



# Consequential Life Cycle Assessment of energy generation from waste wood and forest residues: The effect of resource-efficient additives

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## ABSTRACT

Combustion of waste wood can cause slagging, fouling and corrosion which lead to boiler failure, affecting the energy efficiency and the lifetime of the power plant. Additivation with mineral and sulfur containing additives during waste wood combustion could potentially reduce these problems. This study aims at understanding the environmental impacts of using additives to improve the operational performance of waste wood combustion. The environmental profiles of four energy plants (producing heat and/or power), located in different European countries (Poland, Austria, Sweden and Germany), were investigated through a consequential life cycle assessment (LCA). The four energy plants are all fueled by waste wood and/or residues. This analysis explored the influences of applying different additives strategies in the four power plants, different wood fuel mixes and resulting direct emissions, to the total life cycle environmental impacts of heat and power generated. The impacts on climate change, acidification, particulate matter, freshwater eutrophication, human toxicity and cumulative energy demand were calculated, considering 1 GJ of exergy as functional unit. Primary data for the operation without additives were collected from the power plant operators, and emission data for the additives scenarios were collected from onsite measurements. A sensitivity analysis was conducted on the expected increase of energy efficiency. The analysis indicated that the use of gypsum waste, halloysite and coal fly ash decreases the environmental impacts of heat and electricity produced (average of 12% decrease in all impacts studied, and a maximum decrease of 121%). The decrease of impacts is mainly a consequence of the increase of energy generation that avoids the use of more polluting marginal technologies. However, impacts on acidification may increase (up to 120% increase) under the absence of appropriate flue gas cleaning systems. Halloysite was the additive presenting the highest benefits.

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## 1. Introduction

The use of biomass as sustainable energy source has been subject of debate over the last years, both in the public (Van Hilst et al., 2017) and scientific domains (Agostini et al., 2019). Main criticisms are related to the denominated “carbon debt”,<sup>1</sup> the increase in prices for wood-based materials, and the potential displacement or intensification of agricultural production due to bioenergy crops (Matthews et al., 2015). Consequently, waste wood is gaining interest as a bioenergy feedstock that could avoid land competition, reduce greenhouse gas (GHG) emissions, and contribute to meet

the renewable energy targets of the European Renewable Energy Directive (EC, 2018). This last issue is especially relevant in the heating and cooling sector, whose share of renewable sources is increasing at a slower rate than in the electricity sector (3% against 8% in the period 2010–2015) (Bauknecht et al., 2017).

Post-consumer waste wood originates from wood products whose lifetime has finished and are consequently discarded as waste. This wood waste has a limited potential for material recovery due to contaminants. The costs of pre-treatment are not always competitive (Vis et al., 2016). As a consequence, waste wood combustion in combined heat and power (CHP) plants is becoming

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<sup>1</sup> The release of CO<sub>2</sub> emissions from forestry biomass combustion may be higher than the carbon sequestered by the forest regrowth.

common practice in many European countries. Over the year 2016, the European Union (EU28) generated 48.46 Mt of wood wastes (including timber residues<sup>2</sup>), of which 48% were combusted with energy recovery, 49% were recycled, 2% incinerated and 1% land-filled (Eurostat, 2019).

However, waste wood contains impurities that form deposits and alkali chlorides during combustion (Jenkins et al., 1998), increasing the risk of fouling, slagging and corrosion in the boilers of biomass CHP (combined heat and power) plants (Amand et al., 2006). These issues cause planned and unplanned shut downs, which lead to a low load factor of the CHP plant and shorter life-times of the boiler elements. One of the solutions to reduce ash-related problems (fouling, slagging and corrosion) is the use of mineral and sulfur additives (Wang et al., 2012), mixed with the fuel before or during combustion. The decomposition of these additives in the boiler can release acidic elements (e.g., sulfur oxides from gypsum combusting) that react with the alkali chlorides, releasing less corrosive alkali salts and therefore reducing fouling and slagging in the boiler. Additionally, the use of resource efficient additives could provide a useful application to industrial residues such as coal fly ash, halloysite (which is used in biogas filters) or gypsum waste from construction and demolition activities. Several studies on the use of these additives have already demonstrated the technical potential to reduce ash-related problems. For instance, Wu et al. (2013) found that coal fly ash can be an effective additive to minimize the possible ash deposition and corrosion problems during pulverized wood combustion. Paulrud et al. (2015) found that using gypsum as additive during the combustion of waste, wood chips and straw mixes, has the ability to reduce deposit formation/corrosion on the super heaters and convection area. Similarly, Piotrowska et al. (2015) found that the use of shredded waste gypsum board could reduce slag formation when combusting a mix of bark, grass and straw. Though gypsum waste can, in theory, be recycled for 100%, in practice, a large amount of gypsum waste is still landfilled annually in Europe (Jiménez-Rivero and García-Navarro, 2017) instead of being recovered. However, the use of these additives also requires resources to make them available, and addition of inorganic material would reduce the heating values of the fuels.

The use of additives could potentially reduce the unwanted downtime and improve the productivity. In this context, the European research project ERA-NET REFAWOOD (Resource-efficient fuel additives for reducing ash related operational problems in waste wood combustion) is aimed at improving the technical, economic and environmental performance of the use of waste wood fuels in CHP-plants by using resource efficient additives (REFAWOOD, 2019). There are no previous studies looking at the environmental trade-offs of using additives to improve the performance of boilers in biomass CHP plants. Therefore, as part of the REFAWOOD project, this study explores how the quantitative environmental impacts of waste wood combustion could be influenced by different fuel compositions, energy plant characteristics, ashes management, and in particular, additives strategies. This quantification is a necessary step previous to any policy incentive aimed at using additives to improve the performance of waste wood CHP plants. Four waste wood CHP plants located in Western and Central Europe were analyzed using Life Cycle Assessment (LCA), an internationally standardized method to assess the environmental impacts of products or services through their life cycles. LCA is defined as the most comprehensive, consistent and robust

means to assess the environmental performance of bio-based commodities (JRC, 2019).

This article is organized as follows: the methods section contains details about the applied methodology, including the goal and scope of the analysis and the inventory data. The results section describes the outcome from the environmental impact assessment and the sensitivity analysis. The uncertainties of the study (including data and model uncertainty) and the final interpretation of the results are included in the Discussion section.

## 2. Methods

Consequential LCA was applied to explore the environmental consequences of using low-cost additives in waste or residual wood combustion in Europe. The consequential approach was chosen to take into account the effect and consequences of the decision (use of additives) in the analyzed energy system and beyond. Additionally, consequential approaches are especially relevant for policy contexts and bioenergy models (Roos and Ahlgren, 2018). According to the consequential principles, this study uses economic market information to describe how physical flows (and derived impacts) change as a consequence of increasing or decreasing the demand of the product under study. As defined in ISO 14040 (ISO, 2006a), the LCA framework consists of four iterative stages, as follows: Goal and Scope Definition, Life Cycle Inventory Analysis, Life Cycle Impact Assessment and Life Cycle Interpretation. The first two stages are described in sections 2.1 and 2.2 respectively, while the last two stages are described in sections 3 and 4 (Results and Discussion). The LCA was carried out using Simapro software (version 8.5.2).

### 2.1. Goal and scope

The goal of the LCA is to analyze the environmental consequences of using wood waste and residues as feedstock in power plants, and estimate the potential impacts of using resource-efficient additives to improve the performance of the boiler. The results are expected to provide recommendations for decision making regarding the use of additives. To this purpose, four different types of biomass power plants, located in different European countries (Austria, Germany, Sweden, Poland), were investigated by exploring the changes between a baseline scenario (normal operation) and a resource-efficient additives scenario. The temporal scope of the analysis is the present and near future (5–10 years), assuming static inventories (see section 2.2 and supplementary electronic material for inventory data).

