Resource-efficient fuel additives

for reducing ash related operational problems in waste wood combustion

REPORT SUMMARY FROM THE BIOENERGY ERANET PROJECT REFAWOOD

REFAWOOD

ERA-NET Bioenergy

This short report summarizes the results from the Bioenergy Eranet project REFAWOOD and describes resource-efficient and low-cost additives that can be added for reducing ash related operational problems (corrosion/deposits/slagging) in combustion of wood waste fuels. Fuel additive concepts is described. Waste wood and additives in large-scale combustion plants and effect on reductions in downtime as well as environmental and economic consequences is presented. The report can be downloaded at the REFAWOOD web page: www.refawood.com

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Introduction

Wood waste fuels arises via a variety of post-consumer waste and in different fractions, ranging from untreated, pre-consumer off-cuts to treated wood as demolition wood. Depending on the source, waste wood contains more or less elements that increase the risk to get ash-related problems in the boiler during combustion. Alkali chlorides formed from the critical elements released from biomass combustion may lead to severe ash deposition and corrosion problems in biomass-fired boilers. The majority of biomass and wood waste-fired power plant in Europe reports more or less extensive corrosion problems in the superheater as well as on furnace walls that cause unacceptably short life times. One of the measures to reduce the alkali chloride-related problems in biomass combustion is to use additives.

Although there is a wealth of experience in the area of biomass combustion and additives, there is still a clear need for further development in several areas, including studies of new low-cost and resource efficient fuel additives for reducing corrosion/deposits/slagging. Fuel additives can increase the reliability of biomass combined heat and power plants and develop skills to extend the use of different types of biomass fuels, which ultimately may mean that the energy supply of conventional fuels with higher environmental impact can be reduced.

The overall objective of REFAWOOD was to improve economic and environmental conditions for the use of wood waste fuels in combined heat and power plants by using resource efficient additives during combustion. Specific aims of the project were:

- To propose efficient and innovative fuel additive design concepts for reducing ash related operational problems (corrosion/fouling/slagging) in combustion of wood waste fuels.
- To perform full-scale combustion tests to demonstrate effective fuel additive design concepts.
- To determine the environmental and economic effects of using various additives in waste wood combustion in combined heat and power/heating plants.

Wood waste fuels

A European perspective on wood wastes as fuel

The importance of utilizing waste streams to their full potential, including energy value, is well recognized within the EU.[1,2] The replacement of virgin biomass with woody waste in waste-to-energy has created a push for more fuel-flexible combined heat and power plants across Europe. This allows operators to adequately respond to market fluctuations and keep fuel costs low while also contributing to a net reduction of greenhouse gas emissions. Woody waste fuels are already well utilized in the EU but often come with operational challenges for the plant operators.[1] Waste streams may contribute to a circular economy[2] although a simultaneously desired increase in reuse and recycling (see Figure 1) may lead to a more challenging situation for waste-to-energy plant operators.

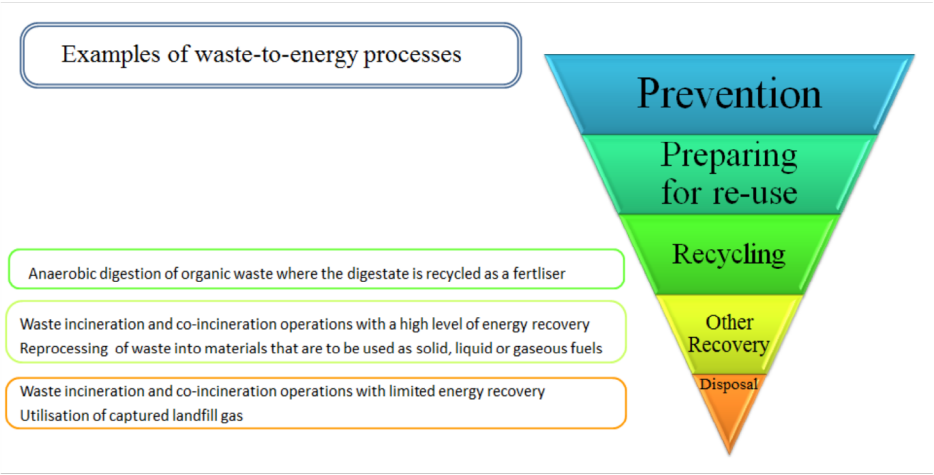


Figure 1: The waste hierarchy andwaste-to-energy processes. Figure adapted from Figure 1 in The role of waste-to-energy in the circular economy, Brussels, 26.1.2017 COM(2017) 34 final.[2]

Fuel properties of wood wastes – focus on ash composition

Waste wood and woody residual fuels pose specific challenges in thermal conversion compared to conventional combustion of clean wood chips, and these generally arise from the inorganic content in the fuel. The ash content is typically higher, the concentrations of certain elements such as Zn is often higher due to residues of paint and other materials from construction, and the concentrations of Cl could be high due to inclusion of plastic materials.

Altogether, this causes waste wood from demolition in particular to have a challenging composition of ash-forming elements with regards to operational problems such as slagging or corrosion. Figure 1 and Figure 2 shows the inorganic composition of some of the waste woods and woody residues used in the current project, spanning a wide range of fuel compositions and fuel types. Notably, high concentrations of K and Na are displayed for some fuels in Figure 1 which indicates a risk of formation of alkali silicates and/or chlorides. These compound are associated with issues in slagging and corrosion.

