REFAWOOD- Economic and environmental impacts of using additives for reducing ash related operational problems- Case study of ENA power plant

B. Corona, L. Shen, M. Junginger
Utrecht University, Copernicus Institute of Sustainable Development

A. Compeer, A. Hoogendoorn
Avans University of Applied Sciences

Report :
REFAWOOD report for WP4

REFAWOOD- Economic and environmental impacts of using additives for reducing ash related operational problems- Case study of ENA power plant

B. Corona, L. Shen, M. Junginger
Utrecht University, Copernicus Institute of Sustainable Development

A. Compeer, A. Hoogendoorn
Avans University of Applied Sciences

Summary

This report is one of the deliverables for the REFAWOOD project, within the work package *WP4 Analysis of sustainability of the value chain* within the REFAWOOD project. The goal of WP4 is to determine the environmental and economic impacts throughout the entire supply chain of using various additives (gypsum, sulphide ore waste, halloysite) in waste wood CHP/heating plants. The environmental analysis was performed by Utrecht University, while the economic analysis was performed by Avans University of Applied Sciences.

This report contains the environmental and economic analysis of a heating plant located in Sweden, using demolition waste wood as fuel. The impacts of using low cost additives are estimated by comparing a baseline scenario (operating with commercial sulphur as additive), with an additive scenario using waste gypsum.

The environmental impacts were estimated through Life Cycle Assessment, considering 1 MJ of heat as functional unit. The impacts in climate change, acidification, particulate matter, freshwater eutrophication, human toxicity and cumulative energy demand were calculated using the ILCD midpoint impact evaluation method. Primary data for the baseline scenario was collected from the power plant operators, and emission data for the additive scenario was collected from onsite measurements performed within the REFAWOOD project. A sensitivity analysis was performed on the allocation parameter for electricity and heat (exergy or energy).

The results for the baseline scenario indicated higher contribution of impacts from the O&M phase, due mainly to the flue gas emissions. This activity contributes to a range of 30%-85% of impacts in the categories of human toxicity, particulate matter, and acidification. Climate change impacts are mainly caused by the nitrous oxide emissions produced in the desulphurization process (36% of total impact in climate change) and the fuel oil combustion for start-up operations (26% of total impact). The results from the additive scenario indicated that replacing sulphur by gypsum does not affect significantly the environmental impacts of producing electricity and heat, since the environmental impacts are clearly dominated by the fuel gas emissions, which are not affected by the change of additive.

The main limitation of this study is the short duration of the trial tests, which does not give clear indications of the effects of additives on the long term performance in energy efficiency. Additionally, inventory data on emissions was limited, and the low-cost additive scenario is modelled considering same amount of emissions than with commercial sulphur. However, even though emissions are expected to be similar, small changes are likely to occur.

The economic analysis of using resource efficient additives in waste wood fuel mix was determined by a cost benefit analysis (CBA). This CBA, in the form of a discounted cashflow model, was more specifically performed to show whether or not the use of additives, gypsum, 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. The results are that a yearly cost reduction between €134.000 and €334.000 (before interest and corporate tax) could be realised by applying 1 wt% gypsum within the fuel mix.

Utrecht University and Avans University of Applied Sciences

Utrecht 2019

Content

Foreword

The REFAWOOD research project is intended at enlarging the market and improving the environmental performance of the use of wood waste fuels in CHP-plants by using resource efficient additives during combustion.

Some of the most important problems reported in waste biomass power plants are corrosion, fouling and slagging in different parts of the boilers. These issues cause planned and unplanned shut downs of the power plant which leads to low production rates and short life times of the boiler elements. One of the most promising solutions to address this problem is using additives during combustion. Although the use of additives in the area of biomass combustion has been widely investigated before, there is still a need for new, cheap and resource efficient fuel additives for reducing corrosion, fouling and slagging. In this context, new additives are being investigated as a means to increase efficiency of combustion using waste biomass while reducing the environmental impacts of the whole life cycle supply chain.

This study is funded by the European Commission under the 9th ERA-NET Bioenergy Joint Call together with the Rijksdienst voor Ondernemend Nederland (Dutch Government Service for Enterprises). The project partners consist of six small and medium-sized enterprises and two large companies related to the supply chain of waste biomass power plants and additives, three research organizations and four universities from 5 different countries (Germany, Poland, Sweden, Austria and The Netherlands).

This report is part of the deliverables of **WP4 Analysis of sustainability (economic, environmental and social) of the value chain**. The goal of WP4 is to determine the environmental and economic impacts throughout the entire supply chain of using various additives (gypsum, sulphide ore waste, halloysite) in waste biomass CHP/heating plants. The assessment will be carried out based on the data obtained of the trials on site. The environmental impacts are calculated by the Copernicus Institute of Sustainable Development, through the application of Life Cycle Assessment methodology. The economic impacts are calculated by Avans University of Applied sciences through the application of Life Cycle Costing and Cost Benefit Analysis.

1. Methodology

This section contains the methodology developed to assess the environmental and economic impacts of using low cost additives for waste wood combustion. This methodology will be applied to all case studies within the REFAWOOD project.

1.1 Life Cycle Assessment

The environmental impacts described in this report have been calculated according to standard methodology described in ISO 14040 Life cycle assessment - Principles and framework. The life cycle assessment (LCA) framework consists of four iterative stages, as described in Figure 1: Goal and Scope Definition, Life Cycle Inventory Analysis, Life Cycle Impact Assessment and Life Cycle Interpretation. The first stage sets the goal of the study and contains a description of the evaluated systems and the system boundaries considered. The Life Cycle Inventory Analysis identifies and quantifies all the inputs and outputs of the evaluated systems. The Life Cycle Impact Assessment uses the information gathered in the former step to estimate the environmental potential impacts according to selected impact categories. The Interpretation stage compares the results produced in the previous two phases to provide recommendations, compare alternatives and assist in decision making.

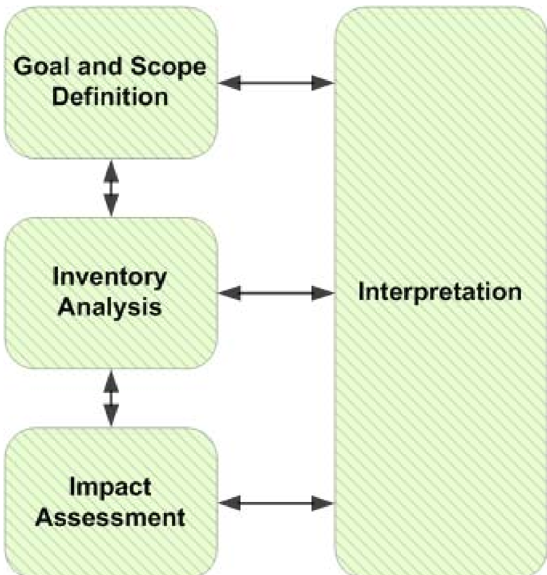


Figure 1 ISO 14040-2006 Life cycle assessment framework

This report includes four chapters containing the LCA of four power plants located in several countries. In order to be able to interpret the results of every LCA in an integrated way, a common methodologic framework has been settled for every case study which is described in the following sections.