The Life Cycle Impact Assessment was performed using ILCD 2011 Midpoint evaluation method (100 years of time horizon), as implemented in Simapro (version 8.5.2). The following impact categories were considered in the study due to their relevance in bioenergy systems, as indicated by previous studies (Cherubini and Strømman, 2011): climate change, terrestrial acidification, human toxicity (carcinogenic and non-carcinogenic), particulate matter, freshwater eutrophication, land use and non-renewable cumulative energy demand (CED). CO<sub>2</sub> emissions from biomass combustion were considered as biogenic emissions with a global warming potential of 1 (kg CO<sub>2</sub> biogenic/kg CO<sub>2</sub> eq). However, it is also assumed that the amount of CO<sub>2</sub> sequestered in the production of biomass equals the amount of CO<sub>2</sub> emitted during the combustion. Therefore, the net emission of biogenic CO<sub>2</sub> is zero.

#### 2.1.1. Functional unit

The power plants located in Sweden (system SE), Poland (system PL) and Austria (system AT) are multifunctional systems providing heat and electricity simultaneously. The fourth plant in

<sup>2</sup> The category of wood wastes in EC statistics include: wood packaging, sawdust and shavings, and other wood wastes such as bark, particle boards and other wood products (both hazardous and non-hazardous) (EC, 2010).

Germany (DE), generates only heat. In order to be able to compare the impacts and influence of additives in all four systems, a common functional unit was defined, representing the total exergy content delivered by each system. Exergy was chosen in order to account for the quality of different energy products. The functional unit (FU) was defined as “the production of 1 GJ of exergy (1 GJ<sub>ex</sub>)”. Additionally, this choice of FU avoids the allocation of impacts between functions, as recommended by the ISO 14044 standards, (avoid allocation of environmental impacts by including in the boundaries every function provided) (ISO, 2006b). Table 1 contains the amount of exergy produced by each system under study based on the net heat and electricity outputs. The exergy content of electricity is the same as the energy content. The exergy content of the heat is discounted by the Carnot efficiency, taking into account the differences of the temperature of the delivered (useful) heat and the ambient temperature. Further details about the exergy calculations are included in the Supplementary material.

### 2.1.2. System boundaries

The following activities were included into the system boundaries of every system under study: provision and pre-treatment of the biomass feedstock, transportation of the fuel to the power plant, operation and maintenance of the power plant, and transportation and disposal of waste (mainly ashes). The simplified system boundaries of the analyzed power plants are depicted in Fig. 1. Capital goods were excluded from the analysis, since no significant changes in infrastructure are expected when using additives. Detailed inventory flows for each power plant are contained in the Supplementary material.

### 2.2. Process description and data inputs: the baseline scenario

The main operation parameters of the power plants under study were gathered via a confidential questionnaire, in which information were asked for the technical characteristics of the power plants (such as installed capacity, planned and unplanned maintenance, type of boiler, operation modes, etc.), inputs and outputs during operation (energy, water, consumables, ashes, transportation distances for ash disposal) and information about the fuel supply chain (type of fuel, origin, transportation distance, etc.). Unless otherwise specified, the data was gathered considering the operation over one year (2015 or 2016, depending on the data availability). Such year was considered as the baseline year.

The LCAs were modeled in the software SimaPro 8.5.2, using the collected primary data as the foreground data. The main source for secondary data was the consequential ecoinvent 3.3 database (Weidema et al., 2013), supplemented with data obtained from literature. The quality of the foreground data was assessed using data quality indices (DQI) based on the Pedigree Matrix (Weidema and Wesnæs, 1996).

The main characteristics of the four analyzed systems are described in Table 2. Each system is identified with two letters, corresponding with the codes of the countries where they are located (SE, PL, AT and DE). The names of the power plant are not disclosed due to confidentiality issues.

**Table 1**  
Heat, electricity and exergy produced per year by the analyzed systems.

	SE	PL	AT	DE
Net electricity, GJ <sub>e</sub>	169,200	28,703	263,912	0
Net heat, GJ <sub>th</sub>	669,600	134,885	120,312	2088
Carnot efficiency of heat <sup>a</sup>	0.24	0.23	0.23	0.23
Total Exergy, GJ <sub>ex</sub>	342,059	60,730	292,478	496

<sup>a</sup> See the details in the SI.

Several assumptions regarding flue gas emissions were made: (1) particle size distribution was not provided by any system; therefore, an assumed share of 86% PM<sub>2.5</sub> was considered in every system attending to values reported in the EMEP/EEA air inventory book (sector 1.A.1. a Public electricity and heat production, technology Dry Bottom Boilers, fuel wood and wood waste) (EMEP/EEA, 2016a), (2) mercury and dioxin emissions were not provided for system PL and AT, therefore, values reported in the EMEP/EEA literature were used instead (EMEP/EEA, 2016a). The emissions due to the combustion of fuel oil (for start-up and back-up fuel in system SE and PL) and natural gas (for system AT) were modeled according to the emission factors of the EMEP/EEA emission inventory guidebook (EMEP/EEA, 2016b).

Particularities of each power plant and choice of marginal technologies in the consequential LCA are described in the following subsections. Detailed inventory tables (flow charts, background datasets used, data sources, DQI and amounts of inputs/outputs per FU) can be found in the Supporting information.

### 2.2.1. Choice of marginal technologies and multifunctionality

Following the consequential approach, the life cycle inventory data was modeled considering the marginal technologies providing the inputs to each system. The marginal technology is defined as “the technology actually affected by a small change in demand” (Weidema et al., 1999), and is usually determined considering the technologies with the lowest costs and that are able to respond to changes in demand by corresponding changes in supply (e.g. unconstrained technologies in terms of natural resources, technical limits, political constraints or market quotas) (Mathiesen et al., 2009). The marginal technologies for foreground data were identified using as guideline the 5-step procedure defined by Weidema et al. (1999), and are described in the following sections. The marginal inventory data corresponding to secondary data was modeled considering the corresponding datasets from the consequential ecoinvent v3 database.

The recycling processes in the system (e.g. recycling of ashes) were modeled by assuming substitution of products/functions somewhere else, i.e. by system expansion through substitution (Schrijvers et al., 2016). Details about products substituted by each system are contained in the next sections.

### 2.2.2. Description of the analyzed systems

System SE is a CHP plant with a nominal thermal output of 45 MW<sub>th</sub>, providing two energy products: (1) heat, to the district heat grid of a nearby city, and (2) electricity, to the Nord Pool grid (Sweden, Norway, Denmark and Finland). The CHP plant has a vibrating grate fired boiler used to produce superheated steam. The steam drives a steam turbine for electricity generation, following a conventional Rankine cycle.

The biofuel combusted in system SE is a mixture of 84 wt% of demolition wood (e.g. from old structures, old packaging and scrap wood that have been crushed or tiled) and 16 wt% of forest wood chips. Forest wood chips are considered unconstrained by-products of forest management, produced directly during harvesting (residual wood from logging).

The waste wood is obtained from the construction and demolition industry and from households (50% is collected in Sweden, 50% is imported from Norway). It is pre-treated to remove nails and other attached elements, and then shredded. Such wood waste is not landfilled in the northern European countries, and is typically not used for material recovery due to contamination (NL Agency, 2013). Therefore, it is considered as waste that would be in any case disposed through incineration with energy recovery. Accordingly, our CLCA model only includes the environmental burden of the pre-treatment and the transportation from the treatment plant

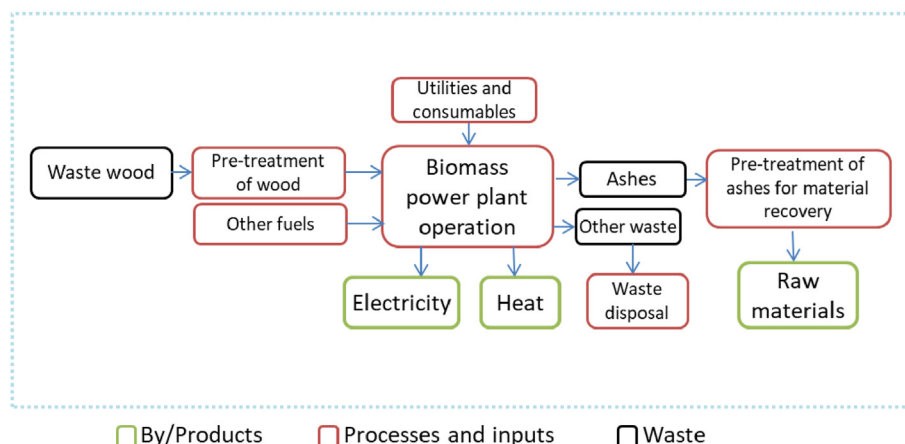


Fig. 1. System boundaries for the CLCA of the biomass power plants.