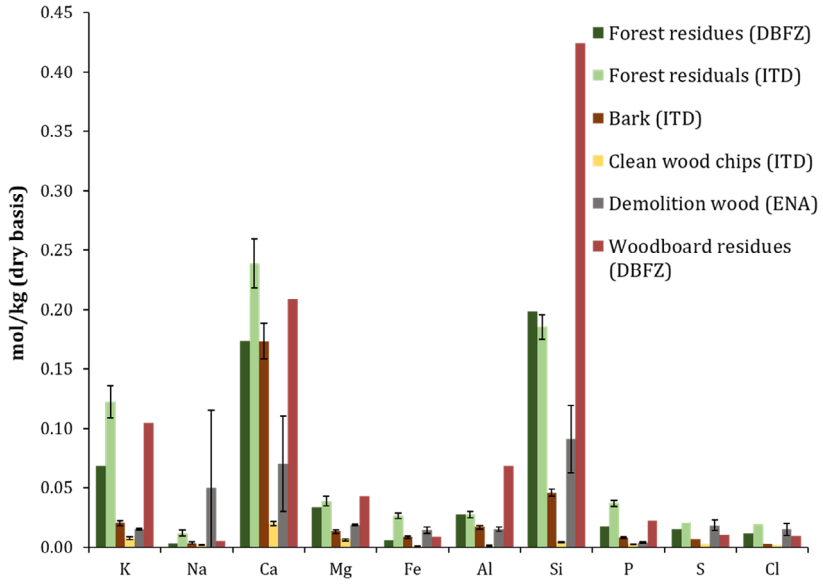


Figure 2: Main ash forming elements in waste wood and woody residue fuels used in the REFAWOOD project by the respective project partners presented as a fuel fingerprint, allowing direct comparison of elemental concentrations.

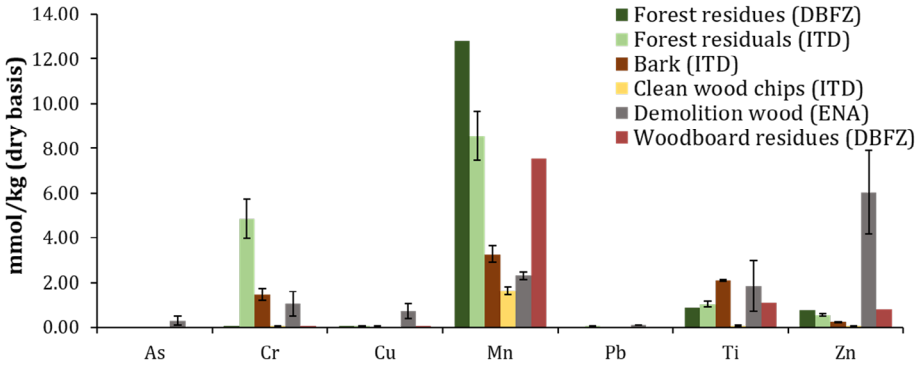


Figure 3: Trace ash forming elements in waste wood and woody residue fuels used in the REFAWOOD project by the respective project partners presented as a fuel fingerprint, allowing direct comparison of elemental concentrations.

1) Towards a better exploitation of the technical potential of waste-to-energy, JRC Science for Policy report, Hans Saveyn, Peter Eder, Mark Ramsay, Grégoire Thonier, Kathryn Warren, Mathieu Hestin, 2016.
2) The role of waste-to-energy in the circular economy, Communication from the commission to the European Parliament, the Council, the European economic and social committee and the committee of the regions, 2017.

Fundamental approaches to additive concepts

The REFAWOOD project aims to investigate the influence of new cheap and resource efficient fuel additives as recycled gypsum, iron sulphide (sulphide ore waste material), and the aluminosilicate additives halloysite and coal fly ash on important ash transformation processes in thermal conversion of wood waste. Managing the challenges associated with thermal conversion of waste woods involves limiting slagging as well as reducing the risk of fouling and deposit formation, including reducing the risk of corrosion. The additives mentioned above could be considered as cost-effective due to their abundance and relatively low purity. This does require a thorough understanding of what exact reactions the additive undergoes and how this may reduce the issues in thermal conversion of woody wastes.

The three additives mentioned above provide different strategies that may be suited for different processes. Recycled gypsum contains calcium that can increase the melting temperature of formed ash particles in the temperature range typically associated with woody waste combustion. Additionally, the gypsum provides sulphur that can outcompete chlorine in the formation of deposits and thereby reduce the risk of corrosion problems. Similarly, the iron(II)sulphide can provide sulphur to reduce chloride formation in fouling and deposits but iron is not generally considered to reduced slagging issues. Finally, the aluminosilicate-containing additives halloysite and coal fly ash can act as reactants to capture the alkali components potassium and sodium in compounds with high melting temperatures. By doing so, the alkali components are also prohibited from forming problematic chloride compounds that could cause corrosion issues. An in-depth view into how these additives will react and some recommendations for additivation strategies are provided below. For all cases, it should be emphasized that one additivation level will not fit all woody waste fuels – plant operators should use typical concentrations of ash-forming elements in their wood waste fuels to find out what additive levels may be suitable in their specific case.

Recycled waste gypsum

What is required for gypsum to work as an additive?