1.1.1 Goal and Scope Definition

As stated in the introduction, the goal of the LCA is to analyse the environmental impacts of using various additives (gypsum, sulphide ore waste, halloysite) in waste wood CHP plants, to account for the expected benefits due to the additives use. The results are intended to support the benefits associated with the innovation provided by the REFAwood project.

This goal will be achieved by applying an Attributional LCA focusing on the impact of the additives in the studied system (the innovation per se). The approach would correspond to the decision context C2 of the ILCD guidelines (where no decision support or changes outside the system are expected) (Wolf et al., 2010). This approach is taken as a first step in order to focus on the impact of the additives in the studied system. However, the second step of this analysis will include a Consequential LCA, analysing the consequences of using additives and providing recommendations for decision making regarding the future use of additives. The methodology and results of this second step will be provided in a separated report together with the integration and interpretation of results for every case study.

The data quality will be evaluated using Data Quality Index (DQI) of the inventory data and uncertainty analysis will be carried out to identify critical parameters.

System boundaries

The geographical scope is Europe and the temporal scope is 1 year of operation (unless otherwise specified), considering 2016 or 2015 (depending on the data availability), as the baseline year without the use of additives in the system. In order to account for the potential environmental benefits achieved by the additives, the baseline scenario representing the business-as-usual operation will be compared to the trial operations with additives.

The environmental analyses take into consideration all the phases in the life cycle of the power plants evaluated, including (see Figure 2): provision and pre-treatment of the biomass feedstock, transportation of the fuel to the power plant, operation and maintenance of the power plant, and disposal of waste. Capital goods are excluded from the analysis, since no significant changes are expected from the baseline scenario to the additives scenario (unless otherwise specified).

The system boundaries for the attributional LCA (step 1) and the consequential LCA (step 2) are indicated in Figure 2. The analyses in step 1 (described in this report) consider a cut-off approach for recyclable waste where the impacts and credits associated with the recycling of waste are allocated to the waste user. The treatment of waste which is finally disposed of (and not recycled) is fully allocated to the waste producer. Therefore, the treatment and recycling of waste wood (input to the system) is allocated to the waste biomass power plant, but the treatment and recycling of ashes (output of the system) is allocated to the next user. However, if the ashes (or other wastes) are not bound for recycling, the disposal impacts of the waste management are associated to the power plant.

The next step will broaden the system boundary to also include the consequences of recycling wood ashes and the consequences of using waste wood for biomass power plants.

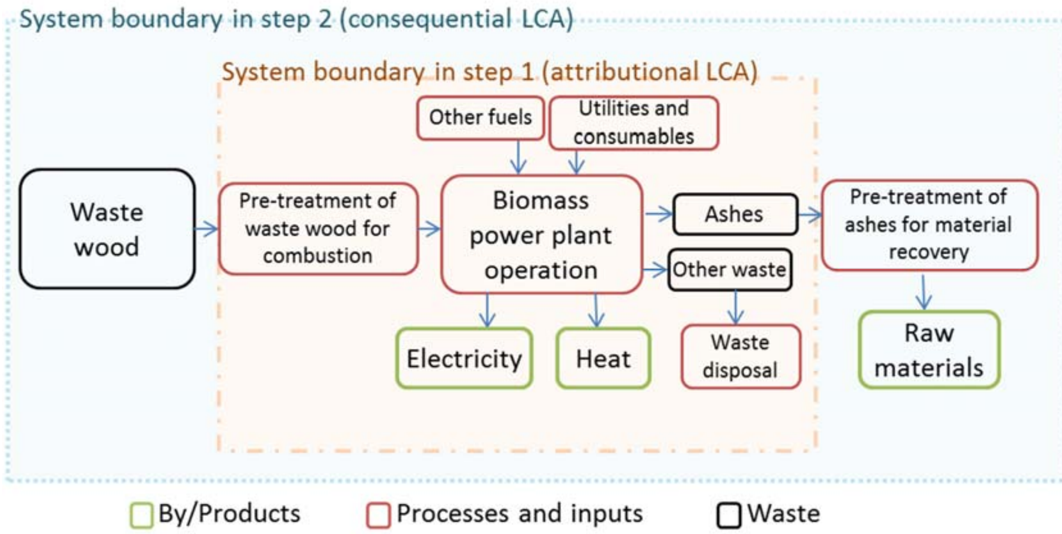


Figure 1 System boundaries for step 1 (attributional LCA) and step 2 (consequential LCA)

Functional unit

The functional unit to which all the impacts are referred is 1 kWh of net electricity delivered into the grid, or/and 1 MJ of heat.

1.1.2 Life cycle inventory analysis (LCI)

The main operation parameters of the power plants under study are gathered by a confidential questionnaire sent to the partners of the consortium, which is included in Annex I. This parameters include 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) and information about the fuel supply chain (type of fuel, origin, calorific value and moisture content, transportation distance, etc.).

Data sources

Primary data will be gathered from the industry partners of the project consortium, including performance data, fuel origin and composition, utilities and consumables, waste and emissions, and other technical characteristics for each power plant. Data on additives performance will be also gathered from the trials carried out by the consortium. Received data is carefully reviewed to rule out any possible inconsistencies prior to modelling. Each energy system will be modelled with Simapro software, using the provided data as foreground data. The main source for secondary data is ecoinvent 3.3 database (Weidema et al., 2013), followed by scientific literature and national or international reports. The quality of the foreground data will be assessed using DQI based on the Pedigree Matrix (Weidema and Wesnæs, 1996).

Allocation principle

When the power plant under study produces both electricity and heat, partitioning of impacts between electricity in heat is chosen against system expansion. This decision is based on the recommendations for decision context C2 (Accounting without interactions with other systems) from the ILCD guidelines (Wolf et al., 2010) and the Renewable Energy Directive (RED) directive, that recommends the energy allocation method for non-policy analysis, as follows: "Co-products from the production and use of fuels should be taken into account in the calculation of greenhouse gas emissions. The substitution method is appropriate for the purposes of policy analysis, but not for the regulation of individual economic operators and individual consignments of transport fuels. In those cases the energy allocation method is the most appropriate method, as it is easy to apply, is predictable over time, minimises counter-productive incentives and produces results that are generally comparable with those produced by the substitution method. For the purposes of policy analysis the Commission should also, in its reporting, present results using the substitution method." (EC, 2009).

