperature to the HT-HE (450°C). During the heat exchange process, between the hot flue gases (850°C) and the compressed air, the temperature of the air was increased up to 750°C. All the main parameters like mass flow rates, temperatures and pressure as well as pressure drops of the compressed air and flue gas were simultaneously controlled.

3.5.4 Results achieved and comparison with the project targets:

The test runs showed that the main assumed parameters of the HT-HE were achieved. The results presented in Figure 37 regarding air and flue gas temperatures and the pressure drops are comparable with values obtained during the CFD modelling. The assumed air parameters were fully obtained. The pressure drops on the air side of about 1,600 Pa is satisfying in comparison to the values assumed at the beginning of the project. On the other hand the pressure drop of the flue gas, on the level of about 60-80 Pa, is much lower than assumed.

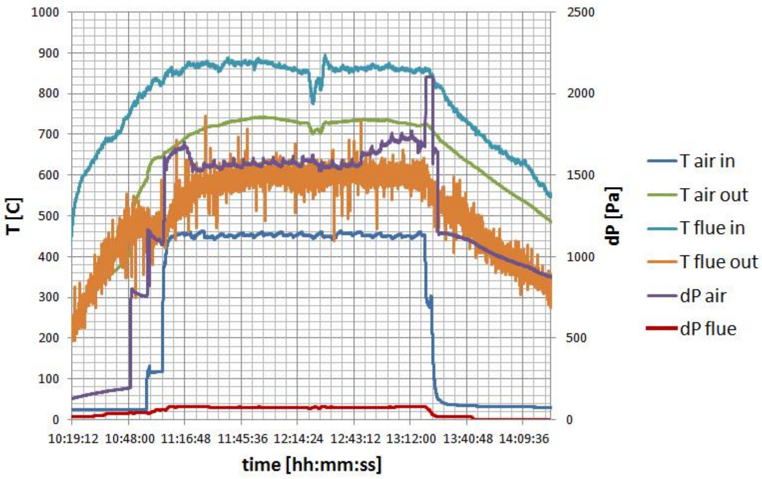


Figure 37: HT-HE operating conditions with milled wood pellets as fuel

Figure 38 shows that also the heat transferred to the compressed air (27-30 kW) is fully comparable to the assumed value and obtained during the CFD calculations. The high peaks at the beginning and at the end of the graph show the moments when the inlet air was not preheated to the initial value of 450°C, and was at the level of about 30°C. Due to much higher temperature differences between the compressed inlet air and the flue gas, the heat exchanged was almost two times higher than the nominal value, which proves that the HT-HE can reach much higher loads for lower inlet temperatures of the compressed air.

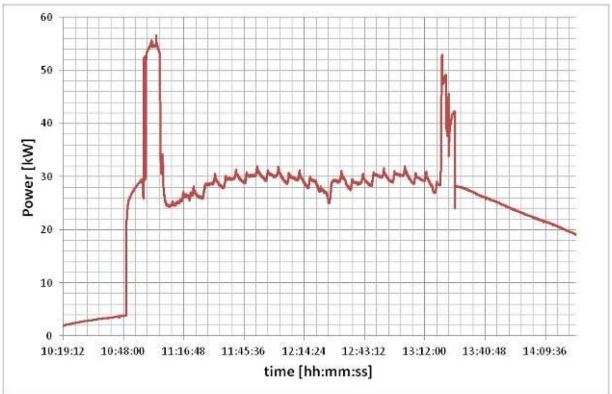


Figure 38: Heat transferred to the HT-HE during a typical test run

3.5.5 Guidelines for HT-HE design and construction:

For the development and operation of a HT-HE, the following guidelines should be considered:

- The recommended framework conditions for the correct operation of the EFGT technology and therefore also for the HT-HE are presented in Table **7**. The most important parameters are the outlet temperature of the pressurized air and the pressure losses of the pressurized air and the flue gas as well as the heat transferred to the pressurized air. The parameters must be achieved for the following parameters of the flue gas.

Table 7: Framework conditions for the construction of the HT-HE

	Unit	Hot side	Cold side dry	Cold side humid
Gas composition		Flue gas	Hot air	Hot humid air
N_2	vol. %	0.702	0.782	0.701
CO_2	vol. %	0.123	0.000	0.000
H_2O	vol. %	0.115	0.012	0.114
O_2	vol. %	0.060	0.206	0.185
Mass flow	kg/s	1.0 – 1.3	0.806	0.864
T inlet	°C	850	451	448
T outlet dry	°C	632 – 683	750	NA
T outlet humid	°C	574 – 659	NA	750

Pressure abs. inlet	bar	0.97	4.32	4.32
Pressure loss target	Pa	< 500	< 1,000	< 1,000
Pressure loss acceptable	Pa	< 1,000	< 2,000	< 2,000
Duty	kW	273.2 – 311.7	273.2	311.7