Gypsum ($CaSO_4 \cdot 1.5H_2O$) decomposes in two steps, first by dehydration into anhydrite ($CaSO_4$) which further decomposes to CaO(s) and SO_2/SO_3(g), where the latter reaction is more efficient at higher temperatures and low O_2-to-fuel ratios, see Figure 3. The decomposition is crucial for its efficiency as an additive. Looking at what effect is desired from the additive for application in waste wood combustion, the addition of CaO(s) will readily assist in increasing melting temperature of formed bed ash already at low additions. The sulphur addition aiming to capture alkali and to some extent Zn and Pb, including that which may be released into gas phase after tertiary ash transformation reactions where Ca substitutes alkali in silicates, should therefore be considered the most important reactive component.

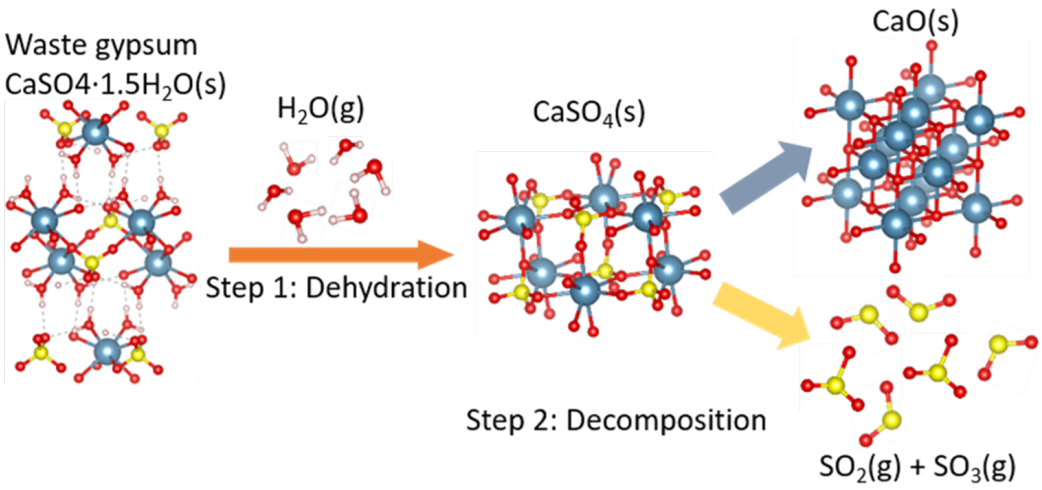


Figure 4: General reaction path of recycled waste gypsum to form its reactive components.

Waste gypsum efficiency limitations

The efficiency of alkali capture in by sulphur from recycled gypsum cannot be expected to be 100% due to several limiting factors. Previous studies have suggested that small amounts of additive will display a decomposition of gypsum as evident by elevated SO_2 levels, but not to 100% decomposition – with significantly lower results in fluidized beds. Gypsum addition in coal combustion have shown decomposition efficiencies as low as 30% but previous bench-scale studies for grate-fired systems would place this number significantly higher. Therefore, a decomposition of gypsum at 80% was used as an estimate in the present project where fixed bed systems dominated the experimental setups both in laboratories and in industrial-scale experiments. Further, the sulphation efficiency was estimated at 80% providing an overall efficiency of 64%.

Approach for calculating gypsum additive levels

The stoichiometric amounts of S for capturing total amount of K, Na, Zn, Pb with the above suggested efficiency were used throughout the project. This will provide information whether these low amounts will already have a noticeable effect. The high addition level corresponds to twice the stoichiometric amount of S according to the assumptions made. This is also the additive level relevant for full-scale experiments. The total molar amount of S to be added, Sadd, can therefore be calculated according to Equation 1:

$$S_{add} = (F_{stoich} \cdot (((K+Na)/2)+Zn+Pb)-0.64S_{fuel})/0.64$$

(Equation 1)

Where S_{add} is the molar amount of S added through gypsum, F_{stoich} is the final molar ratio between available S and K, Na, Zn, Pb molar levels in the fuel based on cation properties, S_{fuel} is the S included with fuel and 0.64 is the factor resulting from the total efficiency estimations.

Using Fstoich = 1 will provide the amount of S_{add} necessary to follow the expectations according to efficiency limitations and may work well in small systems with the additive evenly distributed and in high contact with surrounding fuel particles. Reasonable levels of additive for industrial scale experiments where a few kilograms of additive may get lost in a ton of fuel will perhaps have to be higher, at least for low additive amounts. Until there are studies outlining the actual efficiency of decomposition and sulphation, it is likely more convenient to use F_{stoich} to estimate desired additive levels.

Iron(ii)sulphide

Driving force for additive activation

The addition of iron(II)sulphide in waste wood combustion only aims to reduce chloride-induced corrosion, similar to the mechanism discussed in waste gypsum. While actual iron sulphide waste sources may contain Fe(I)S or/and Fe(II)S, this is a suitable starting component to investigate the system. The oxidation of iron(II)sulphide is exothermic since both Fe and S is oxidized in the net reaction, see Reaction 1 for ΔG of oxidizing 1 mol Fe(II)S at 1000 °C. Compared to waste gypsum where energy is required to both remove crystalline water and sulphate decomposition, this reaction is likely to be more efficient. A general reaction structure is shown in Figure 4.

$$FeS(s) + 1.75\ O_2(g) \rightleftharpoons \tfrac{1}{2}\ Fe_2O_3(s) + SO_2(g)$$
$$\Delta G = -431.66\ kJ\ at\ 1000\ °C$$

(Reaction 1)