Therefore, when the power plant under study produces both electricity and heat, the impacts are allocated to both heat and electricity considering two allocation parameters: (1) the energy content (as recommended but the current RED directive), and (2) the exergy content of each product (expressed by the Carnot factor).

The exergy allocation method was chosen in order to account for the higher quality (ability to produce work) of the electricity with respect to the produced heat (as would also happen in an economic allocation). Exergy allocation is also recommended by ANNEX V of the proposal for a new RED, published in 2016 (EC, 2016), as follows:

"*Where a cogeneration unit – providing heat and/ or electricity to a fuel production process for which emissions are being calculated – produces excess electricity and/or excess useful heat, the greenhouse gas emissions shall be divided between the electricity and the useful heat according to the temperature of the heat (which reflects the usefulness (utility) of the heat). The allocation factor, called Carnot efficiency Ch, is calculated as follows for useful heat at different temperatures:*

$$C_h = \frac{T_h - T_0}{T_h}$$

where:

T_h = Temperature, measured in absolute temperature (kelvin) of the useful heat at point of delivery.
T_0 = Temperature of surroundings, set at 273 kelvin (equal to 0°C)
For Th , < 150°C (423.15 kelvin), C_h can alternatively be defined as follows:
C_h = Carnot efficiency in heat at 150 °C (423.15 kelvin), which is: 0.3546

For the purposes of this calculation, the actual efficiencies shall be used, defined as the annual mechanical energy, electricity and heat produced respectively divided by the annual energy input.
For the purposes of this calculation, the following definitions shall apply:
(a) "cogeneration" shall mean the simultaneous generation in one process of thermal energy and electrical or mechanical energy;
(b) "useful" heat shall mean heat generated to satisfy an economical justifiable demand for heat;
(c)"economically justifiable demand" shall mean demand that does not exceed the needs for heating and which would otherwise be satisfied at market conditions."

1.1.3 Life cycle impact assessment (LCIA)

Life Cycle Impact Assessment is performed using Simapro software. The considered time horizon is 100 years (excluding long term emissions), and the impact evaluation method is ILCD Midpoint, with biogenic emissions reported separately. The impact categories considered in the study are: climate change, terrestrial acidification, freshwater and marine eutrophication, human toxicity, particulate matter formation and cumulative energy demand (renewable and non-renewable). These categories were selected due to their relevance in bioenergy systems (Astrup et al., 2015, Cherubini and Strømman, 2011, Muench and Guenther, 2013). Photochemical oxidant formation was included between the analysed categories at the befining of the study. However, the category was finally exluded after some LCA iterations due to data unavailability (lack of the associated emission data from the power plants).

1.1.4 Life Cycle Interpretation

The main significant issues regarding the environmental impacts of waste biomass CHP plants using additives will be identified according to the previous two life cycle stages (LCI and LCIA). The results obtained will be evaluated considering their completeness, limitations, consistency, sensitive parameters, and comparison with similar studies.

1.3 Life Cycle Costing

The goal of the life cycle costing (LCC) for the REFAWOOD project is to decide the economic effects of using resource efficient additives in waste wood fuel mix. Due to this fact it was chosen to perform a cost benefit analysis (CBA). This CBA was more specifically performed to show whether or not the use of additives, in this case gypsum and halloysite, 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.

Since the aim of this cost benefit analysis is to show the potential benefits for the use of additives, 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 additivesTo be able to make a comparison of the effect of using additives, a baseline scenario has to be created first. Therefore, the following data is required as shown in Table 1.

Table 1: Required plant data for creating a baseline (REFAWOOD) CBA scenario

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/year
Operational (full load) hours of steam turbine	hours/year
Net heat production	MWh/year
Net electricity production	MWh/year

The parameters in Table 1 are straightforward except for the exploitation and insurance costs. This parameter includes all operational costs for the total plant (including costs for ash disposal, staff, fluegas cleaning materials, maintenance and logistics on site) and insurance cost for the plant (excluding project depreciation). Next to that a certain price inflation (on yearly basis) is taken into account which is fixed and set on 1,5%. The required plant data should be data of a regular year of operation which is representative for the specific plant.

Additionally, information should be provided for the case in which additives are being used (additives scenario) in order to make a comparison with the baseline scenario. Basically these are additional costs and investments and cost reductions, translated into the following parameters shown in Table 2.

Table 2: Required additional data for additives (REFAWOOD) CBA scenario

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	%

The parameters from Table 2 are the parameters necessary for the additives scenario which will be compared with the baseline scenario. Basically the additives scenario is the same as the baseline scenario only some parameters which are affected by the parameters from table 15.

The first parameter, investment in gypsum dosing equipment, is added to the total project costs. The costs of the additives and, if applicable, the additional costs for fluegas desulphurization and additional (ash and gypsum) disposal costs are all added to the exploitation and insurance costs. Contrary, the cost reductions due to decreased downtime and due to increased lifetime of the heat exchanger or the superheater(s) are extracted from the exploitation and insurance costs. The increased boiler efficiency affects the thermal supply of wood chips, by reducing that amount with the increased boiler efficiency percentage. This will result in less fuel supply while the same required amount of heat and energy is delivered by the plant. A reduction will take place in the total yearly fuel costs. Figure 2 shows the outline of the baseline scenario and the additives scenario. Next to that it also visualizes how the additional parameters affect the baseline scenario in order to create the additives scenario.