Table 2

Main characteristics of each biomass power plant without using resource-efficient additives.

Product system	SE	PL	AT	DE
Location	Sweden	Poland	Austria	Germany
Installed capacity, MW	22 MW <sub>e</sub>	1,2 MW <sub>e</sub>	10 MW <sub>e</sub>	0.8 MW <sub>th</sub>
Fuel input, GJ/yr	1,069,249	194,750	1,153,420	2373
Fuel mix (% in primary energy)	Waste wood (91%) and forest wood chips (9%)	Forest wood chips (100%)	Forest wood chips (45%), Residual dust from wood chipboard production (40%), Bark (7%), sunflower shells (5%), Chips and sawdust (3%)	Forest wood residues (100%)
Fuel transportation distance	Imported wood: 190 km Local wood: 30 km	50 km	55 km (in average)	115 km
Net combined energy efficiency	78.4%	84%	33.3%	88%
Flue gas cleaning (FGC)	Dust precipitator, Selective non-catalytic reduction, desulphurization	Dust precipitator (Multicyclone)	Dust precipitator (Cyclone), dust filter, and desulphurization	Dust precipitator (multicyclone)
FGC agents	Ammonia, Sodium hydroxide	—	Urea, Calcium hydroxide	—
Planned downtime, h/yr	1550	240	378	100
Unplanned downtime in baseline year, h/yr	100	160	109	0

to the power plant.

All utilities and additives/chemicals used in the operation and the maintenance (O&M) of the power plant are accounted for, as indicated in Fig. 2.

System PL is a tri-generation plant with a nominal thermal output of 5.5 MW<sub>th</sub>, that provides heat and electricity to a hotel located within a low populated area in Poland (also cool water,

which was left out of the boundaries of the study). The plant follows an organic Rankine cycle (ORC), and counts with a grate firing biomass boiler and two back-up fuel oil boilers.

System PL burns forest wood chips, which were modeled similarly as in system SE. The inputs and outputs from plant operation are depicted in Fig. 3. All the ashes produced in the operation of the power plant are used for hardening and

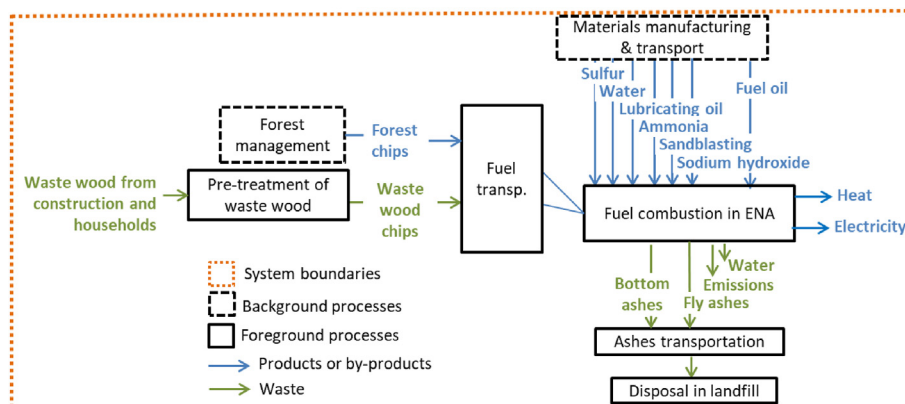


Fig. 2. Overview of the process tree and system boundaries for baseline scenario SE.



stabilization of the soil surface of internal roads and squares. Therefore, it was considered that the wood ashes would be used to substitute limestone in the production of bituminous asphalt pavement (da Costa et al., 2019). The model included the transportation of the ashes, their pretreatment, and the avoidance of limestone.

System AT is part of a wood-based panel factory, and produces heat and electricity for self-consumption. The heat is used to dry the raw materials, and the electricity is used to run the manufacturing factory. The system is designed for a nominal thermal output of 40 MW<sub>th</sub>, follows a conventional Rankine cycle, and counts with a grate fired biomass boiler and a back-up natural gas boiler.

The fuel used in AT is a blend of fresh residual wood (forest chips and bark), residues from the manufacturing processes (screening dust, sawdust and chips), and agricultural waste (sunflower shells). Bark, sawmill chips and sawdust are by-products of a sawmill, and are a constrained resource. They are mainly used for particle board production. An increased use of sawdust for bioenergy will lead to lower amount of sawdust and chips available for particle boards, resulting in an increase of forest wood chips (virgin wood) demand for particle boards. Therefore, these fuels were modeled considering the changes in the demand of their equivalent marginal substitute, which is virgin wood chips.

The screening dust is residual dust produced in the activities carried out inside the factory. As reported by the company, this residual dust is a waste without further economic value. Therefore, the screening dust is modeled as waste which would be in any case used for energy recovery, with no pretreatment required. Sunflower hulls are agricultural residues obtained in the dehulling process of sunflower seeds. The obtained hulls are considered as residues with low economic value but relatively high heating value (LHV of 16.4 MJ/kg w. b.), used either to obtain process heat (by burning) or for minor agricultural purposes (mulching and adding fiber to animal diets). In this assessment, sunflower shells are considered as a waste of sunflower farming which would be in any case used for energy, and no changes (i.e. inputs or outputs) were modeled except for the primary energy content and the transportation.

Other inputs and outputs from the operation of the plant are depicted in Fig. 4. Most (95%) of the bottom ashes are recycled for concrete production. Therefore, 95% of the bottom ashes were

modeled through the products that would be replaced in the market, and the electricity consumption required to recycle them. The rest of the bottom ashes and the fly ashes are landfilled.

System DE is a small-scale boiler (0.8 MW<sub>th</sub>) located in Germany. It provides steam for space heating to the surrounding industrial neighbors for 8 months of a year, from September to April. The system burns pre-dried forest residues pre-dried using the excess heat of a nearby biogas plant (moisture content reduced from 35% to 8%). Forest residues are direct by-products of forest management, assumed to be produced directly during harvesting.

The inputs and outputs during the power plant operation are depicted in Fig. 5. Due to unavailability of yearly average data, the flue gas emissions were calculated considering concentration values measured during the tests performed in the REFAWOOD trial period (with wood logging residues). The combustion tests were performed without additives and the emissions were based on half hour mean values. The ashes resulting from wood combustion are collected from the bed of the boiler (bottom ashes) and the multi-cyclone used as flue gas cleaner (fly ashes). All the ashes are managed together with the municipal solid waste (sanitary landfilled).

### 2.3. Resource-efficient additives scenarios

Different low cost additives (gypsum waste, halloysite and coal fly ash) were tested as additive agents in the analyzed systems within the REFAWOOD project. The changes of boiler performances, direct emissions and dust fractions were monitored and analyzed. Tests were done in short period of time (e.g. in weeks). The observations from the tests were extrapolated to a period of one year of operation. The amounts of each additive in each scenario, together with the expected energy production, are summarized in Table 3. The optimum amount of additive for each fuel mix and power plant was determined by considering fundamental ash chemistry, thermochemical analyses and experimental evaluations (lab-scale tests) (REFAWOOD, 2019). System SE already used commercial elementary sulfur as additive to decrease ash-related problems in the boiler. Therefore, the additive scenario for SE was aimed at comparing the environmental impacts of using commercial sulfur versus (represented in the baseline scenario) using a resource-efficient additive (gypsum waste, represented in the additive scenario).