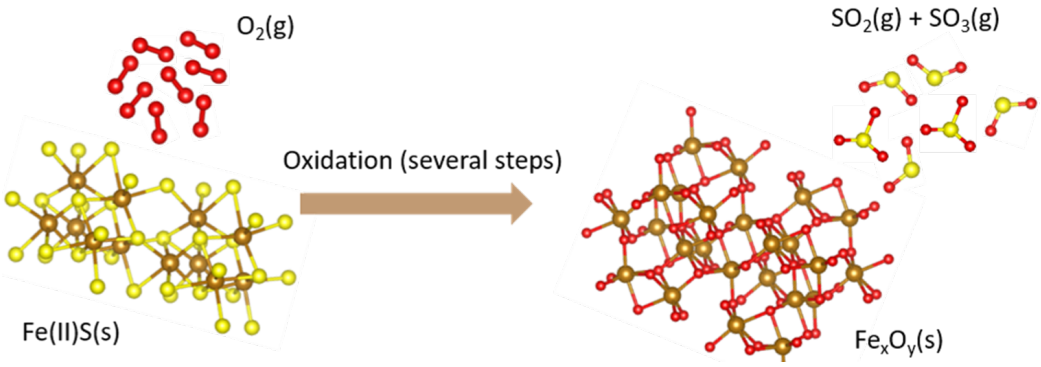


Figure 5: General oxidation reaction schematic for iron sulphide, simplified to only consider oxygen as oxidation source and with FeO(s) representing the iron oxides.

Approach for calculating iron(II)sulphide additive levels

Since little is known about the efficiency of decomposition of Fe(II)S and subsequent sulphate formation in flue gas, a simple stoichiometric strategy was employed for determining additive amounts. As shown in Equation 2, the total molar concentrations in the fuel for the elements K, Na, Zn, Pb were considered together with amounts of S. Again, an F_{stoich} parameter was included to allow adjusting additive dosage with a known factor where F_{stoich} = 1 would correspond to the exact amount of S necessary for complete sulphation of K, Na, Pb, and Zn which is an idealized case.

$$S_{add} = F_{stoich} \cdot (((K+Na)/2)+Zn+Pb)-S_{fuel}$$

(Equation 2)

Aluminosilicate additives

Identifying the key component for alkali capture

To find the potential for alkali metal capture of a given aluminium silicate additive we can safely assume that it acts by bonding one K or Na – likely through a tertiary ash transformation reactions with K/Na-OH(g) or possibly by reacting with K_2SiO_3 (s,l) – for each aluminium atom in the aluminium silicate structure. The reaction product of these reactions are compounds such as leucite ($KAlSi_2O_6$), kalsilite ($KAlSiO_4$), microcline ($KAlSi_3O_8$) or analogues containing Na.

While the direct reaction may or may not be targeting the aluminium site specifically, the likely reaction products suggest that one aluminium in the additive corresponds to a possibility to bond one alkali metal ion. The alkali metal ion capture potential, Alk_{cap}, of aluminium silicates should therefore be based on the number of reactive sites originating from the number of moles of aluminium per kilogram of additive (Al_{add}).

Existing cations in the additive

In order to assess the number of reactive sites in an aluminium silicate additive, the amount of already associated components needs to be included or it is likely that the efficiency is overestimated. Suitable minerals as kaolinite or halloysite may already contain certain cations such as K^+, Na^+, Ca^{2+}, and Mg^{2+} (K_{add}, Na_{add}, Ca_{add}, Mg_{add}) when lower qualities are used, and sources such as coal fly ash often contains a complex matrix of cations. The total Alk_{cap} can, according to the reasons described previously, be calculated as the number of moles of aluminium in the additive, Al_{add}, that is not already associated with cations in the additive (K_{add}, Na_{add}, Ca_{add}, Mg_{add}), in concentrations of mol/kg according to equation 3.

$$Alk_{cap} = Al_{add} - (K_{add} + Na_{add} + 2(Ca_{add} + Mg_{add}))$$

(Equation 3)

Approach for calculating aluminosilicate additive levels

Previous work with stem wood and kaolinite as additive has shown the effectivity of kaolinite to be in the range of 0.85 – 0.90, which may also be necessary to apply when assuming additive amounts. The higher value will be used here, assuming 90% efficiency. Basing this on analysis of fuel and additive in mol/kg, either on wet or dry basis for both, and a 90% efficiency provides the following formula to assess how many kg of additive is necessary per kg of fuel (Equation 4):

$$Amount_{add} = ((K_{fuel} + Na_{fuel})/Alk_{cap})/0.90$$

(Equation 4)

The resulting fraction from Equation 2 is how many kg of additive is necessary per kg of fuel. This is readily converted into kg/ton or similar units more practical for large scale applications.

Using waste wood fuels and additives in large-scale combined heat and power/heating plants

Waste wood as in terms of demolition wood is today about 10 EUR/MWh cheaper than forest wood chips. However, operation and maintenance costs are higher when this type of waste wood is combusted. The use of additives may reduce the operation and maintenance costs. Therefore, the European combined heat and power plants, are highly interested in finding new, low-cost additives to be able to use cheap wood waste without causing an increase in maintenance costs. Within the REFAWOOD project, full-scale combustion trials have been performed in wood waste fired combined heat and power plants of different sizes (8-70 MW) and with different technologies.

Additive levels and blending

The additive level depends on the chemical properties of the fuel and the additive used. In the REFAWOOD project, calculated additive levels of gypsum and coal fly ash amount to 1-3 wt-% of the waste wood fuels used in this work.