Figure 2: Gypsum additives

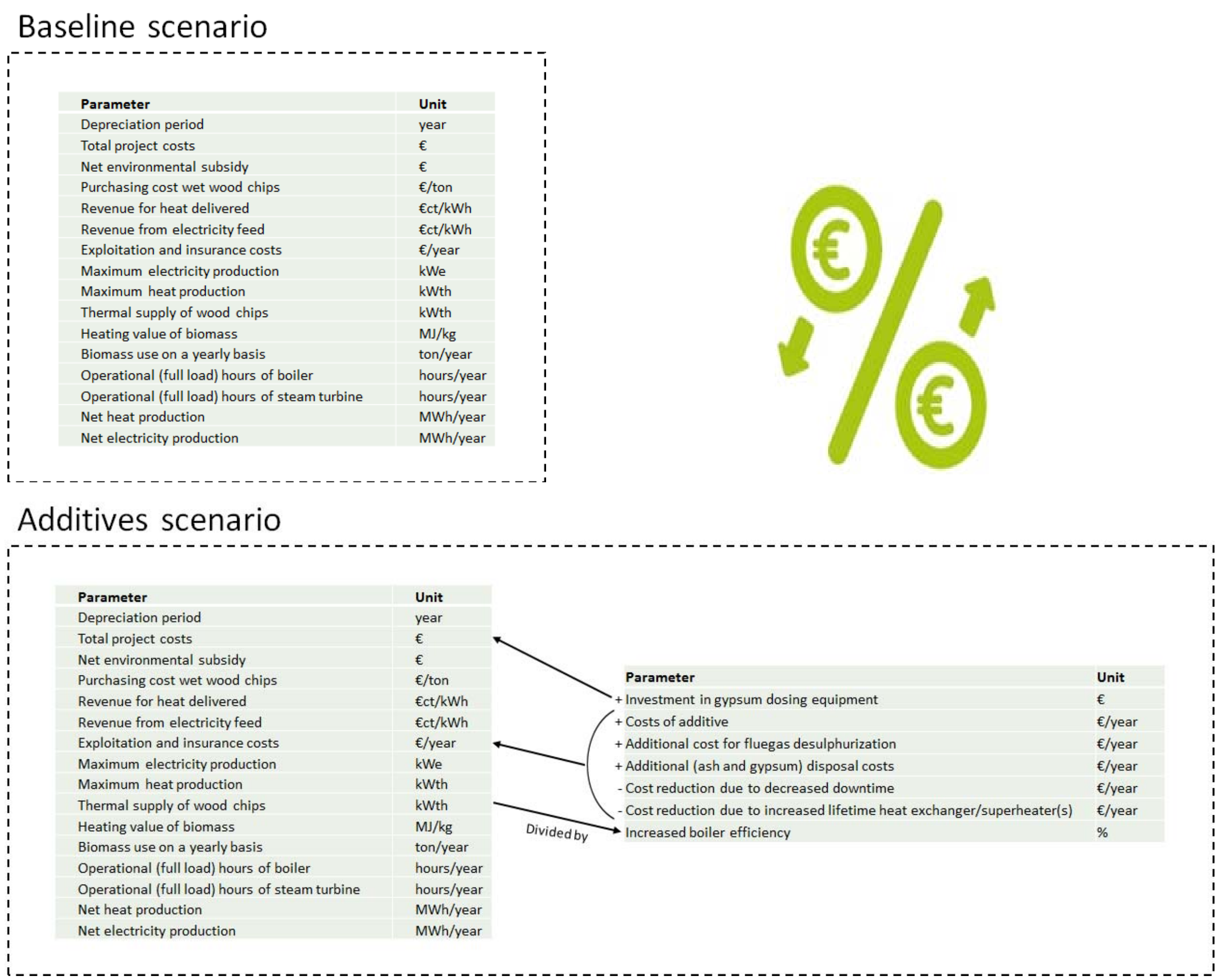


Figure 3: Outline of baseline scenario and how additional parameters influence the baseline scenario to create the additives scenario

The baseline scenario data is obtained from project partners via a questionnaire and additional meetings to gather all necessary data. Regarding the additives scenario, these parameters are outcomes from full scale tests that are performed at the plant. A test report (from WP3) and additional data about cost reduction estimations (from WP2.3) are used as input for the CBA.

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 cost reduction (or increase) can be determined. Since the cost reduction calculations from WP2.3 are all estimations, the additives scenario will be calculated twice. The first time it will be based on the estimations as given in the report of WP2.3 (referred to as additives scenario (high)), the second time it is calculated with only half of the estimated benefits for downtime reduction, cost reduction due to increased lifetime heat exchanger or superheater(s) and increased boiler efficiency (referred to as additives scenario (low)). The final result is that a range can be given for the cost reduction due to the use of additives.

The baseline scenario data is obtained from project partners via a questionnaire and additional meetings to gather all necessary data. Regarding the additives scenario, these parameters are outcomes from full scale tests that are performed at the plant. A test report (from WP3) and additional data about cost reduction estimations (from WP2.3) are used as input for the CBA.

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 addition of gypsum. By calculating the difference between the two outcomes, the cost reduction (or increase) can be determined. Since the cost reduction calculations from WP2.3 are all estimations, the additives scenario will be calculated twice. The first time it will be based on the estimations as given in the report of WP2.3 (referred to as additives scenario (high)), the second time it is based on only half of the benefits for downtime reduction, cost reduction due to increased lifetime heat exchanger or superheater(s) and increased boiler efficiency (referred to as additives scenario (low)). The final result is that a range can be given for the cost reduction due to the use of gypsum additives.

2. ENA power plant: System definition

ENA is a bio-based CHP plant located in Enköping, Sweden, and was first commissioned in the year 1994. Since then, the power plant has been providing heat to the district heating system in the city, and electricity to the Nord Pool market (Sweden, Norway, Denmark and Finland). Currently, the power plant supplies 47.000 MWh of electricity and 669.600 GJ of heat. The district heating network obtains heat from the ENA plant in a closed water circuit at a temperature of about 85-105°C (depending on outdoor temperature).

The CHP plants consists of a grate fired boiler used to produce superheated steam (at around 540°C and 100 bar). The steam drives a steam turbine for electricity generation, following a conventional Rankine cycle. A flue gas condenser is used to benefit from the heat of water condensation by transferring it to the water of the district heating network. The steam is thus transformed into water and sent again to the boiler. The flue gases of the power plant are also used to preheat the water of the district heating network a few degrees before entering into the flue gas cleaning unit, consisting on a dust precipitator, a selective non-catalytic system (SNCR) and a desulfurization unit.

The biofuel combusted in ENA is a mixture of 84% of demolition wood (e.g. from old structures, old packaging and scrap wood that have been crushed or tiled) and 16% of forest wood chips. The CHP plant runs for most of the year, except for some weeks in summer when the heat demand is too low and a smaller boiler is used instead. This boiler is sometimes used also for peak generation during the coldest winter days. ENA is already using chemical sulphur as additive (16 t/yr, or 0,02 wt% of fuel) to improve the combustion efficiency.

The main technical characteristics of the power plant are described in Table 3. ENA has an installed electrical capacity of 22 MWe, and a net electricity production amounting to 47.000 MWh in year 2016. The unplanned maintenance is approximately 10% of the planned downtime, being one of the power plants least affected by unexpected maintenance. The generated heat amounts to 669.600 GJ/yr.

Table 3 Characteristics of ENA power plant

Power plant capacity, MWe	22
Load factor	80%
Designed lifetime, years	40
Type of boiler	Grate fired
Fuel primary energy, GJ/yr	776.104
Net electricity generated, MWh/yr	47.000
Net heat, GJ/yr	669.600
Net efficiency (as reported)	80,6%
Planned downtime, h	1500-1600
Unplanned downtime, h	100-200

3. LCA: ENA POWER PLANT

3.1 Goal and scope definition

As stated in the introduction, the goal of this attributional LCA is two-fold: (1) to identify environmental hotspots in the life cycle of the power plant under study (hereinafter ENA) in order to improve the future technology development and the supply chain management; and (2) to understand the trade-offs between potentially lowering the combustion efficiency and reducing the maintenance burden by using additives.