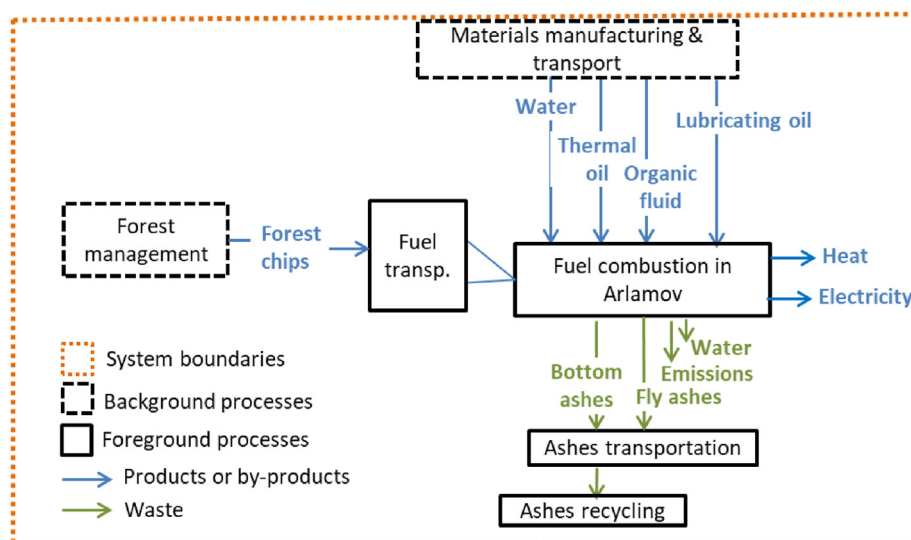


Fig. 3. Overview of the process tree and system boundaries for baseline scenario PL.

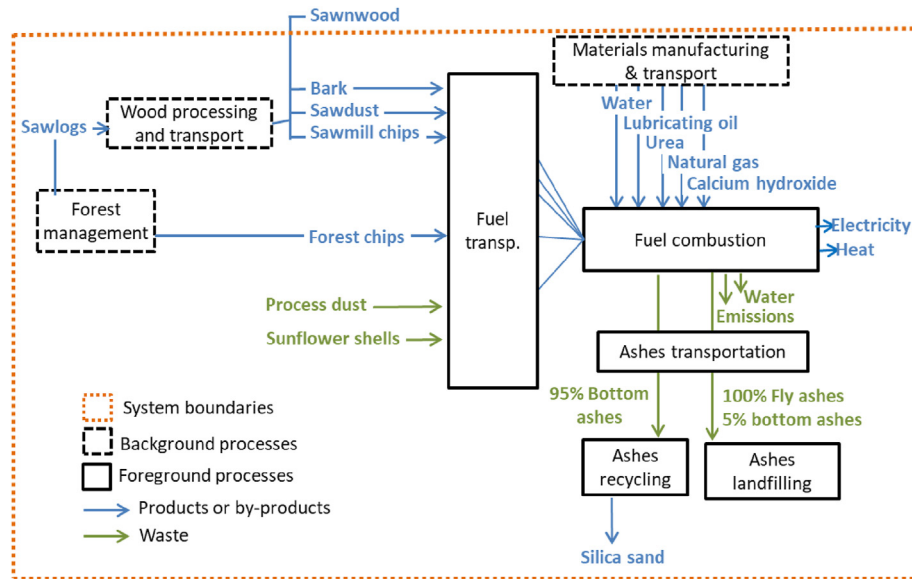


Fig. 4. Overview of the process tree and system boundaries for baseline scenario AT.

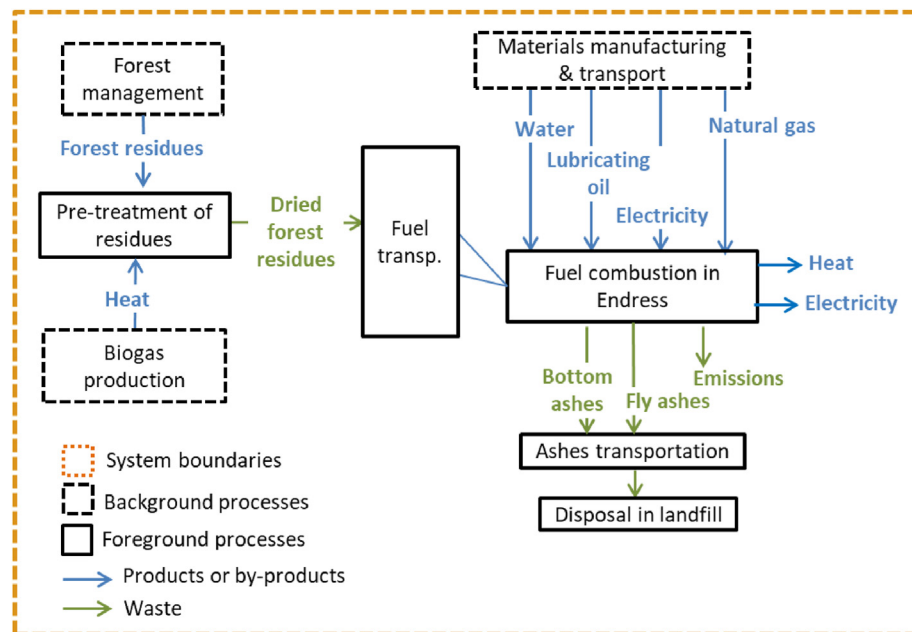


Fig. 5. Overview of the process tree and system boundaries for baseline scenario DE.

Table 3

Main characteristics of the resource-efficient additive scenarios for each system under study.

	SE		PL		AT		DE	
	Gypsum	Gypsum	Halloysite	Halloysite	Gypsum	Coal Fly Ash	Gypsum	Halloysite
Additives, t/yr	130	231	231	231	690	2060	1827	4002
Fuel primary energy, GJ/yr	1,069,249	1,153,420	1,153,420	1,153,420	194,750	194,750	2373	2373
Net electricity generated, MWh/yr	47,000	8068	8420	8420	75,510	74,409	—	—
Net heat, GJ <sub>th</sub> /yr	669,600	136,491	142,432	142,432	123,924	122,118	2088	2088
Estimated increase in energy efficiency <sup>a</sup>	0%	+1%	+4.7%	+4.7%	+1%	+0.5%	+1%	+3.5%
Estimated reduced planned downtime <sup>a</sup> , h/yr	—	0	0	0	132 (35% reduction)	95 (25% reduction)	20 (2% reduction)	20 (2% reduction)
Estimated reduced unplanned downtime <sup>a</sup> , h/yr	—	150 (94% reduction)	150 (94% reduction)	150 (94% reduction)	38 (35% reduction)	27 (25% reduction)	—	—

<sup>a</sup> Increase in energy efficiency and reduced downtime could not be measured over an extended period of time. Values were estimated by the project partners considering the findings obtained within the project, e.g. results from deposit and corrosion probes.

The additives scenarios were modeled considering the changes that the additives produce in the amount of flue gas emissions, ashes generated, and flue gas cleaning agents. An exception was made for system SE, where the REFAWOOD tests indicated inconclusive results regarding the effects of using gypsum as additive. According to previous research by the project partners, the decrease of ash-related problems (fouling, slagging and corrosion) due to gypsum and sulfur are expected to be the same (Paulrud et al., 2015). The data providers also reported that the amount of sodium hydroxide (for desulphurization), direct emissions after flue gas treatment, and other activities in the power plant would remain the same for both sulfur and gypsum. Therefore the only modeled change in SE was the input of gypsum waste instead of commercial sulfur.