- Based on the test results obtained from the field tests in WP2, the recommended material for the HT-HE elements operating at elevated temperatures and pressures, like pipes and inlet and outlet collectors is Kanthal APMT, or a FeCrAlY with similar properties. However, the selection of appropriate material is a compromise between high quality, processing properties and low price. The rest of the components like flue gas box (housing of the HE pipes and other elements which do not work at elevated pressures) the steel quality EN 1.4828 (309S) can be used.
- Excel sheet calculations to obtain the preliminary pipe configurations are recommended. Thereby, several configurations can be obtained, of which one is chosen (e.g. minimum mass or specific dimensions - length, width, height).
- The HT-HE construction is made of a set of parallel meander shaped pipes which ensures self compensations of elongations and stresses. The possible radius of pipe bending should be considered during the design process – this also influences the final external dimensions of the HT-HE.
- To avoid concentrations of thermal stress, the manifolds should be separated from the lid of the exhaust gas duct. Also the pipes should not be connected (welded) with the lid – they should go through the holes in the lid. This can eliminate or minimize thermal and assembling stresses between the pipes and the housing.
- It is preferable that the inlet and outlet manifolds/collectors have a cylindrical shape.
- The pipes should be free hanged on the upper lid/wall. The possible solution is shown in Figure 39. This eliminates additional mechanical stresses inside the pipes.

Figure 39: Possible solution of the pipes hanging in the HT-HE

- The pipe meanders should be tightened with distance brackets on the bottom part to eliminate or minimize them moving sideways (Figure 40).

Figure 40: Possible solution of applying distance brackets for the pipes in the HT-HE

- The thermal insulation used for the housing of the HT-HE should be high temperature resistant (e.g. ceramic). In this case the Ceramic Fibre Blanket Hitermic HT 1200 is recommended (see Figure 41). The most important properties of the material are: high refractoriness, resistance of thermal shocks, low thermal conductance and the low coefficient of heat accumulation, which gives significant energy savings in insulated elements. To ensure that the maximum temperature of the external walls of the HT-HE do not get higher than 40°C, for a $\lambda_{ins} = 0.2\ ^{W}/_{mK}$ at an average temperature of 800°C, the thickness of the insulation should be at least $d_{ins} = 250$ mm. The insulation can also be made with two layers: The first one from with the Ceramic Fibre Blanket Hitermic HT 1200 with a thickness of 50 mm, and the other one made with a Rockwool of thickness of 150 mm. Another type of insulation in the HT-HE can be made with an air insulating layer in a closed double walled space with a thickness of at least 100 mm.

Figure 41: HT-HE with the ceramic insulation material (partial filling)

- To eliminate thermal bridges and heat loses due to conduction, thermal separators should be used, especially between air collectors and the external housing.
- The HT-HE should be equipped with an ash pan over the whole length of the HE and with an automatic system to remove ash, for example a screw conveyor. The conveyor can systematically remove the ash from the bottom of the HT-HE box. It is recommended to leave a certain level of ash in the conveyor to cover the screw and protect it against the hot flue gas. A possible solution of the screw conveyor for the ash removing is shown in Figure 42.