3.1.1 Function and functional unit

The function of the analysed biomass power plant is to produce heat for the local district heating system and electricity for the Nord Pool grid using waste biomass as part of the feedstock. There are two functional units to which all the impacts are referred: 1 kWh of electricity poured into the electricity network, and 1 MJ of heat (95 °C) distributed into the district heating system.

3.1.2 System boundary

The geographical scope is Sweden and the temporal scope is 1 year of operation, considering 2016 as the baseline year. This environmental analysis takes into consideration a cradle to gate approach, including the following activities of the ENA CHP plant life cycle: provision of fresh wood and pre-treatment of the waste wood, transportation of the fuel to ENA CHP plant, operation and maintenance of the power plant, and disposal of waste. Capital goods are excluded from the analysis, since no changes are expected from the baseline scenario to the additives scenario (unless otherwise specified).

As indicated in the methodology description and shown in Figure 1**,** this analysis considers a cut-off approach for all recyclable wastes. According to this approach, the impacts and credits associated with the recyclable waste are allocated to the waste user and not to the waste producer. Thus, when the power plant uses recyclable waste as input, the pre-treatment for waste wood, pruning chips and shreds (chipping) are included in the system boundaries of energy generation. Following the same principle, the recycling of the combustion ashes is not included into the system boundary of energy generation because the impacts and credits are allocated to the future users of ashes. This study also considers that the transportation of recyclable waste (from the waste producer to the waste treatment plant) is allocated to the waste user. Therefore, the transportation of ashes to the recycling plant is included into the study in order to account for the change in ashes generation from the baseline scenario to the additives scenario.

The foreground processes in the modelled life cycle are the transportation of every fuel, the pre-treatment of waste wood, the inputs and outputs during the fuel combustion, and the ashes transportation.

3.1.3 Low-cost additive scenario

ENA power plant already uses commercial sulfur as additive to decrease ash-related problems in the boiler. The trials carried out as part of the WP3 in the Refawood project indicated inconclusive results regarding the effects of using gypsum as additive. However, according to previous research realized by the scientific partners, the decrease of ash-related problems due to gypsum and sulfur are expected to be the same. The researchers also reported that the amount of sodium hydroxide (for desulphurization), the amount and composition of flue gas emissions, and other activities in the power plant would remain the same both for sulfur and gypsum (changes on ashes amount and composition are assumed negligible). As reported by the Swedish partners, the amount of gypsum necessary to substitute sulfur is 6,5 kg of gypsum per kg of sulfur. Necessary amounts of each additive in each scenario are described in Table 4.

Table 4 Additives used in the baseline and low-cost additive scenario

	Baseline scenario	Low cost additive scenario
Commercial sulfur, t/yr	20	-
Gypsum waste, t/yr	-	130
Fly ashes, t/yr	650.000	650.000
Bottom ashes, t/yr	2.400.000	2.400.000

3.1.4 Assumptions and hypotheses

CO_2 emissions from biomass combustion are considered as biogenic emissions with a global warming potential of 1 (kg CO_2 biogenic/kg CO_2 eq). However, it is also assumed that the amount of CO_2 sequestered in the production of biomass equals the amount of CO_2 emitted during the combustion. Therefore, the total balance of CO_2 intake and release within the system boundaries due to biomass generation and combustion is neutral.

It is assumed that the weight of all the lorries used for transportation of fuels ranges between 16 and 32 metric ton, and that they are in compliance with the European Emission Standards EURO3. Transport, freight, lorry 16-32 metric ton, EURO4 {RER}| transport, freight, lorry 16-32 metric ton, EURO4 | Alloc Rec, U.

3.1.5 Data quality requirements

The following data quality requirements are considered in this study:

- Regarding the representativeness of the data: the age of the data should be less than 10 years, therefore, datasets should represent activities taking place after year 2007. Foreground data should come from similar technologies than the ones involved in the life cycle system and from European locations (whenever national data is not available)

- Sources of the data: When primary data is not available, secondary data should be taken from worldwide recognized databases, official reports (from national or international organisms) or publications in indexed research journals.
- A qualitative assessment of the accuracy of the data regarding source reliability, completeness, temporality, geography and technology should be provided through DQI.

1.1.5 Information about the iterative process

LCA is an iterative process, where several iterations of the first methodologic steps are done in order to refine the data used and assumptions considered. This analysis followed several iteration processes, including refining of inventory data and impact assessment step.

After the first iteration, sensitivity analysis on different inventory parameters were conducted and in some occasions the datasets were modified to better represent the system under study (see next section 1.1.6). Regarding the inventory step, changes implemented in the first iteration included:

- Refining the electricity mix used for wood processing industries in the ecoinvent datasets to better represent the Swedish electricity mix.
- Differentiating $PM_{2,5}$ and $PM_{2,5\text{-}10}$ within the dust emissions reported by the company (more information in section **Error! Reference source not found.**) .
- Elimination of the photochemical ozone formation due to lack of emissions data.

The impact assessment method was also changed from ReCiPe Midpoint to ILCD Midpoint+ in order to have a better characterization of all the elementary flows as reported in the inventory (ReCiPe method did not characterize some of the emissions reported by the company).

1.1.6 Information about sensitivity analyses

Performing sensitivity analysis in different variables of the scope, inventory and impact assessment helps in identifying focus points for improved and more accurate results/conclusions. The focus of the sensitivity analysis are those parameters with high uncertainty or high influence in the results of the study.

This sensitivity analysis performed in this study explored the influence of the allocation procedure, by applying energy allocation instead of exergy allocation (see section 3.2.2).

3.2 Life cycle inventory analysis

Data was collected in several steps. The first step included preliminary data collection via a questionnaire that was sent to the contact person in the power plant. Afterwards, more specific information was gathered during several personal meetings.

The process tree depicted in Figure 4 describes the activities taking place in the life cycle, as well as the system boundaries considered. As indicated by the orange dotted line, the life cycle starts with the gathering of the fuels and the pretreatment of the residues/waste, and finishes with the energy generation and ashes disposal. Otherwise indicated, data for foreground processes (see Figure 4) was collected from ENA and background processes were modelled using ecoinvent v3 database.