The additives can be blended with the fuels at a terminal, dosed directly on the fuel at the augers upstream of the furnace or added to the fuel in the boiler by fuel injectors. To be able to adjust the amount, an additive dosing system is preferred. However, the dosing system needs to be adjusted to different fuel feeding systems and to each specific combustion system.

Influence of additives on emissions

During the full-scale combustion tests the flue gases were analyzed with respect to SO_2, HCl, NO_x, CO, O_2 and aerosols and total dust particles.

When using gypsum as additive, the flue gas analysis shows that the gypsum particles are dehydrated and later decompose to release gaseous SOx shown by higher concentrations of SO_2 detected for the cases of gypsum addition. HCl(g) increases in cases of gypsum addition, which demonstrates that significant amounts of Cl are removed from solid deposits to be found in flue gases instead. There is clear evidence of K capture in particles with Ca and in bottom ash particles, as well as similar indications in the entrained fly ashes.

For coal fly ash the particle measurements (particles <1 µm) showed that the addition of coal fly ash minimises the amount of particles, as less alkali metals (K and Na) are released to the gas phase.

Influence of additives on dust and deposits

The concentrations of major elements in dust collected during addition of additives are shown in Figure 6. In general, the addition of additives to the flue gas increases the amount of dust. The chemical analysis of the total dust showed that elements which have high concentrations in the additive can be found in the total dust, which is roughly consistent with the dust separated in the cyclone.

The result from the combustion trials showed higher Al and lower K and Zn concentrations in the dust for coal fly ash addition compared to the reference case without additive. This is due to high amounts of Al and reduces the release of K and partly of Zn.

For the gypsum additive, a decrease in the Cl- and K-content in the dust can be seen, and an increase of the S- and Ca-contents are explained by entrainment of $CaSO_4$ or CaO from the additive (figure 6).

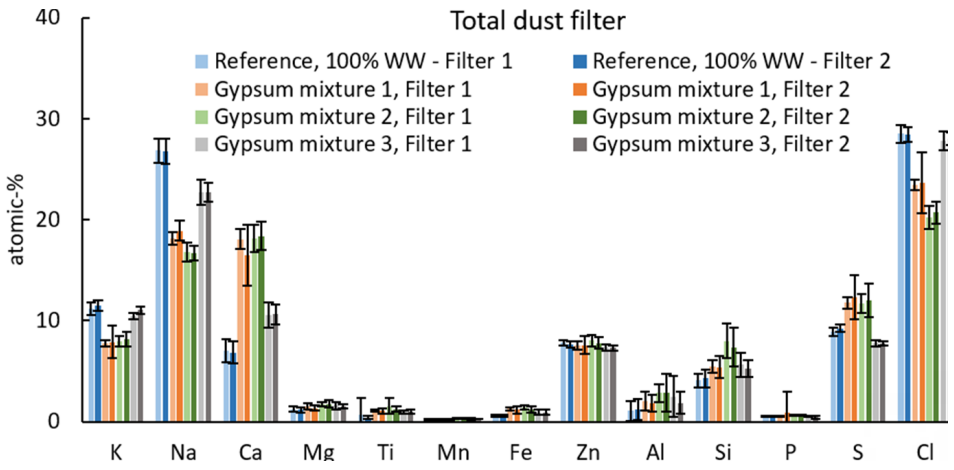


Figure 6: Elemental composition of fly ash according to SEM-EDS analysis normalized on (C, O)-free basis, compared with XRF results.

A variation in deposit build up could be seen between the different combustion systems. Some measurements showed an increased deposit buildup when adding gypsum. For one CHP plant using fuel dust injectors, the deposit buildup decreased for gypsum addition. Common for all measurements is that the deposits mainly consist of K, Ca, and S which would indicate sulphate formation.

When using coal fly ash there was an increased deposit buildup. A relatively large variation in chemical composition was noted but in general, the concentrations of Si, Al and Fe are increased compared to the reference sample.

Reducing plant downtime

Because of the additives, the combined heat and power plants may need additional cleaning to remove slagging and fouling. For one waste wood fired combined heat and power plants, estimations of the need for changes in cleaning intervals were made.

For this estimation indices are used. Indices are calculated from the chemical composition of the fuels and additives and allow an estimation of certain aspects occurring during combustion [1].

The indices are:

- the molar 2S/Cl ratio which allows an estimation of the high temperature corrosion risk.
- the molar (Si+K+P)/(Ca+Mg) ratio and the molar (Si+K+P)/(Ca+Mg+Al) ratio.

Both indices can predict the potential regarding ash melting or slagging. Indices and the relative improvement compared with the reference case are found in the table 1.

The improvement in % of the index ratio is linearly proportional to the extension of planned cleaning intervals per year. It was also assumed that about 50% of the improvements of the index values have a real effect in the real-scale combustion system. This assumption is based on the fact that in real combustion plants, operation of the plant, abrasion effect caused by flow conditions, insufficiently described deposit built-up – transformation and chemical reactions of ashes cannot be completely considered.

If the corrosion rate is constant the result of the calculations showed that the coal fly ash addition improves the corrosion behaviour with 8% whereas for gypsum an improvement of 200% can be assumed. Concerning slagging of formed deposits an improvement of about 13% and 17% for coal fly ash and gypsum respectively can be assumed.

Table 1. Indices based on fuel and additive compositions in the different cases, and the relative change of indices as compared with the reference case.