By application of resource-efficient additives, a rise in energy production was achieved due to increased energy efficiency and decreased downtime. Consequently, the additives scenarios were modeled considering that the additional supply of heat and electricity by the systems under study would displace the corresponding marginal technologies in each market. For the electricity generated, the marginal technology is represented by the mix of marginal technologies providing electricity to the national markets, as defined by the corresponding national electricity mix within ecoinvent v3.3 consequential datasets. In the case of heat, the marginal technology depends on the characteristics of the power plant and the national market for heat technologies. In system SE, heat and electricity is supplied to a district heating system. It is therefore assumed that the heat displaces heat produced by a 5 MW wood chips boiler, since it is the main dominant fuel and technology for heat district supply in Sweden (Werner, 2017), that can adapt to a change in demand. In system PL, where heat and electricity is supplied to an isolated hotel, the wood-based heat displaces the use of a fuel oil boiler located within the power plant. For system AT, the produced heat displaces the use of a natural gas boiler, which is the back-up fuel used in the power plant, can easily adapt to a change in demand, and is the main dominant fuel in Austria for CHP and heat generation (Fleiter et al., 2016). In the case of system DE, heat is assumed to displace heat produced by a natural gas boiler, which is also the main technology supplying heat to the industrial sector in Germany (and expected to increase supply in the following decade) (Fleiter et al., 2017).

The increase in energy efficiency could not be measured onsite, thus, conservative values were estimated by the project partners considering the findings obtained within the project. These numbers should be taken only as potential scenarios and not as prediction of real operation. The increase in energy efficiency was assumed to be proportional in both heat and electricity. Due to the high uncertainty on the estimated energy efficiency increase, a sensitivity analysis was performed considering  $\pm 50\%$  of the estimated efficiency increase, see section 3.2.1. A Monte Carlo uncertainty analysis was also performed on the comparison between the additives scenarios and their corresponding baseline scenario. Such analysis was aimed at evaluating the influence of data uncertainty propagation into the conclusions of the study (further details of the analysis can be found in the Supporting Information).

Most of the additives were modeled as waste that would have otherwise been landfilled (i.e. landfilling of such material is avoided). Gypsum waste additive derives from either the construction industry, or from power plants with desulphurization systems. The coal fly ashes were modeled as waste coming from a coal power plant located 30 km away from system AT. Halloysite was modeled differently depending on the system. The halloysite additive used in PL is a product mined from a site located at 415 km of the power plant. Since data about halloysite mining was not available, mining of clay was used as proxy. In the case of system DE, halloysite was

modeled as a waste coming from the biogas filter of a nearby biogas plant (1 km distance). Further details and datasets used to model the changes in each system are available in the Supporting information.

### 3. Results

#### 3.1. Baseline scenario

The environmental impacts of the four systems in the baseline scenario are described in Table 4. The breakdown contribution of each life cycle activity is shown in Fig. 6. The results indicate different environmental profiles per functional unit for each power plant, due to their different fuel characteristics, transportation distances, operation parameters and combustion emissions.

Systems SE, PL and AT present a similar range of results for most of the environmental categories (an exception is Land use in system PL). However, system DE has higher impacts in every impact category. Such higher impacts are primarily due to a combination of low exergy efficiency (the system produces only heat), longer fuel transportation distance, and high amount of fuel gas emissions per functional unit.

As observed in Fig. 6, most of the environmental impacts caused by the analyzed systems are originated in the O&M phase, followed by the fuel procurement phase. The contribution of the transportation phase is more relevant for system DE, due to the longer distance from the fuel source (150 km of transportation causes 30%–50% of the total impacts in the categories climate change, human toxicity, CED and eutrophication). The disposal of ashes has a minor contribution to the impacts of the analyzed systems. However, systems SE and DE present higher absolute impacts in this phase when compared to PL and AT, which have benefits from the ash disposal due to the recycling of ashes (instead of land-filling). Every system has a high contribution of the fuel procurement to the land use category, due to the intensive forest occupation required to harvest forest wood chips.

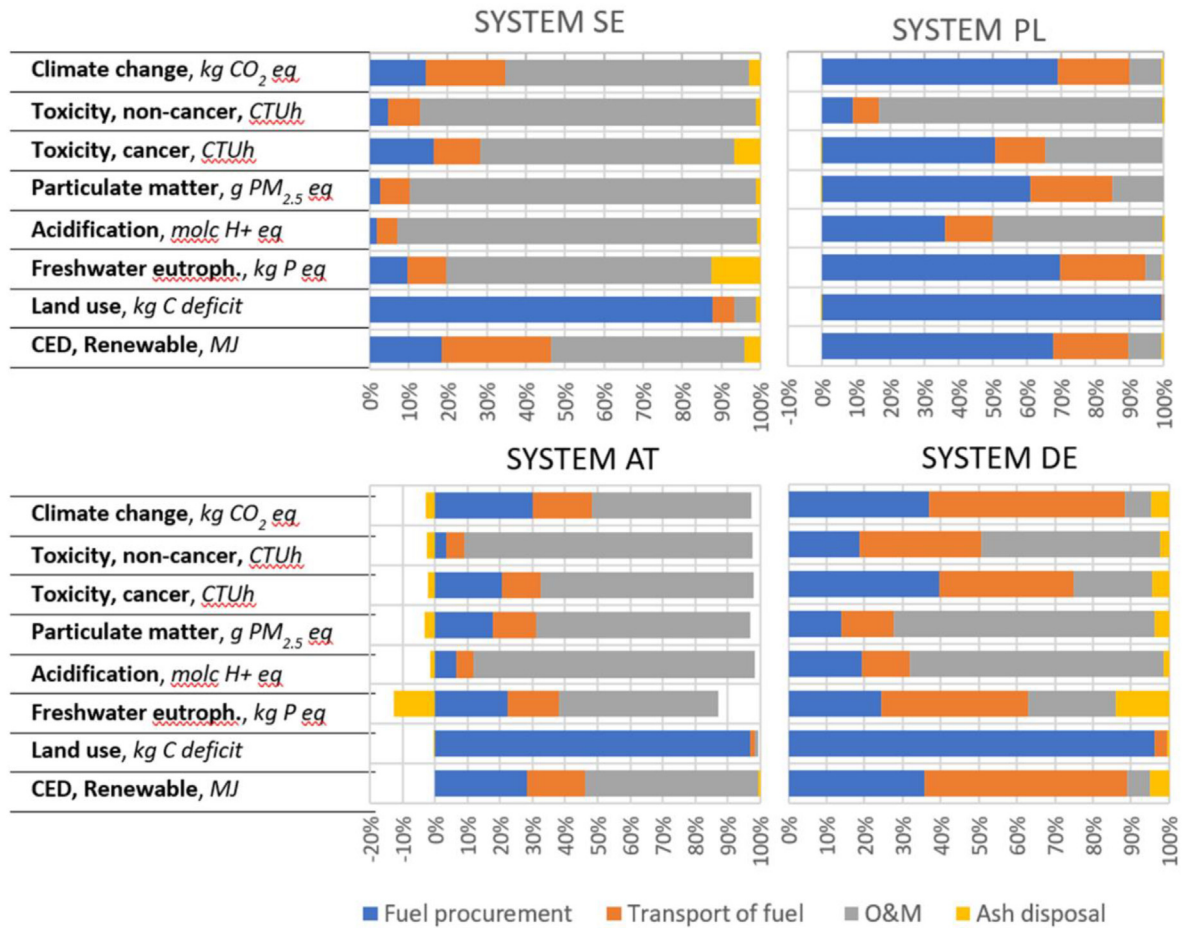
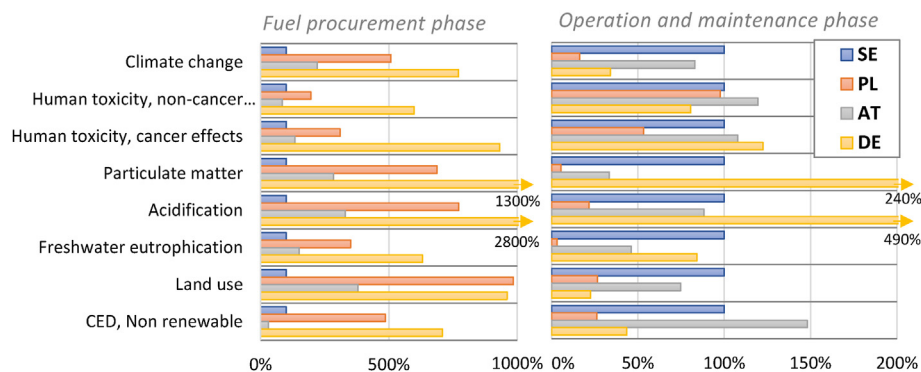
Fig. 7 shows the comparison of the characterized impacts from the fuel procurement phase and from the O&M phase, for every analyzed system, per functional unit and for the baseline scenario. Results in every impact category and system are normalized to the results of system SE. As observed in Fig. 7, the fuel procurement phase has lower impacts in the systems SE and AT than in the systems PL and DE. Such differences are due to the higher content of waste within the fuel mix (91% demolition wood waste in SE, and 45% of mixed waste in AT). The fuel procurement impacts are especially higher in system DE. Such higher impacts are due to several factors: (1) between 20% and 65% of the impacts (depending on the category) are due to the fuel drying pre-treatment, and (2) as indicated before, the power plant has lower fuel efficiency per functional unit.