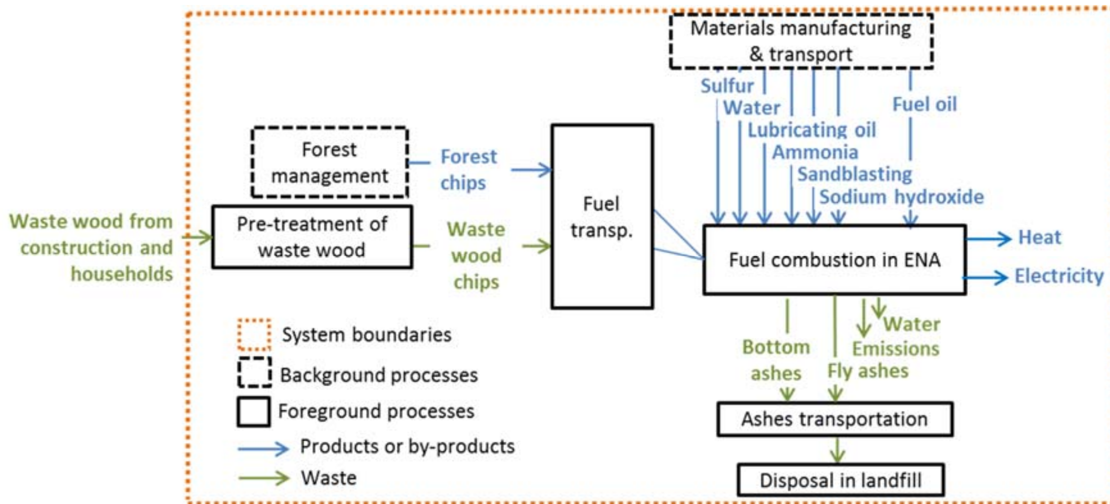


Figure 4 Overview of the process tree and system boundaries for the ENA baseline scenario

3.2.1 Data collection and description

This section include information about the unit processes, datasets, sources and data quality (measured by DQI) for each stage of the study.

Fuel procurement and transport

ENA burns two types of wood: residual wood from forests, and waste wood from demolition activities and households. The main characteristics of the fuel mix regarding the amount combusted per functional unit, price per ton, cost per functional unit, moisture content, low heating value and transportation distances are described in Table 5. Details about the datasets used and the DQI are provided in Table 6.

It is assumed that the weight of all the lorries used for transportation of fuels ranges between 16 and 32 tonnes, and that they are in compliance with the European Emission Standards EURO3.

The energy content of the woody feedstock is included in every fuel dataset in order to account for the life cycle primary energy cumulative demand (also for the waste fuels).

As indicated in **Error! Reference source not found.**, forest residues contribute to 13% of the primary energy of the fuel mix, while waste wood contributes to the remaining 87%.

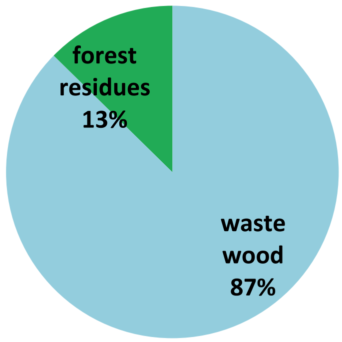


Figure 5 Share of primary energy per fuel in ENA power plant

Table 5 Composition of the fuel mix and main characteristics of each fuel, per year

Fuel type	Amount t w.b. /yr	Price €/ton	Cost €/yr	Moisture content	LHV w.b.	Average transp dist. (km)
Forest residues (chips)	14.513	20	290.260	45%	8,9	30
Waste wood	73.444	12	881.328	25%	12,9	205

Table 6 Amount of fuels (per functional units), ecoinvent datasets used to model the fuel upstream processes and corresponding DQI

Fuel type	Ecoinvent datasets	Amount /kWh	Amount/MJ	unit	DQI*
Forest chips	Wood chips, wet, measured as dry mass {SE}| softwood forestry, spruce, sustainable forest management | Alloc Rec, U	3,73E-02	2,68E-03	Kg	3,1,1,1,2
	Wood chips, wet, measured as dry mass {SE}| softwood forestry, pine, sustainable forest management | Alloc Rec, U	3,47E-02	2,48E-03	Kg	3,1,1,1,2
	Wood chips, wet, measured as dry mass {SE}| hardwood forestry, birch, sustainable forest management | Alloc Rec, U	1,69E-02	1,21E-03	Kg	3,1,1,1,2
Waste wood	Wood chipping, industrial residual wood, stationary electric chipper {SE}| processing | Alloc Rec, U	7,73E-01	5,54E-02	kg	3,1,1,2,3
	Biomass, feedstock (elementary flow)	9,97E+00	7,14E-01	MJ	2,1,1,1,1

*Numbers given represent the data quality indicators in the following order: Reliability of source, Completeness, Temporal differences, Geographical differences, Technological differences

Forest chips are direct by-products of forest management, assumed to be produced directly during harvesting for energy purposes (residual wood from logging). The inventory includes as background processes the production and harvesting of wood (including chipping at stand for chips according to the corresponding ecoinvent database). The ecoinvent datasets for forest chips differentiates between hardwood (birch) and softwood (pine and spruce). Since the nature of the wood was not specified by the data provider, the average share of softwood and hardwood produced in Sweden (39% pines, 19% birch and 42% spruce) was used as proxy, according to the values reported by the Swedish forest agency (Black-Samuelsson, 2012).

Waste wood comes from the construction and demolition industry, and from households. It undergoes a pretreatment consisting on removal of nails and other attached elements and shredding. Only the pretreatment and the transportation from the treatment plant to the power plant are included in the study, since according to the system boundaries described in section 3.1.2, other previous life cycle activities of the waste wood are allocated to the waste producer.

The dataset for wood chipping was taken from ecoinvent. A sensitivity analysis on the impacts of chipping waste wood with respect to the total impacts revealed a high contribution from the electricity consumed for chipping. Therefore, the original dataset “Wood chipping, industrial residual wood, stationary electric chipper {RER}| processing | Alloc Rec, U ” was adapted to the case under study by using the Swedish electricity mix (“Electricity, medium voltage {SE}| market for | Alloc Rec, U”) as energy source for chipping instead of the average RER electricity mix (“Electricity, medium voltage {RER}| market group for | Alloc Rec, U”).

Fuel transportation

ENA reported that 50% of the waste wood comes from the area around Sweden, while the rest comes from Norway. For the foreign waste wood it is assumed a transportation distance of 380 km, while the local feedstock is transported an average of 30 km. The company specified that the lorry never goes empty, and the return trip is used to carry other goods. The ecoinvent dataset for transportation includes an empty return trip. Since in the case under study the return trip to Norway is used for other purposes, an allocation factor based on transported distance of 0,5 was used in the dataset in order to only account for the waste wood transportation.

Operation and maintenance (O&M) of the power plant

The operation of the power plant requires the use of chemical sulfur as additive, ammonia for the flue gas treatment, sodium hydroxide for flue gas desulphurization, water for the steam cycle, and fuel oil for startup operations. The amount of each consumable and the ecoinvent dataset used for the modelling is described in Table 7.

The maintenance of the power plant requires the consumption of lubricating oil and sand for sandblasting during boiler cleaning.