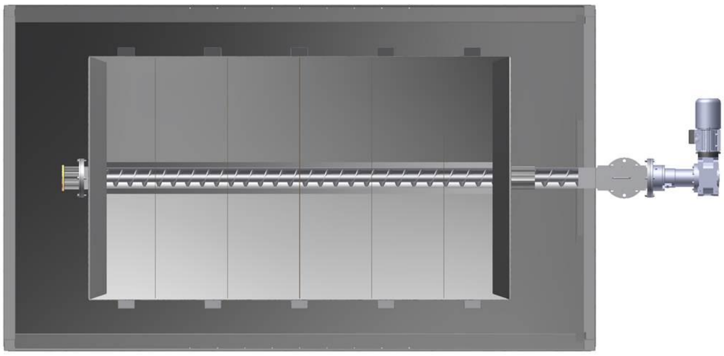


Figure 42: Top view of the screw conveyor for ash removal

- The ash pan should be equipped with at least on obstacles/baffles (more baffles are recommended) to prevent a flow shortcut of the flue gases below the EH tubes. Also similar obstacles/baffles should be mounted at the top lid where the pipes are hanged (Figure 39) to prevent the flue gas from flowing above the bended pipes.
- The HT-HE should also be equipped with an ash cleaning system for the heat exchanging surfaces. It can be a pressurized air blowing system. The air nozzles of the cleaning system should be placed along the vertical walls of the HT-HE to create horizontally oriented air streams. Locations of the air nozzles on the upper lid are not recommended, because the vertical air streams can blow-up ash from the bottom ash pan. It would be best if the nozzles were located at every row of the HE pipes to ensure an efficient cleaning process. Since the lab-tests proved that an efficient distance between nozzle and pipes was 0.5 m, it is recommended to locate the nozzles on the both opposite sides of the HT-HE. The system should work in periodic intervals to prevent possible slagging with a recommended duration of about 15-30 minutes between the pulses. Because of high slagging risks of agricultural biomass, this type of fuel is not recommended for the HT-HE technology.
- To ensure constant parameters of the outlet air from the HT-HE, an appropriate control of the flue gas inlet temperature is very important. To avoid an overheating of the HT-HE it is necessary to apply flue gas recirculation. This requires an additional fan. In case of emergency when the air compressing system breaks down, the flue gases should at least partially bypass the HT-HE or they should be strongly diluted with fresh air taken from additional throttles connected with the flue gas duct before the inlet to the HT-HE. Simultaneously the furnace should be switched off in such a case.
- The start-up process should be characterised by a stepwise increase of power load of the furnace and the HE. The recommended and safety heat-up rate of the pressurised air in the HT-HE is 25°C/min. In this case it is possible to achieve the final temperature of 750°C of pressurized air at the outlet of the HT-HE in 30 min. The similar procedure should be considered during the normal shutdown process and the rate of cooling of the outlet air should be the same - 25°C/min. In both cases – heating-up and shutting down - the pressurized air should not be switched off if the temperature of the pressurized air and/or of the flue gases at the HT-HE inlet is higher than 450°C.

3.5.6 Highlights and outlook:

The targets defined for this work package have been achieved. The model of the HT-HE was built and successfully tested. The results obtained during the tests are promising and comparable with numerical calculations. The concept of the construction fulfills the requirements regarding pressure drop and outlet air temperature. Also the full scale geometry of the HT-HE was developed and the concept is ready for tests in a pilot plant. The experimental tests show that the ash / slag cleaning system based on pressurised air is very important especially when energy crops are used as fuel. However, for the operation of the HT-HE only wood biomass fuels are recommended. The full scale unit of a HT-HE requires additional tests of the final position of the cleaning nozzles for de-dusting, which cannot be fully predicted by CFD calculations. The recommendations regarding the start-up and shutdown procedures, to avoid any unknown troubles, shall also be checked and revised during the full-scale operation of the HT-HE in future.

3.6 WP6: Techno-economic analyses of the new biomass based micro-CHP technologies

Authors: BIOS: Ingwald Obernberger, Gerhard Weiß

Within WP6 a detailed techno-economic analysis report has been worked out for each of the three technologies investigated. At the beginning of the project the general structure for the techno-economic analysis has been defined and agreed by the project partners. Subsequently, questionnaires for the different technologies have been prepared by BIOS and forwarded to the respective partners. Based on the filled-in questionnaires and on the data gained from the test runs performed with the first testing plants the preliminary techno-economic analyses have been prepared. After the final tests of the new technologies and an update of the questionnaires as well as based on the discussions and definitions within the project meetings BIOS prepared the final version of the techno-economic analysis reports. The main results of the techno-economic analyses are presented subsequently.

Within the technical evaluation the issues regarding installation and interfaces (required space, required connections, …), the operating behaviour (partial-load behaviour, start-up, shutdown, …) as well as the maintenance effort (service intervals of the different units, fuel feeding & ash removal) have been pointed out. Furthermore, the electrical and thermal efficiency, the annual utilisation rate as well as pollutant and noise emissions have been evaluated.

Regarding the economic evaluation the framework conditions for residential heating systems regarding full load hours, capacity, fuel, electricity and investment costs as well as for funding vary strongly within the EU 27. Thus, the calculations have to be referred to a specific regions for each technology:

- Pellet stove with TEG: Austria and Germany
- Micro-ORC technology: Austria and Germany
- Externally fired gas turbine: Austria and Sweden

Furthermore, the new technologies have been compared with state-of-the-art (SoA) technologies. Thereby, the following technologies were compared:

- Pellet stove with TEG: common pellet stove and pellet stove with water jacket
- Micro-ORC technology: small-scale Stirling engine combined with a biomass boiler
- Externally fired gas turbine: small-scale ORC, gasifier with gas engine and a heat only biomass boiler

Finally, sensitivity studies for the most relevant influencing parameters (e.g. investment costs, electric efficiency and full load operating hours) have been performed for the three technologies.

3.6.1 Pellet stove with TEG:

The dimensions of the pellet stove with TEG as well as the operation behaviour and the service intervals are comparable with common pellet stoves. Since the TEG is a silent and almost maintenance-free electric power generation system also the maintenance effort is only slightly higher than for pellet stoves without TEG. For the new components TEMs, accumulator and water pump robust and durable components have been selected. The actual lifetimes will be evaluated in detail within the long term test runs ongoing.

The main advantages of the new technology compared to the state-of-the-art technologies are the grid-independent operation as well as the possibility to charge external devices (e.g. mobile phones) when operating the pellet stove. Furthermore, the new technology offers the opportunity to heat an additional living room with radiators.