		Reference	Coal fly ash	Gypsum
2S/Cl	mol/mol	1.84	2.13	7.77
(K+P)/(Ca+Mg)	mol/mol	0.25	0.24	0.17
(K+P)/(Ca+Mg+Al)	mol/mol	0.20	0.15	0.13
2S/Cl	%		116	423
(K+P)/(Ca+Mg)	%		6	34
(K+P)/(Ca+Mg+Al)	%		26	35

1) Peter Sommersacher, Thomas Brunner, Ingwald Obernberger. Fuel Indexes: A Novel Method for the Evaluation of Relevant Combustion Properties of New Biomass Fuels. Energy & Fuels 2012 26 (1), 380-390

Conclusions

Gypsum as an additive for simultaneous addition of Ca and S to problematic wood waste streams shows potential. The results from the REFAWOOD project show that the underlying chemical reactions work as intended.

Fuel admixing worked similarly well regardless of strategy, but the additive dosing system needs to be adjusted to different fuel feeding systems and to each specific combustion system.

Alkali capture in Ca-sulphate particles was readily observed which indicates good potential to reduce chloride formation.

Increased flue gas concentrations of HCl in combination with elevated SO_2 concentrations shows a reduction of chloride formation.

Power plant capabilities for handling of total particulate matter concentrations in cyclone or filters as well as flue gas cleaning must be considered if gypsum is used as an additive.

The particle measurements have shown that the addition of coal fly ash minimises the amount of particles as less alkali metals (K and Na) are released to the gas phase. However, by adding the coal fly ash the amount of total dust is increased.

Environmental consequences of using additives

In order to understand the environmental consequences of using low-cost additives for waste wood combustion, the environmental profiles of four different power plants were investigated through a life cycle assessment (LCA). Such assessment allowed to explore the contribution of different parameters (e.g. additives strategies, combustion emissions or wood fuel composition) to the total life cycle environmental impacts of producing heat and electricity in a combined heat and power plant.

The first step of the assessment consisted in evaluating a baseline scenario where the power plants operated without the use of low-cost additives. The primary data for such baseline scenario was collected from the power plant operators, and included the inputs and outputs during the operation of the power plants in year 2016 or 2015. The characteristics of the power plants evaluated under the baseline scenario are described in Table 2. Only one power plant (22 MWe) was already using commercial sulphur as additive.

Table 3 shows the impacts of producing 1 MJ of heat and 1 kWh of electricity in each power plant, which were calculated for the following environmental impact categories: climate change, acidification, particulate matter, freshwater eutrophication, human toxicity and cumulative energy demand. The graph shows the contribution of each life cycle stage to the total environmental impacts of producing energy in each power plant.

The life cycle stages that are contributing the most to the environmental impacts are the fuel procurement (due to harvesting operations) and the operation of the power plant (due to combustion emissions). The power plants containing higher amount of pre-treated waste wood in their fuel blend present lower impacts in the fuel procurement phase, i.e. system A (91% of demolition wood in primary energy) and system C (around 50% of waste in primary energy). However, the impacts of operating such plants are higher due to: (1) higher emissions contributing to acidification, toxicity and particulate matter, and (2) higher need of additives in the flue gas cleaning system (e.g. ammonia, urea, sodium hydroxide). Transportation plays a minor role within the total life cycle impacts, although it has a relative high contribution for system D, whose average fuel transportation distance is 115 km. The ash disposal has a low relative contribution to the total life cycle impacts, especially in the cases where the

Table 2. Main parameters and characteristics of the power plants under study

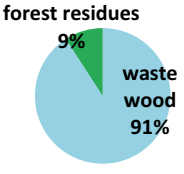
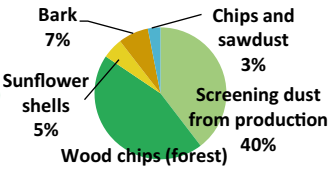
	WASTE WOOD POWER PLANTS			
	A	**B**	**C**	**D**
Installed capacity, MW	22 Mw_e, 45 MW_{th}	1.2 MW_e, 5.5 MW_{th}	10 MW_e, 40 MW_{th}	0.8 MW_{th}
Net electricity, MWh	47,000	7,973	73,309	-
Net heat, GJ	669,600	134,885	120,312	2088
Net energy efficiency, %	74%	84%	33%	88%
Average fuel transportation distance, km	164	50	55	115
Ash disposal	Landfill cover	Road stabilization	cement industry and landfill	landfill
Fuel blends, in %Primary energy				

Table 3. Characterization results and distribution of impacts per life stage of the power plants under study (baseline scenario). Calculated with the ILCD midpoint impact evaluation method (exergy allocation between heat and electricity).

	Values /kWh$_e$	/MJ$_{th}$
Climate change, *g CO_2 eq (fossil)*	38 – 52	2.3 – 10.5
Toxicity, non-cancer, *CTUh*	1.7-2.1 (x10^{-8})	1.2-1.6 (x10^{-9})
Toxicity, cancer, *CTUh*	4.0-5.7 (x10^{-10})	2.8-10 (x10^{-11})
Particulate matter, *g $PM_{2.5}$ eq*	0.03-0.09	0.006-0.041
Acidification, *molc H+ eq*	5.2-18 (x10^{-4})	1.2-7.9 (x10^{-4})
Freshwater eutroph., *kg P eq*	6.8-13 (x10^{-7})	4.5-52 (x10^{-8})
CED, Non-renewable, *MJ*	0.53-0.79	0.04-0.13
CED, Renewable, *MJ*	12-19	0.8 1.2