Contrary to the fuel procurement phase, the systems with higher contribution of impacts from O&M are SE and AT, followed by DE in several categories. The higher impacts of SE and AT are associated with two factors: (1) combustion emissions present higher amount of pollutants probably due to contamination in the waste fuel, and (2) these systems use flue gas cleaning agents (ammonia, urea and/or sodium hydroxide) whose production contributes to the categories of climate change, eutrophication, and CED. O&M (operation & maintenance) impacts in system PL are especially low due to the combination of a clean fuel mix and a high fuel efficiency per functional unit. Acidification and particulate matter impacts are high in DE due to a combination of low dust removal efficiency, absence of a desulphurization process, and low exergy efficiency.

System SE presents relatively high impacts in climate change

**Table 4**Characterized environmental impacts per FU of the four systems under study, in the baseline scenario (no additives). FU = 1 GJ<sub>ex</sub>.

Environmental impact categories	Unit/GJ <sub>ex</sub>	SE	PL	AT	DE	Visual comparison
Climate change	kg CO <sub>2</sub> eq	11.3	12.0	11.4	34.1	
Human toxicity, non-cancer effects	CTUh	5.35E-06	5.40E-06	5.91E-06	7.91E-06	
Human toxicity, cancer effects	CTUh	1.31E-07	1.31E-07	1.35E-07	5.08E-07	
Particulate matter	kg PM <sub>2.5</sub> eq	2.59E-02	8.03E-03	1.10E-02	7.05E-02	
Acidification	molc H <sup>+</sup> eq	3.15E-01	1.26E-01	2.86E-01	8.69E-01	
Freshwater eutrophication	kg P eq	8.07E-04	3.73E-04	3.87E-04	2.01E-03	
Land use	kg C deficit	202.0	1759.0	686.1	1770.3	
CED, Non renewable	MJ	138.4	189.0	191.1	506.7	

**Fig. 6.** Contribution of each life cycle stage to the environmental impacts per FU of each system under study (baseline scenario). FU = 1 GJ<sub>ex</sub>.**Fig. 7.** Comparison of the characterized impacts for the fuel procurement phase and operation and maintenance phase, in every analyzed system, for the baseline scenario and per functional unit. System SE is set at 100%.



due to the O&M phase. Even though biomass is considered to be carbon neutral, the O&M phase is responsible for 7.1 kg CO<sub>2</sub> eq/GJ<sub>ex</sub> (62% of the system's life cycle impacts in climate change). Almost 40% of such climate change impacts are associated with the emission of N<sub>2</sub>O during operation of the plant. The nitrous oxide emissions may be originated during the combustion of the fuel because of low temperatures of around 730 °C in the combustion chamber (Bates, 1998), but also during the flue gas cleaning process, due to reaction with reduction agents or to high temperatures when reducing NO<sub>x</sub> emissions (IrBEA, 2016). Additionally, nitrous oxides can also be formed from reduced sulphates (Bates, 1998). While the amount of nitrous oxide released to the air (in the form of N<sub>2</sub>O) is relatively low, it is a GHG with a high global warming potential, causing 2.7 kg CO<sub>2</sub> eq/GJ<sub>ex</sub> in system SE. The rest of the O&M climate change impacts in system SE are due to fossil CO<sub>2</sub> emission caused by back-up fuel oil and to the ammonia's production (used for DeNO<sub>x</sub> flue gas cleaning).

### 3.2. Resource-efficient additives scenarios

Table 5 describes the changes in the characterized environmental impacts of the four analyzed systems when operating with resource-efficient additives. System SE presents a negligible change (i.e. less than −0.01%) with respect to the baseline scenario, which is only related to the substitution of commercial sulfur by gypsum waste.

As indicated in Table 5, the environmental impacts of systems PL, AT and DE in the additive scenarios are generally lower than in the baseline scenario, except for the acidification and eutrophication category. Such decreased impacts (median decrease of 3% and average decrease of 12% per category) are due to the increased efficiency (linked with the marginal technology displacement for heat and electricity) and the decrease in the flue gas emissions of some pollutants, which compensates the additional impacts of the additives transportation, ashes management, extra flue gas cleaning agents, and additional emissions. However, the use of gypsum increases the emission of acidifying pollutants in DE (120% increase with respect to baseline) and very slightly in systems PL and AT (0.1% increase), due to higher SO<sub>2</sub> emissions. The high increase of acidification in system DE relates primarily to the absence of a desulphurization unit, which is not usually present in such small size systems. Eutrophication impacts also increase slightly in systems AT and DE, mainly due to the additional transportation of additive and ashes.

The benefits of using additives are specially high in system PL, which even presents net negative impacts in climate change (−106%) and non-renewable CED (−107%). Such environmental benefits are derived from the substitution of the marginal technologies for heat and electricity, whose environmental impacts per functional unit are much higher than in the systems under study.

Therefore, the increase of energy efficiency leads to high benefits due to the avoidance of other more polluting technologies.

As observed in Table 5, the benefits are generally higher for halloysite (due to the associated higher energy efficiency), followed by gypsum. The benefit of using halloysite in systems PL and DE is especially high for the particulate matter category (32–54% decrease). Such decrease of impacts is directly related to the expected decrease of dust in the flue gas emissions, where tests indicated a significant decrease of dust emissions (up to 50%) due to the use of gypsum and halloysite. Such decrease is more relevant for the system PL, whose marginal technology has higher impacts in particulate matter than the system under study.

When looking at the results with coal fly ashes, the lower expected increase in energy efficiency leads to higher impacts (or lower benefits) than the gypsum scenario, and in some categories, than the baseline scenario. Additional impacts for the coal fly ashes are mainly due to the increased use of ammonia, and to the coal fly ashes landfilling (and transportation).

#### 3.2.1. Sensitivity analysis on the increase of energy efficiency

The results in previous section indicated that most of the benefits derived from the use of additives are due to the increase of energy supplied by the systems. Therefore, a sensitivity analysis was conducted on the value estimated for the increase of energy efficiency due to the use of additives. Two sensitivity scenarios were explored: (1) Low efficiency increase, considering half of the reported efficiency increase (−50%), and (2) High efficiency increase, considering 1.5 times the reported efficiency increase (+50%). The energy efficiency increase for each scenario, additives and systems are described in Table 6. The scenario titled as MED (Medium) correspond to the additives scenario described above (see section 3.2). No sensitivity analysis was performed for system SE, since the energy efficiency was not expected to change due to the substitution of commercial sulfur by gypsum.