Within the techno-economic analyses also the energy efficiency index (EEI) according to the energy labelling of local space heaters (EU 2015/1186 24/04/2015) has been calculated. Thereby, the pellet stove with TEG reaches the energy efficiency class A++ (best rating).

Table 8: Specific heat generation costs of the pellet stove with TEG in comparison to the state-of-the-art-technologies for Austria

		Pellet stove with TEG	Pellet stove (conventional)	Pellet stove with water jacket
Investment costs	[€]	5,950	4,500	7,500
Total heat production	[kWh_{th}/a]	5,044	5,044	5,044
Heat production water system	[kWh_{th}/a]	1,059	-	4,035
Annual fuel demand heat production	[kWh/a]	5,447	5,447	5,447
Annual additional fuel demand for electricity production	[kWh/a]	20	-	-
Capital bound costs	[€/a]	467	338	581
Maintenance costs	[€/a]	213	213	213
Biomass costs	[€/a]	341	340	340
Electricity costs / savings	[€/a]	- 3	2	10
Total costs per year	[€/a]	1,019	893	1,144
Specific heat generation costs (no subsidies)	**[€/MWh]**	**202**	**177**	**227**

The full cost evaluation pointed out, that the main influencing factor on economic performance are the investment costs and thus also funding possibilities and incentives. Based on the defined framework conditions and basic data the specific heat generation costs of the RIKA pellet stove are in Austria with 177 €/MWh lower than those for pellet stoves with TEG (202 €/MWh). The specific heat generation costs for the pellet stove with water jacket are with 227 €/MWh the highest. Thus, the specific heat generation costs for the new technology are in-between the costs for the state-of-the-art technologies (see Table 8).

The full cost evaluation for Germany shows that, due to the national investment funding for pellet stoves with water jacket, the specific heat generation costs for the new TEG technology are with 184 €/MWh the lowest of the three technologies investigated. The specific heat generation costs for the pellet stove with water jacket are with 211 €/MWh the highest (seeTable 9).

Table 9: Specific heat generation costs of the pellet stove with TEG in comparison to the state-of-the-art-technologies with and without subsidies for Germany

		Pellet stove with TEG	Pellet stove (conventional)	Pellet stove with water jacket
Investment costs	[€]	5,950	4,500	7,500
Subsidies	[€]	2,000	-	2,000
Total heat production	[kWh_{th}/a]	5,044	5,044	5,044
Heat production water system	[kWh_{th}/a]	1,059	-	4,035
Annual fuel demand heat production	[kWh/a]	5,447	5,447	5,447
Annual additional fuel demand for electricity production	[kWh/a]	20	-	-
Capital bound costs	[€/a]	320	338	434
Maintenance costs	[€/a]	213	213	213
Biomass costs	[€/a]	401	400	400
Electricity costs / savings	[€/a]	- 4	3	16
Total costs per year	[€/a]	930	954	1,063
Specific heat generation costs (with subsidies)	**[€/MWh]**	**184**	**189**	**211**

Electricity savings: saving of electricity costs in case of using the surplus electricity production of the pellet stove with TEG via USB port

The sensitivity studies pointed out, that the full load operating hours are significantly influencing the heat generation costs. With increasing full load operating hours the difference between the heat generation costs is decreasing, but no change of the ranking occurs. Furthermore, the sensitivity studies have shown, that an increase of the investment costs of 1,000 € leads to an increase of the heat generation costs of 14.5 €/MWh (Austria) and 12.5 €/MWh (Germany).

3.6.2 Micro-ORC technology combined with a wood chip / pellet boiler:

For the technical and economic evaluation of the new micro-ORC technology of ORCAN two different sizes of the ORC (0.45 and 1.3 kW_{el} corresponding to a thermal output of 10 kW_{th} and 30 kW_{th} respectively) have been investigated. In addition, regarding the implementation of the micro-ORC an add-on as well as an integrated solution have been considered for the economic evaluations (in cooperation with a biomass boiler manufacturer).

The dimensions of the micro-ORC system are with 0.4 x 0.4 x 0.9 m for the small and 0.8 x 0.4 x 0.9 m for the larger unit quite small. The ORC is implemented in the hydronic system of the building between the boiler (hot water feed and return) and the heating circuit (buffer storage in- and outlet). The ORC system needs only little maintenance (once a year together with boiler inspection) and is, due to the good insulation, comparably silent.

To achieve high electric efficiencies feed temperatures as high as possible (105°C should be possible with state-of-the-art biomass hot water boilers) and return temperatures as low as possible (low temperature costumers with return temperatures of 30 – 40°C) are required. Due to the limited part load applicability and to achieve high thermal efficiencies as well as a high number of full load operating hours, the ORC unit should be designed for about 2/3 of the nominal thermal power of the boiler. Moreover, a buffer storage for the heat is recommended to smooth the heat demand variations.