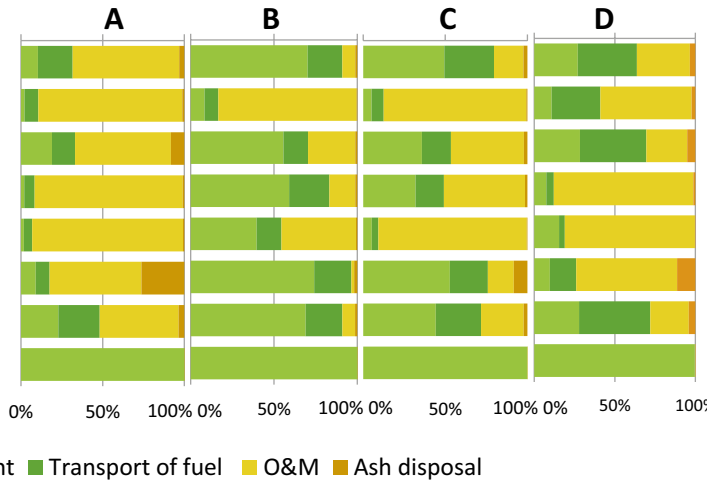


Table 4. Percentual changes in the environmental impacts of the additives scenario when compared to the baseline scenario. Percentages in brackets indicate the amount of additive per fuel (in weight).

Impact categories	U/FU	A Gypsum (0,5%)	B Gypsum (1%)	B Halloysite (1%)	C Gypsum (1%)	C Coal fly ash (3%)	D Gypsum (1,5%)	D Halloysite (3%)
Climate change	g CO_2 eq	-0.1%	-0.4%	-3.6%	-2.0%	-1.5%	-7.3%	-13%
Human toxicity, non-cancer	CTUh	-0.03%	-0.8%	-4.6%	-3.2%	-1.8%	-0.8%	-2.9%
Human toxicity, cancer	CTUh	-0.2%	-0.4%	-3.6%	-3.0%	-1.6%	0.6%	-0.8%
Particulate matter	kg $PM_{2.5}$ eq	-0.04%	-0.7%	-2.8%	-3.0%	-1.7%	-31%	-40%
Acidification	molc H+ eq	-0.1%	+6.4%	+0.7%	-3.2%	-1.8%	12%	-0.3%
Freshwater eutrophication	kg P eq	-0.1%	-0.1%	-2.8%	-2.8%	-1.5%	0.1%	0.4%
CED, Non renewable	MJ	-1.2%	-0.4%	-3.5%	-2.8%	-1.5%	-0.6%	-2.3%
CED, Renewable	MJ	0.0%	-1.0%	-5.1%	-3.3%	-1.8%	-1.1%	-3.8%

ashes are being partially recycled. Landfilling of ashes has higher contribution for power plants A and D, especially in eutrophication.

In conclusion, the use of low-cost additives have the potential to slightly reduce the environmental impacts of producing energy with waste wood, especially in the case of medium to big scale power plants using pre-treated waste wood as feedstock. However, impacts on acidification may increase under the absence of appropriate flue gas cleaning systems (desulphurization and NOx reduction). Halloysite was the additive presenting the highest benefits.

The main limitation of this study lies on the reliability of the results for the combustion emissions. The tests were conducted only on a limited number of flue gas emissions and for short periods, which is not enough time to confidently predict the behaviour of power plants. Additionally, the increase in energy efficiency was not measured onsite, and estimations from experts were considered instead. Therefore, the obtained results should be considered as potential scenarios, and not as a prediction of real impacts.

Economic consequences of using additives

One of the goals of the REFAWOOD project was to determine the economic effects of using resource efficient additives, such as gypsum, coal fly ash or halloysite, in waste wood fuel mixes. More specific, to show whether or not the use of additives within the fuel mix will result in reduced operational and maintenance costs. These reduced costs could be caused due to an increase in boiler performance and operational hours, and a decreased amount of maintenance. This was done by performing a cost benefit analysis (CBA). It was decided to use a discounted cashflow model for the CBA. The discounted cashflow model is created manually in order to fulfill the demands of the requested REFAWOOD tasks. A case specific model was built including all necessary parameters to decide the economic effects of using additives.

To be able to make a determine the effects of using additives, per plant, a baseline scenario was created which was representative for a regular recent full year of operation. Additionally, information was provided for the case in which additives were used in order to make a comparison and determine the economic effects. Different parameters involved in this analysis are shown in Table 5 .

Table 5. Overview of the required parameters for the baseline scenario and the additional additives scenario as input for the CBA

Baseline scenario parameters

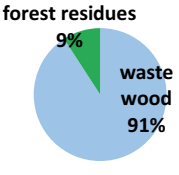
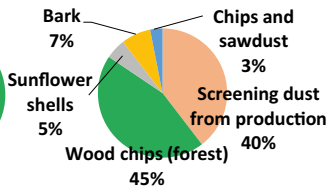
Parameter	Unit
Depreciation period	year
Total project costs	€
Net Environmental Subsidy	€
Purchasing cost wet wood chips	€/ton
Revenue for heat delivered	€ct/kWh
Revenue from electricity feed	€ct/kWh
Exploitation and insurance costs	€/year
Maximum electricity production	kWe
Maximum heat production	kWth
Thermal supply of wood chips	kWth
Heating value of biomass	MJ/kg
Biomass use on a yearly basis	ton/year
Operational (full load) hours of boiler	hours
Operational (full load) hours of steam turbine	hours