The results of the sensitivity analysis, per impact category, type of additive and evaluated system are depicted in Fig. 8. The charts depict the absolute difference (increase or decrease) of impacts in the additives scenario with respect to the baseline scenario. Results at the left of the vertical axis indicate a decrease of impacts (per FU) because of the use of additives, while results at the right of the vertical axis indicate an increase of impacts. The grey bars represent the medium scenario (as described in section 3.2), the green dots correspond to the high efficiency scenario, and the red dots correspond to the low efficiency scenario. As observed in the figure, when considering a conservative scenario (low increase of energy efficiency), the additives scenarios are still performing better than the baseline scenario, except for the coal fly ash additive. Likewise, when considering an optimistic scenario (high), the additives scenarios performing worse than the baseline are still performing worse in most of the impact categories. An exception is system DE

**Table 5**

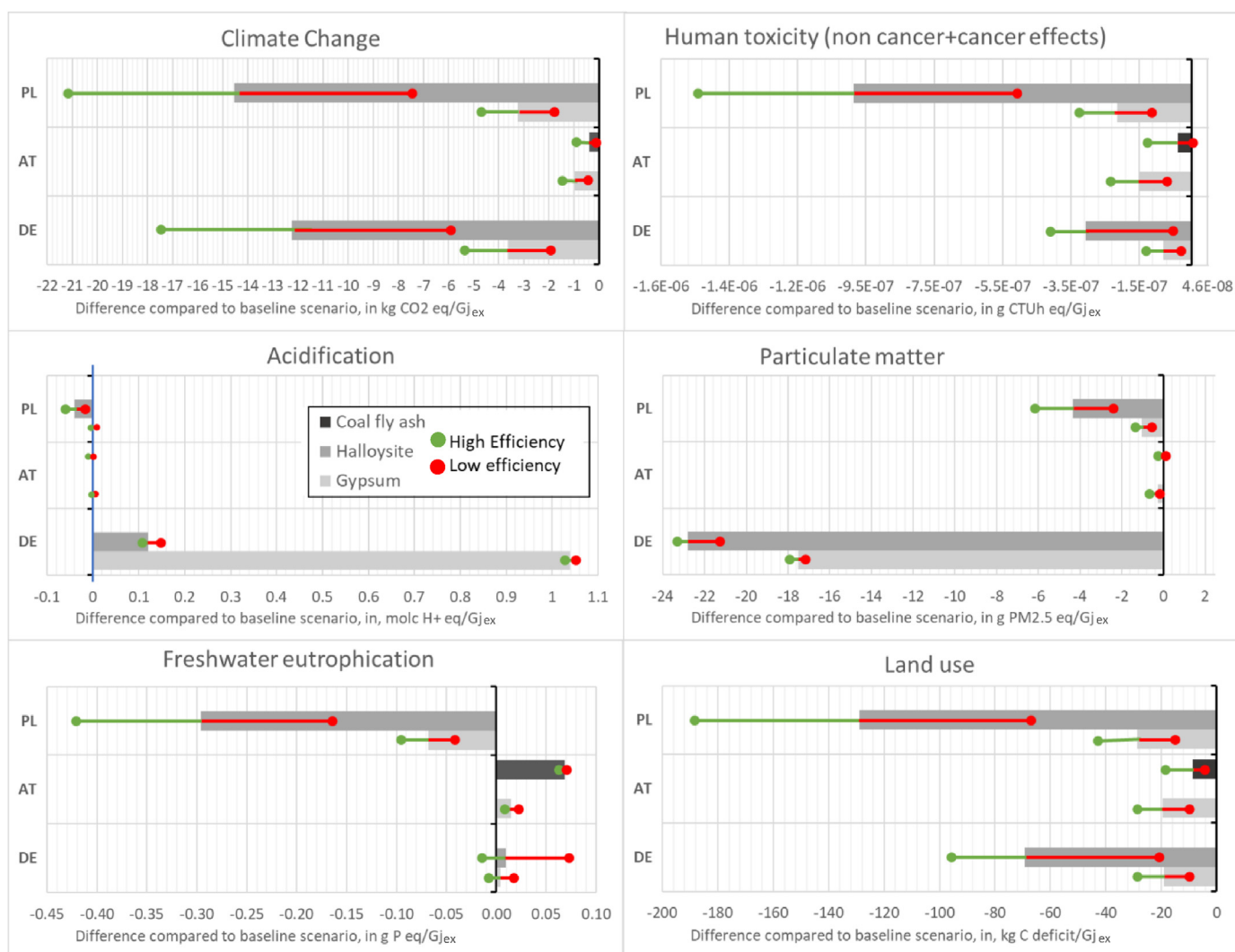
Changes in the characterized environmental impacts of the four analyzed systems when operating with resource-efficient additives. The percentages indicate the increase or decrease in the impacts compared to the baseline scenario.

	SE			PL			AT			DE		
	Baseline (sulfur)	Gyp. (0.5%)		Baseline	Gyp. (1%)	Halloy. (1%)	Baseline	Gyp. (1%)	Coal ash (3%)	Baseline	Gyp. (1.5%)	Halloy. (3%)
<b>Climate change, kg CO<sub>2</sub> eq</b>	11.3	<−0.1%		12.0	−27%	−121%	11.4	−8.4%	−3.3%	34.1	−11%	−36%
<b>Toxicity, non-cancer, CTUh</b>	5.35E-06	<−0.1%		5.40E-06	−3.8%	−17%	5.91E-06	−2.6%	−0.8%	7.91E-06	−1.0%	−3.6%
<b>Toxicity, cancer, CTUh</b>	1.31E-07	<−0.1%		1.31E-07	−8.5%	−38%	1.35E-07	−1.7%	+2.8%	5.08E-07	−1.3%	−4.6%
<b>Particulate matter, g PM<sub>2.5</sub> eq</b>	2.59E-02	<−0.1%		8.03E-03	−13%	−54%	1.10E-02	−2.4%	−0.0%	7.05E-02	−25%	−32%
<b>Acidification, molc H<sup>+</sup> eq</b>	3.15E-01	<−0.1%		1.26E-01	−0.6%	−32%	2.86E-01	+0.1%	−0.9%	8.69E-01	+120%	+14%
<b>Freshwater eutroph., kg P eq</b>	8.07E-04	<−0.1%		3.73E-04	−18%	−79%	3.87E-04	+3.8%	+18%	2.01E-03	+0.2%	+0.5%
<b>Land use, kg C deficit</b>	202.0	<−0.1%		1759.0	−1.6%	−7.3%	686.1	−2.8%	−1.3%	1770.3	−1.1%	−3.9%
<b>CED, Non-renewable, Mj</b>	138.4	<−0.1%		189.0	−23%	−107%	191.1	−9.5%	−3.5%	506.7	−11%	−40%

**Table 6**

Values for net energy efficiency increase with respect to the baseline scenario, as considered in the sensitivity analysis.

	GYPSUM			HALLOYSITE			COAL FLY ASH		
	LOW	MED	HIGH	LOW	MED	HIGH	LOW	MED	HIGH
System PL	+0.5%	+1%	+1.5%	+2.35%	+4.7%	+6.35%			
System AT	+0.5%	+1%	+1.5%				+0.25%	+0.5%	+1%
System DE	+0.5%	+1%	+1.5%	+1.75	+3.5%	+5.25			

**Fig. 8.** Sensitivity analysis on the increase of energy efficiency due to the use of additives in each evaluated system, per GJ of exergy ( $\pm 50\%$ ). The values represent the absolute difference of impacts per functional unit with respect to the baseline scenario.

in the freshwater eutrophication category, where a high efficiency scenario would provide a decrease of impacts due to the use of additives (instead of an increase, as described in Table 5). In such scenario, the increased impacts due to increased transportation of additives and ashes would be compensated by the increase in energy supply.

The impact categories more sensitive to the increase of energy efficiency are human toxicity, land use, freshwater eutrophication and climate change. Such higher sensitivity is due to the higher contribution of the electricity and heat marginal technologies in such impact categories.