For the economic evaluation the micro-ORC technology was compared with a Stirling engine in the same power range. The main advantages of the new micro-ORC technology compared to the state-of-the-art technology are that the system is suitable for all biomass heating systems with a thermal output >10 KW_{th} and can be implemented as an add-on solution in existing heating systems. Furthermore, for the new technology considerably lower maintenance effort and longer lifetime are expected in comparison to a Stirling engine.

The new ORC technology shows a clearly better economic performance than the Stirling engine technology. Thereby, the number of full load operating hours and the efficiency of the ORC unit play a major role - 2,000 full load operating hours and a net electric efficiency of 4.5% should be taken as guiding values in this respect.

The full cost evaluation for Germany shows that, due to the national funding for micro-CHP technologies available, the specific electricity generation costs are for the add-on options about 30% higher (small system) and 2% lower (larger system) than the electricity costs of private households. For the integrated options the specific electricity generation costs are about 36 - 43% lower than the electricity costs of private households (see Figure 43). The integrated solution is cheaper because parts of the hydronic connections and insulation can be saved when the ORC and boiler housing are combined. Furthermore, synergies regarding the control system further reduce the investment costs.

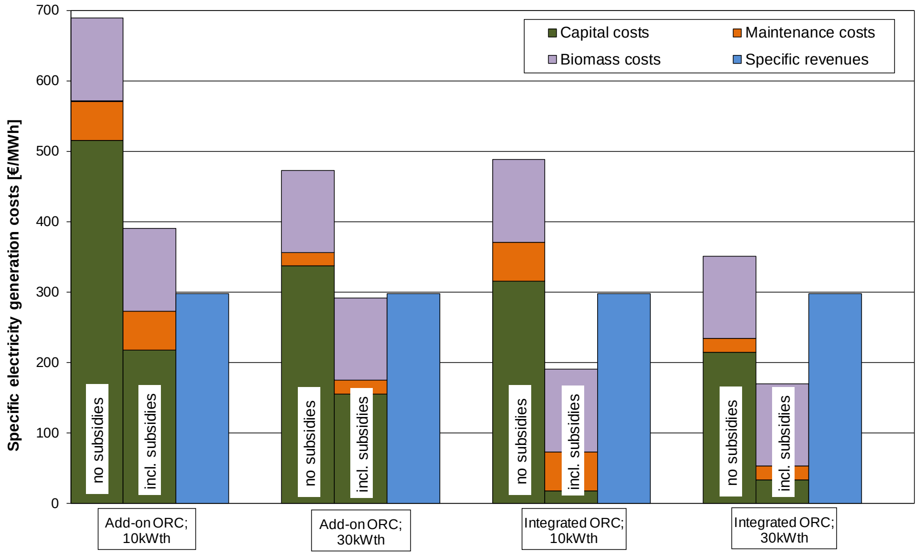


Figure 43: Comparison of the calculated specific electricity generation costs for the 4 options investigated under consideration of the costs savings when the electricity is used to cover the own electricity demand for Germany

Explanations: Fuel used: wood pellets; Average electricity production and consumption (private households) costs for the first year of operation.

For Austria the current framework conditions for biomass micro-scale CHP systems are unfavourable since the electricity costs for consumers are with 202 €/MWh_{el} about 30% lower than in Germany with 297 €/MWh_{el} and in Austria currently no suitable funding for micro-scale CHP systems is available. Thus, based on the current framework conditions for Austria no economically feasible result can be achieved for the new micro-ORC technology of ORCAN.

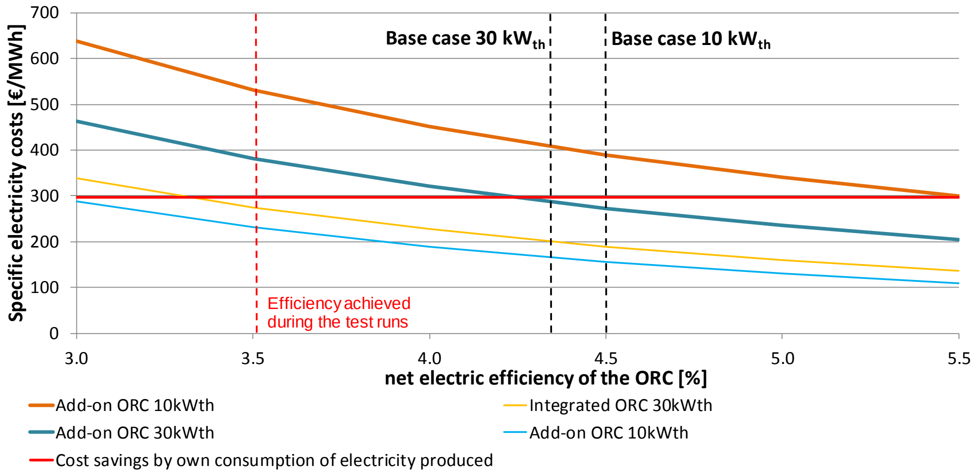


Figure 44: Specific electricity generation costs in dependence of the net electric efficiency of the micro-ORC (under consideration of subsidies) for Germany

Explanations: Fuel used: wood pellets; Average electricity production and consumption (private households) costs for the first year of operation.