The outputs of the system during O&M are water, ashes, lubricant oil, sandblast material, and combustion emissions. Ten percent of the consumed water is assumed to be evaporated during the process, while the rest is sent to the water treatment plant. An additional amount of 20000 tons of water coming from the condensation of flue gas is also sent to the water treatment plant. Combustion emissions regarding main pollutants are modeled with respect to the data provided by ENA for the year under study. The lubricant oil and sandblast material are disposed of in a hazardous waste incinerator.

Table 7 Amount of consumables (per functional units) and ecoinvent datasets used to model the O&M stage.

Processes	Ecoinvent datasets	Amount /kWh	Amount/ MJ	U/FU	DQI*
Ammonia, liquid	Ammonia, liquid {RER}| market for | Cut-off, U	2,32E-03	1,66E-04	kg	3,1,1,2,2
Sand	Sand {GLO}| market for | Cut-off, U	3,16E-04	2,26E-05	kg	3,1,1,2,2
Sulfur	Sulfur {GLO}| market for | Cut-off, U	2,11E-04	1,51E-05	kg	3,1,1,2,2
Lubricating oil	Lubricating oil {GLO}| market for | Cut-off, U	1,05E-05	7,54E-07	kg	3,1,1,2,2
Sodium hydroxide	Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Cut-off, U	1,73E-03	1,24E-04	kg	3,1,1,2,2
Fuel oil	Heavy fuel oil {Europe without Switzerland}| market for | Cut-off, U	2,02E-03	1,44E-04	kg	3,1,1,2,2
Water consumption	Water, deionised, from tap water, at user {Europe without Switzerland}| water production, deionised, from tap water, at user | Cut-off, U	2,11E-01	1,51E-02	kg	3,1,1,2,2
	Wastewater, average {Europe without Switzerland}| treatment of wastewater, average, capacity 1E9l/year | Cut-off, U	4,00E-01	2,87E-02	L	3,1,1,2,2
Disposal lubricant oil	Waste mineral oil {Europe without Switzerland}| market for waste mineral oil | Cut-off, U	9,47E-06	6,79E-07	Kg	3,5,1,2,4

*Numbers given represent the data quality indicators in the following order: Reliability of source, Completeness, Temporal differences, Geographical differences, Technological differences

Combustion emissions

Combustion emissions regarding CO, NO_x, SO_x, N_2O, HCl, Hg, Dioxins, NH_3 and dust are modelled with respect to the data provided by ENA for the year under study. The inventoried emissions related to biomass combustion (after flue gas cleaning) are described in Table 8. The emissions related to NMVOC were not provided by ENA, therefore, the corresponding emission factors reported in the EMEP/EEA air pollutant emission guidebook were used (sector 1.A.1.a Public electriciy and heat production, technology Dry Bottom Boilers, fuel wood and wood waste) (EMEP/EEA, 2016a). The emissions due to the combustion of fuel oil (as back-up fuel) are modelled according to the EMEP/EEA emission inventory guidebook (EMEP/EEA, 2016b), as described in Table 9.

Dust emissions were reported without considering the size distribution of the particle. This has been associated to the difficulty in measuring the particle size, but also to the fact that the regulations do not require a specification of the particle size within the reported dust emissions. Typically, most of the dust contained in the fly ash of combusted biomass have a particle size lower than 0,2 µm of diameter, with reported values of 80% of the particle mass weight corresponding to aerosol with diameters <1 µm (Hasler and Nussbaumer, 1998), and even lower than 0,5 µm for domestic boilers (Tiwari et al., 2014). According to the values reported in the EMEP/EEA air pollutant emission guidebook (EMEP/EEA, 2016b), an average of 155 g/GJ of PM_{10} are emitted when burning wood and clean wood waste, and 86% of that amount (133 g/GJ) corresponds to $PM_{2,5}$. Therefore, it is assumed that 86% of the reported mass of emitted dust corresponds to $PM_{2,5}$, while 14% corresponds to $PM_{2,5-10}$. This amounts to 1878 kg/year of $PM_{2,5}$ and 306 kg/year of $PM_{2,5-10}$.

Table 8 Flue gas emissions associated with biomass combustion (the emissions related to burning of fuel oil are not included in this table) (ENA is located in a high density population area, >400 p/km^2 in less than 2km radius)

Flue gas emissions	Amount	Unit
CO	51786	Kg/year
NO_x (as NO2)	62861	Kg/year
SO_2	15458	Kg/year
Dust	2184	Kg/year
NH_3	6340	Kg/year
HCl	3056	Kg/year
Hg	1.49	Kg/year
NMVOC	7837	Kg/year
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	$5x10^{-6}$	kg TEQ/year

Table 9 Flue gas emissions associated with fuel oil combustion, as reported by EMEP/EEA air pollutant inventory 2016 (sector 1.A.1.a, assuming LHV=41,2 MJ/t).

Flue gas emissions	Amount	Unit
NMVOC	118	Kg/year
Cu	0,0789	Kg/year
Benzo(b)fluoranthene	0,071	Kg/year
Zn	0,0789	Kg/year
SO_2	1100	Kg/year
Ni	2,37	Kg/year
Benzo(a)pyrene	0,0631	Kg/year
Cd	0,00237	Kg/year
Indeno(1,2,3-cd)pyrene	0,0237	Kg/year
As	0,00789	Kg/year
NOx	789	Kg/year
Hg	0,000789	Kg/year
Cr	0,158	Kg/year
Pb	0,158	Kg/year
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	$78,9x10^{-6}$	Kg/year
CO	316	Kg/year
PM2.5	23,7	Kg/year

Ashes disposal

The ashes resulting from wood combustion are collected from the bed of the boiler (bottom ashes) and the flue gas cleaners (fly ashes). The amount of bottom ash generated in year 2016 was 2.450 t, while the amount of fly ash was 650 t. ENA reported that all the ashes produced in the operation of the power plant are disposed into a landfill.

However, it is expected that in the short future (probably in 5 years' time), new legislation will force power plants to recycle the produced ashes (e.g. in road pavements). ENA informed of an average transportation distance to the landfill of 35 km by lorry.

3.2.2 Allocation rules

This LCA follows a cut-off approach were the burdens or benefits avoided due to the use of waste as feedstock are not considered (the waste comes burden-free).

According to the ISO 14040 standards, allocation of processes shared with various products was avoided by dividing those processes into several sub-processes attending to their direct causality. When subdivision was not possible, partitioning was applied, as recommended by the guidelines ILCD for the decision context C2 (Wolf et al., 2010).

Regarding the upstream processes for the forest chips (non-waste fuel), forest management is modelled in the ecoinvent datasets as a combined production where the output volumes of the (combined) products can be independently varied, thus, the different activities are subdivided according to the share of each product with respect to total production volume from forest management (below bark).