## 4. Discussion

### 4.1. Data uncertainty

To estimate the effect of data uncertainty propagation, a Monte Carlo uncertainty analysis was performed on the comparison between the baseline and additives scenarios. By considering 500 iterations and 95% of confidence interval, the Monte Carlo analysis indicated a very high confidence level in the conclusions for the climate change and land use categories, where 100% of the iterations presented better performance for the additives scenario than

for the baseline scenario (in every system). The categories that presented worse performance for the additives scenario than for the baseline scenario (acidification and freshwater eutrophication) indicated lower confidence level in the results, since up to 15% of the iterations indicated a better performance for the additives scenario than for the baseline scenario. The lowest confidence level was obtained in human toxicity, where at least 20% of the iterations indicated different conclusions than the ones of the study (i.e. additives scenarios were performing worse). Detailed tables describing the uncertainty results are included in the Supporting Information.

It should be noted that the emissions values present certain uncertainties due to the absence of direct long term measurements in the power plants. Information of only a few pollutants was provided by each system (mainly CO, NO<sub>x</sub>, SO<sub>2</sub>, N<sub>2</sub>O, HCl, and dust) which were initially measured to ensure the compliance with legally defined emission limits. Therefore, several assumptions and secondary data had to be used for modelling some of the combustion emissions.

#### 4.2. Model uncertainty

The analysis indicated different environmental profiles for each of the analyzed systems, depending mainly on the nature of the fuel, transportation distance, energy efficiency of the plant, and flue gas emissions. Systems burning waste wood fractions presented higher impacts in the O&M phase than those burning fresh residues, while impacts from the fuel procurement phase were higher for systems burning fresh residues. This study assumed that the wood waste from construction and demolition and screening wood dust in systems SE and AT are waste that would in any case treated through energy recovery. However, such waste is sometimes also used for material recovery. Including such alternative use in the consequential model would lead to an increase in the impacts allocated to the fuel procurement phase for both SE and AT Systems.

In addition, an attributional LCA was parallelly performed by the authors on each of the energy systems, with the goal of exploring the role of additives without interaction with other systems. Conclusions of such attributional LCA's on the additives scenarios were similar to the consequential LCA presented in this study, but indicated a lower reduction of impacts, since neither the displacement of marginal technologies nor the recycling of ashes were considered (REFAWOOD, 2019).

#### 4.3. The use of resource-efficient additives to improve boiler performance

The results indicated that using resource-efficient additives

would reduce the impacts of producing heat and electricity from wood wastes and residues (except for acidification and eutrophication). Impact reduction was higher for halloysite and for system PL, where the increase of energy efficiency displaced a highly polluting marginal technology for electricity and heat generation.

However, results between different power plants and additives are not fully consistent, due to differences in power plant operations (e.g. different flue gas cleaning systems), marginal technologies for energy generation, fuel origin, and mostly, to different results in the tests measurements. Additionally, the flue gas emissions considered in the additives scenarios correspond to short-term preliminary measurements that should be validated by longer periods of trials (over months).

Since the potential increase in energy efficiency presented high uncertainty, a sensitivity analysis was performed considering  $\pm 50\%$  of the reported increase in energy efficiency. Such analysis indicated that, although absolute difference of impacts can significantly change, the conclusions remain mostly the same (benefits and/or impacts would change in the same direction).

The REFAWOOD project also explored the cost reductions that could be achieved through the use of additives, due to reduced costs for maintenance, increased efficiency, and increased lifetime of the boiler components. Such analyses indicated a range of cost reductions between 19,000 and 60,000 €/year for system PL, 19,000–149,000 €/year for system AT, and 900–5500 €/year for system DE, depending on the additive and different scenarios of energy efficiency increase. Such analyses suggest that the use of additives can provide significant cost reductions for plant owners next to the potential environmental impact reduction.

#### 4.4. Potential benefits of using additives at a European scale

The EU28 is currently treating 23 Mt of wood wastes through energy valorization (Eurostat, 2019). Assuming that the power plants analyzed in this study are a representative sample of the different energy plants burning wood wastes and residues in Europe, potential environmental savings of using additives at a European level were estimated. The calculated potential savings in every impact category, considering the low efficiency and high efficiency scenarios (see section 3.2.1), are indicated in Table 7. Results suggest that the use of gypsum as additive could potentially save between 47,600 t CO<sub>2</sub> and 201,600 t CO<sub>2</sub> eq per year, while the use of halloysite could potentially save between 192,000 t CO<sub>2</sub> eq/yr and 2,034,000 t CO<sub>2</sub> eq/yr.

### 5. Conclusions

The consequential LCA carried in this study resulted in different environmental profiles for each of the analyzed systems, depending

**Table 7**

Potential yearly environmental savings of using gypsum and halloysite at a European scale (assuming each year 23 Mt of wood waste needs to be treated).

Categories	Unit/year	Potential savings with Gypsum <sup>a</sup>		Potential savings with Halloysite <sup>a</sup>	
		LOW efficiency scenario	HIGH efficiency scenario	LOW efficiency scenario	HIGH efficiency scenario
Climate change	kg CO <sub>2</sub> eq	−4.76E+07	−2.02E+08	−1.92E+08	−2.03E+09
Human toxicity, non-cancer	CTUh	−5.77E−03	−2.42E+01	−1.23E−02	−1.31E+02
Human toxicity, cancer	CTUh	−7.14E−05	−6.48E−01	−6.59E−04	−6.93E+00
Particulate matter	kg PM <sub>2.5</sub> eq	−3.29E+01	−8.24E+04	−6.36E+01	−6.10E+05
Acidification	molc H <sup>+</sup> eq	5.05E+02	−2.89E+05	−4.12E+02	−5.71E+06
Freshwater eutrophication	kg P eq	9.18E−01	−9.31E+02	−4.10E+00	−4.03E+04
Land use	kg C deficit	−8.31E+05	−3.05E+09	−1.69E+06	−1.79E+10
CED, Non renewable	MJ	−1.71E+06	−6.58E+09	−2.94E+06	−3.30E+10

<sup>a</sup> Calculated considering the total exergy produced by wood wastes in Europe in 2015 and the average environmental savings produced in the systems AT, PL and DE per exergy produced, for each scenario. See Supporting information for more details about the calculations.

mainly on the nature of the fuel, transportation distance, energy efficiency of the plant, and flue gas emissions. Results indicated that recycling or landfilling the wood ashes has a low relative contribution to the environmental profile of producing 1 GJ of exergy, where the procurement of the fuel and the combustion emissions have the higher contributions.

This study found that the use of resource-efficient additives (gypsum waste, halloysite and coal fly ash) could decrease the environmental impacts of producing heat and electricity from wood wastes, especially when using halloysite as additive. The decrease is mainly due to an increase in energy generation that displaces other more polluting technologies for energy generation. However, the use of additives (especially gypsum) could increase the acidifying emissions in the flue gas, and would be only recommended in power plants with efficient desulphurization gas cleaning systems. The change of commercial sulfur per gypsum waste as additive has a negligible impact in the environmental profile of the analyzed product. These results are, however, presenting uncertainties in the assumed increase of energy efficiency, and are based on short-term measurements that should be validated with emission data from long-term tests. Nevertheless, the conclusions of the study were validated and deemed robust through a sensitivity analysis in the energy efficiency, and an uncertainty analysis on the inventory data.

Using mineral and sulfur containing additives, such as halloysite and gypsum, would decrease the environmental impacts of producing energy from waste biomass CHP plants. It is unknown how many power plants could benefit from this measure in Europe, but gross estimations indicated that using additives in waste wood incineration could lead to potential GHG emission savings up to 2.03 Gt CO<sub>2</sub> eq/yr (using halloysite for a high efficiency scenario). Future work could focus on investigating the effects of using low-cost additives in incineration plants burning municipal solid waste.

### Credit author statement

**Blanca Corona:** Investigation, Validation, Writing -Original Draft. **Li Shen:** Supervision, Project administration, Writing - Review & Editing. **Peter Sommersacher:** Investigation, Writing - Review & Editing. **Martin Junginger:** Writing - Review & Editing, Supervision, Funding Acquisition.

### Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2020.120948>.

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