The sensitivity studies pointed out that the full load operating hours are significantly influencing the heat generation costs and an investment cost reduction would especially supports the add-on solutions as for the integrated solution the funding is already sufficient. Furthermore, the sensitivity studies have shown, that a reasonable electric efficiency of the micro-ORC is essential to achieve good economic results. The current electric efficiency of 3.5% has to be further increased up to the target values of around 4.5% to achieve competitive systems (especially for the add-on solutions).

3.6.3 External fired gas turbine (EFGT) combined with a wood chip fired boiler:

Within the project a high temperature heat exchanger (HT-HE) for the use in an externally fired gas turbine (EFGT) has been developed. In order to get basic information about the economic competitiveness of the new system for the techno-economic evaluation the EFGT has been evaluated, since an evaluation of the HT-HE alone does not seem reasonable.

Within WP5 several options for the implementation of the EFGT into the biomass boiler have been evaluated regarding size of the biomass boiler, use of the exhaust air from the EFGT as combustion air and humidification of the turbine air cycle. The optimum setup regarding total efficiency (Case 4 - turbine exhaust air pre-heats the water circuit and is afterwards used as combustion air for the furnace; furnace size optimized to match turbine exhaust air; thermal power 1,414 kW$_{th}$, net electric power 63 kW$_{el}$, total efficiency 87%) has been selected for the techno-economic evaluation. The electric net efficiency is with 3.7% comparably low. However, a net marginal electrical efficiency (NME - efficiency of the extra fuel that has to be supplied to the system in order to produces the resulting amount of electricity, as compared to producing only the heat) of 52% can be achieved by the EFGT (see WP5).

Based on the evaluation of the EFGT a comparison with state-of-the-art technologies (ORC technology with a thermal power of 660 kW$_{th}$ and 103 kW$_{el}$ as well as gasifier technology with gas engine with a thermal power of 260 kW$_{th}$ and 157 kW$_{el}$) has also been done. Furthermore, three “heat-only” systems based on a biomass boiler and related to the thermal output of the different CHP technologies have been evaluated to calculate the specific heat generation costs. Based on the framework conditions defined for Austria the current heat generation costs are between 36 and 43 €/MWh$_{th}$.

Table 10: Specific electricity generation costs of the EFGT in comparison to the state-of-the-art technologies for Austria

Explanations: Average heat and electricity production costs for the period under consideration of the first year of operation.

		EFGT	ORC technology	Gasifier technology	Heat-only 1.4 MWth	Heat-only 0.66 MWth	Heat-only 0.26 MWth
Total investment costs	**[€]**	**1,064,500**	**1,041,500**	**691,500**	**590,500**	**356,000**	**189,000**
Capital bound costs	[€/a]	116,603	103,813	92,290	54,937	32,653	17,500
Maintenance costs	[€/a]	19,545	17,760	37,485	13,125	7,740	4,170
Operation based costs	[€/a]	20,645	17,215	20,915	17,705	8,060	3,690
Consumption based costs	[€/a]	3,000	3,000	4,000	2,000	1,500	1,000
Biomass costs	[€/a]	209,877	139,645	161,834	206,886	96,566	38,041
Electricity costs for heat production	[€/a]	11,878	5,544	-	11,878	5,544	2,184
Total costs per year	**[€/a]**	**381,548**	**286,977**	**316,524**	**306,530**	**152,064**	**66,585**
Heat production	[MWh/a]	8,509	4,026	1,623	8,484	3,960	1,560
Electricity fed into the grid	[MWh/a]	378	620	942	-	-	-
Heating price average	[€/MWh]	36.1	38.4	42.7	36.1	38.4	42.7
Revenue heat production	[€/a]	307,420	154,608	69,275	306,530	152,064	66,585
Annual costs for electricity production	[€/a]	74,128	132,369	247,249	-	-	-
Specific electricity generation costs	**[€/MWh]**	**196**	**213**	**262**			

Table 10 shows the annual costs for the different technologies investigated and the resulting specific electricity generation costs. The EFGT shows the lowest electricity generation costs with 196 €/MWh. Thus, under consideration of a revenue for electricity produced for small-scale biomass CHPs in Austria of 222 €/MWh$_{el}$ an economically feasible result for the new technology has been achieved. However, in comparison to the electricity costs for industry (70 €/MWh$_{el}$) the electricity production costs are more than two times higher.

The main influencing factor are the fuel costs. Since for the new technology in addition to wood chips the use of low cost biomass fuel fractions (e.g. SRC or forest residues) will be possible, suitable boundary conditions for an economically feasible operation are given. The sensitivity studies have shown, that high full load operating hours (>5,500 hrs/a) are essential to reach economically feasible results (see Figure 45). Furthermore, the revenue of the heat produced strongly influences the specific electricity generation costs of the EFGT.