Additional additives scenario parameters

Parameter	Unit
Investment in gypsum dosing equipment	€
Costs of additive	€/year
Additional cost for fluegas desulphurization	€/year
Additional (ash and gypsum) disposal costs	€/year
Cost reduction due to decreased downtime	€/year
Cost reduction due to increased lifetime heat exchanger/superheater(s)	€/year
Increased boiler efficiency	%

Table 6. The 4 different waste wood power plants

WASTE WOOD POWER PLANTS

	A	B	C	D
Installed capacity, MW	22 MW_e, 45 MW_{th}	1.2 MW_e, 5.5 MW_{th}	10 MW_e, 40 MW_{th}	0.8 MW_{th}
Fuel blends, in % primary energy				
Tested additives	1 wt% gypsum	1 wt% gypsum 1 wt% halloysite	1 wt% gypsum 3 wt% coal fly ash	1 wt% gypsum 3 wt% halloysite

The baseline data is used as input to determine the project result in euros per year (before interest and corporate tax) through a discounted cashflow calculation. This again is done for the additives scenario with the adjusted values affected by the use of additives. By calculating the difference between the two outcomes, the economic effects can be determined. This was done for 4 different power plants applying different additives, see Table 6.

The additional additive scenario parameters were estimations, therefore a range was applied for each additives scenario. All estimated values were considered as the top of the range (most beneficial, high scenario), while also a scenario (least beneficial, low scenario) with only half of the benefits in downtime reduction, increased lifetime of heat exchanger / superheater and increased plant efficiency compared to the high scenario was determined.

Finally, the economic effects, a yearly cost reduction (before interest and corporate tax) range (low scenario – high scenario), was calculated for all the additives that were tested in each power plant. The yearly cost reduction result is the difference between the baseline scenario (where no additives are used) and the scenario in which additives are used, see Figure 7.

- For power plant A (22 MWe / 45 MWth), a yearly cost reduction between €134,000 and €334,000 could be realized by applying 1 wt% gypsum within the fuel mix.

- For power plant B (1.2 MWe / 5.5 MWth), a yearly cost reduction between €29,000 and €60,000 could be realized for applying 1 wt% gypsum. For the use of 1 wt% halloysite, a yearly cost reduction of €19,000 could be realized, whereas it also might also result negative, costing €29,000 per year.

- For power plant C (10 MWe / 40 MWth), a yearly cost reduction between €19,000 and €128,000 could be realized for applying 1 wt% gypsum. The use of 3 wt% coal fly ash as additive would not be interesting from an economic point of view. This result will be negative, costing €86,000 up to €149,000 per year.

- For power plant D (0.8 MWth), a yearly cost reduction between €3,000 and €5,500 could be realized for applying 1.5 wt% gypsum. For the use of 3 wt% halloysite, the a yearly cost reduction of €900 up to €3,000 per year could be realized.

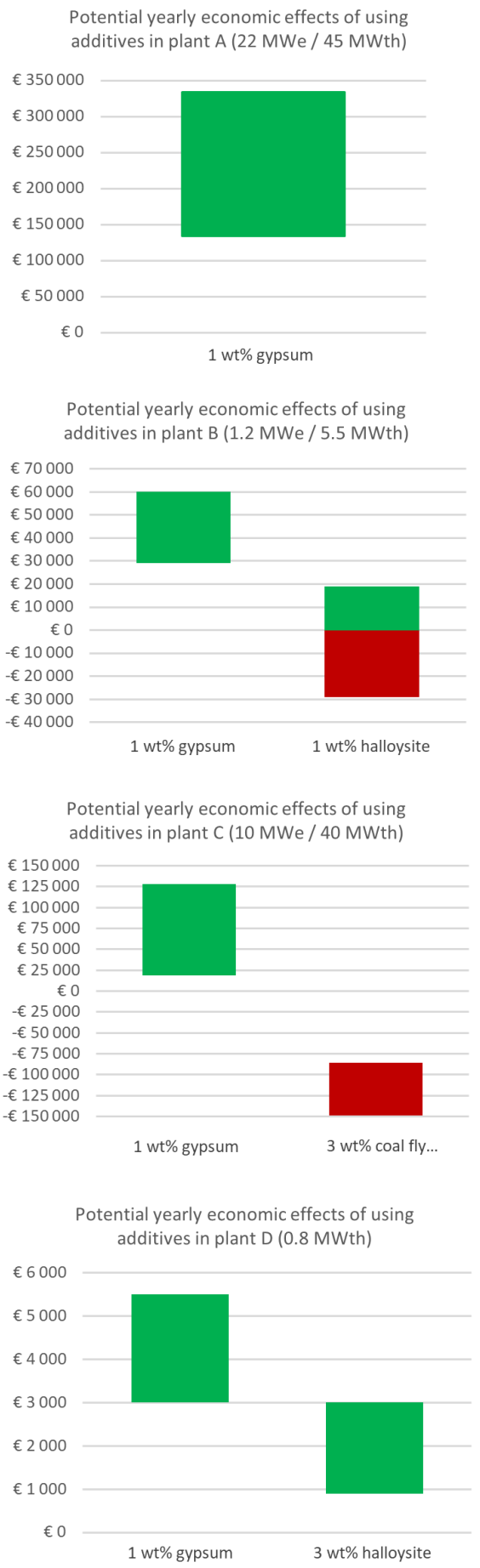


Figure 7. Overview of economical cost-benefit analysis for different power plants

Partners

The REFAWOOD Consortium have consisted of 16 partners from Sweden, Austria, Germany, the Netherlands, and Poland.

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REFAWOOD

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