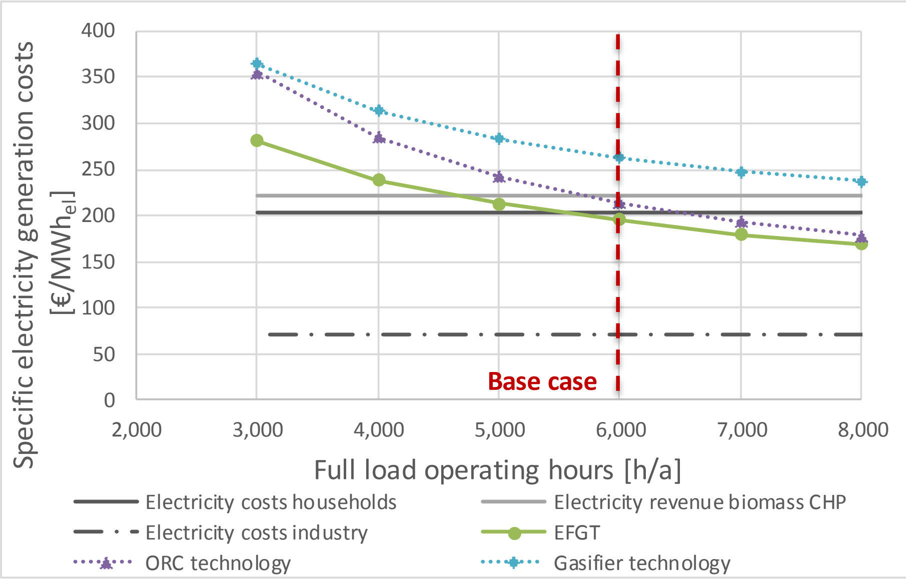


Figure 45: Specific electricity generation costs in dependence of the full load operating hours of the EFGT and the state-of-the-art technologies for Austria

Explanations: Calculated for the first year of operation.

Since for Sweden the revenue for biomass based electricity production is only in the range of the electricity prices for industry (about 60 €/MWh$_{el}$), currently the economic framework conditions are unfavourable. However, due to the decision of Sweden to shut down four nuclear reactors before 2020 a certain effect on the electricity prices is expected which will have a positive effect on renewable electricity production in Sweden.

The techno-economic analyses of the three technologies investigated formed a good basis for the technology development and pointed out the economic competitiveness of the new CHP technologies and the key influencing parameters to be considered. Based on the framework conditions defined and the input data gained from the industrial partners as well as the test runs performed, all three technologies investigated can achieve good economic results in comparison to the state-of-the-art technologies.

3.7 WP7: Dissemination of results

WP7 focused on the dissemination of project results. Therefore, a project webpage (www.minibiochp.eu) is online since November 2014 and provides up-to-date and general information about the project. Furthermore, relevant outcomes of the project (e.g. the presentations of the final project workshop) are available for download on the webpage.

In order to disseminate the project results to a broad public, an international workshop has been organised as a final event of the project. The project workshop took place on 2nd of March 2017 within the framework of the "Pellet conference 2017" which is part of the World Sustainable Energy Days in Wels, Austria. Within the workshop the main results of the project achieved have been presented and discussed with the audience. The workshop was a big success, well attended and the audience showed high interest in the project results. Furthermore, the project results have been presented at the ERA-

NET-Bioenergy-Seminar in Stockholm in June 2017. In addition, the project results have already been and will be disseminated by publications, conference participations and participations of the industrial partners at trade fairs.

3.8 WP8: Management and coordination

The national Austrian project and the international ERA-NET project were coordinated by BIOS. Within the project every half year a project coordination meeting took place. In addition, several bilateral meetings concerning specific topics regarding the different WPs have been organised. Within all WPs a very good cooperation between the project partners have led to a smooth and efficient work with promising results Within this work package also the national funding and ERA-NET reports have been prepared and submitted in time.

4 Ergebnisse und Schlussfolgerungen / Conclusions

Within the project 3 new micro-CHP technologies have been developed. Therefore, comprehensive calculations and simulations (e.g. CFD - Computational Fluid Dynamics), experimental research on individual key components as well as the construction and testing of testing plants took place. One work package was focussing on the investigation of ash-related problems (deposit formation, corrosion), which is a key issue for the new CHP technologies especially for the EFGT system. In addition, techno-economic analyses have been performed for the technologies investigated. In the following the CHP technologies developed and the results achieved within this project are briefly outlined:

- **Pellet stoves with a thermoelectric generator (TEG):** The pellet stove with TEG is suitable for stove owners who want to cover their need for auxiliary energy by own electricity production and thereby facilitate grid-independent operation. With a TEG heat is directly converted into electricity. The system is a wear- and maintenance-free as well as noiseless technology and thus ideally suitable for applications in living rooms. The electricity produced by the TEG system is stored in an accumulator and covers the energy demand for operation and start-up of the pellet stove. The surplus electricity produced can be used to charge mobile phones or other small consumers via an USB-port. In addition, due to the water cooling system of the TEG, a second living room can be heated by the new technology. Within the project appropriate system components have been selected and two testing plants have been constructed, manufactured, tested and optimised. The electricity demand of the pellet stove could be reduced by more than 50% and the electricity production of the TEG has been optimised by adjusting the TEG position and cooling system. The final design of the new micro CHP technology and long-term testing of the new components is currently ongoing. Its market introduction is planned within the next two years.
- **Small-scale biomass boilers with a micro-ORC process:** With a thermal power of 10 to 30 kW_{th}, residential/public buildings or micro-grids can be heated by the new micro-ORC. The electric output of 0.4 to 1.3 kW_{el} is suitable to cover the base electricity demand of the customers. To achieve high electric efficiencies a high temperature difference between input and output is

needed. Thus, the micro-ORC system is especially suitable for customers with low temperature heating systems (e.g. floor heating). The micro-ORC has a very compact design and can be directly mounted in the boiler room. Due to the add-on solution only minor adaptations of the biomass boiler are needed and thus, in addition to new installations of biomass boilers with the micro-ORC also retrofitting of existing boilers becomes possible. Within the project the new micro-ORC technology has been tested and optimised. Thereby, a special focus was put on the optimisation of the hydronic integration and the control strategy in order to maximise the electric output of the CHP technology. This work has been supported by monitoring data regarding heat and electricity demand for residential building and transient system calculations to optimise the control strategy. Currently, tests with the final design of the ORC are ongoing, a market introduction is planned within 2018.

- **High temperature heat exchanger (HT-HE) for an externally fired gas turbine (EFGT):** With a thermal capacity of about 1,500 kW_{th} the CHP technology based on a biomass boiler and an EFGT is suitable for district heating systems (base load), or process heat consumers (e.g. wood manufacturing industry). The electricity produced by the gas turbine (up to 100 kW_{el}) can be used to cover the own electricity consumption of a company and/or fed into the grid. Within the project the HT-HE which represents the core component of the system has been designed, constructed and successfully tested at flue gas temperatures up to 900°C. Thus, appropriate guidelines for a compact design of the HT-HE and recommendations have been worked out to minimize thermal stresses as well as ash related problems regarding ash deposit formation and high temperature corrosion. Furthermore, different concepts for the overall EFGT system have been worked out and evaluated. A first testing plant shall be installed and evaluated within the next two years.

The technological development of the new CHP technologies has been supported by techno-economic analyses performed within the project. Based on the framework conditions defined and the input data gained from the industrial partners as well as the test runs performed, all three technologies investigated show acceptable economic results in comparison to state-of-the-art technologies. The technological performance and the suitability of the new technologies for the fields of applications defined have been proven. Thus, a sound basis for pilot plant tests and field tests as well as for a subsequent market introduction by the industrial partners is given.

5 Ausblick und Empfehlungen / Outlook and Recommendations

The ERA-NET project has been finalised after a duration of 3 years in April 2017. The work schedule has been kept and all milestones have been achieved in time. The main objective of the project, the development and test of three different CHP concepts in different capacity ranges which are suitable for different types of small-scale biomass combustion systems has been achieved. It is the dedicated aim of the industrial partners to continue after the end of the project with the demonstration and market introduction of the respective CHP technologies.

Regarding the pellet stove with TEG, the final design is currently ongoing and long-term tests of the new technology are scheduled. Its market introduction is planned by RIKA within the next two years. With the new micro-ORC technology currently tests regarding the final design are ongoing and a market

introduction is planned by ORCAN within 2018. A first testing plant for the EFGT technology with the HT-HE developed within this project shall also be installed and evaluated within the next two years.
Following, for all three technologies a market introduction within the next 2 to 5 years seems possible. Consequently, a comprehensive and market oriented exploitation of the project results should be guaranteed. From the scientific partners point of view a considerable know-how gain regarding the three new small-scale CHP technologies as well as concerning ash related issues could be gained and will be applied in future R+D projects.
By the close cooperation of the four countries Germany, Austria, Poland and Sweden within the framework of the 7th call for ERA-NET Bioenergy projects, a clear added value for all project partners has been achieved. Especially the interdisciplinary cooperation of the industrial and scientific partners from different sectors made a comprehensive know-how exchange possible. Moreover, the different expertise of the partners could be combined and made the project work more efficient. As a consequence in several fields of activities (e.g. ash related problems, material selection as well as CFD and TRNSYS simulations) an inter-work-package-cooperation within the project took place.

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7 Anhang / Annex

In addition to this report on the project webpage www.minibiochp.eu general information regarding the project and the project partners as well as the presentations of the final project workshop in Wels 2017 are available for download.

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