As mentioned in section 3.1.1, the functional units are 1 kWh of electricity and 1 MJ of heat. The existence of both functional units require partition of impacts between electricity and heat. As explained in the methodology document, partitioning of impacts between electricity in heat is chosen against system expansion. Therefore, allocation will be carried out considering both energy and exergy partitioning. This decision is based on the recommendations for decision context C2 (Accounting without interactions with other systems) from the ILCD guidelines (Wolf et al., 2010) and the Renewable Energy Directive (RED) directive, that recommends the energy allocation method for non-policy analysis (EC, 2009). However, exergy allocation is also recommended by ANNEX V of the proposal for a new RED, published in 2016 (EC, 2016), because it is able to reflect the higher quality (usefulness) of the electricity and the high temperature heat.

For the calculation of life cycle impacts per unit of electricity and heat, considering exergy partitioning, the following equations [1] and [2] were used:

$$I_{el} = \left(\frac{I_T}{E_{el}} \cdot \underbrace{\frac{C_{el} \cdot E_{el} \cdot 3{,}6}{C_{el} \cdot E_{el} \cdot 3{,}6 + C_h \cdot E_h}}_{\text{AF}}\right) \qquad \text{Equation [1]}$$

$$I_{h} = \left(\frac{I_T}{E_{h}} \cdot \underbrace{\frac{C_h \cdot E_h}{C_{el} \cdot E_{el} \cdot 3{,}6 + C_h \cdot E_h}}_{\text{AF}}\right) \qquad \text{Equation [2]}$$

Where:

$I_{h,el}$ = Life cycle impacts per unit of energy commodity (heat, electricity).

I_T = Total life cycle impacts in the system

E_{el} = Annual electricity produced based on its energy content (in kWh).

E_h = Annual useful heat output based on its energy content (in MJ).

C_{el} = Fraction of exergy in the electricity, and/or mechanical energy, set to 100 % (C_{el} = 1).

C_h = Carnot efficiency (fraction of exergy in the useful heat, defined by Equation [3]).

$AF_{h,el}$ = Exergy allocation factor for each energy commodity (heat, electricity).

The Carnot efficiency (*Ch*) for useful heat is calculated according to Equation [3] (EC, 2016).

$$C_h = \frac{T_h - T_0}{T_h} \quad [1] \text{ (EC, 2016)}$$

Where:

T_h = Temperature, measured in absolute temperature (kelvin) of the useful heat at point of delivery.
T_0 = Temperature of surroundings, set by the RED proposal at 273 kelvin

The average temperature of the useful heat at the point of delivery, according to ENA, is 95°C. Therefore, according to Equation [3], the Carnot efficiency of the heat (*Ch*) is 0,258. The calculated allocation factors considered exergy and energy partitioning are described in Table 10.

Table 10 Allocation factors for electricity and heat considering both exergy and energy allocation

	BASELINE: Exergy allocation factor (AF)	SENSITIVITY: Energy allocation factor
Electricity	0,495	0,202
Heat	0,505	0,798

3.2.3 Validation of data

The consistence of the data provided by ENA regarding the most important parameters (fuel amounts and energy produced) was checked by energy balances. It was also confirmed that every dataset is consistent with the system boundaries proposed, the allocation rules, and the data quality requirements described in section 3.1.5.

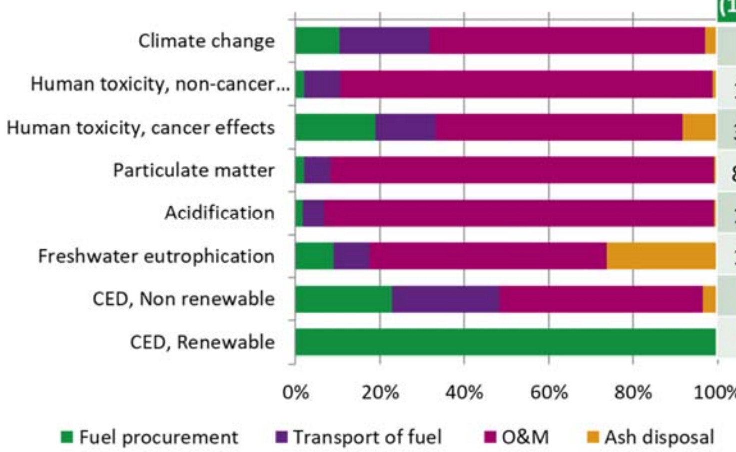
3.3 Life cycle impact assessment

3.3.1 Selection of impact categories and characterization models

Life Cycle Impact Assessment is performed using ILCD Midpoint+ (100 years of time horizon). The following impact categories were considered in the study due to their relevance in bioenergy systems (Astrup et al., 2015, Cherubini and Strømman, 2011, Muench and Guenther, 2013): climate change, terrestrial acidification, freshwater eutrophication, human toxicity, particulate matter formation and cumulative energy demand (renewable and not renewable).

3.3.2 Results

The characterized results described in Figure 6 represent the potential environmental impacts per kilowatt-hour of electricity and per megajoule of heat in the selected midpoint impact categories.



Electricity (1 kWh)	Heat (1MJ)	U/FU
37,6	2,69	g CO2 eq
1,68E-08	1,21E-09	CTUh
3,98E-10	2,85E-11	CTUh
8,74E-05	6,26E-06	kg PM2,5 eq
1,10E-03	7,92E-05	molc H+ eq
1,29E-06	9,26E-08	kg P eq
0,527	0,038	MJ
11,60	0,831	MJ

Figure 6 Characterization results per FU for ENA baseline scenario, with share of impacts per life stage. (O&M=Operation and maintenance)

The results indicate a strong contribution from the O&M stage to the environmental impacts in every impact category (except for renewable CED, which is attributed to the biomass fuel). Lower contributions are obtained from the fuel procurement stage, fuel transportation, and ashes disposal. This last stage causes higher relative impacts in freshwater eutrophication (26% of total life cycle impacts) and human carcinogenic toxicity (8% of total life cycle impacts) due to the landfilling of ashes (which potentially releases phosphate, chromium VI and zinc to water during the treatment of leachate).

The disaggregation of activities within the O&M stage and their contribution to the total impacts of such stage are described in Figure 7. As observed, most of the impacts in particulate matter, human toxicity and acidification are associated with the combustion emissions. Even though biomass is considered to be carbon neutral, the O&M phase is responsible of 24,5 g CO_2 eq/kWh (58% of total life cycle impacts). Almost 40% (9,7 g

CO_2 eq/kWh) of the global warming impacts of the O&M stage are associated with the emission of N_2O during operation of the plant. The nitrous oxide emissions may be originated during the combustion of the fuel (due to 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 NOx emissions (IrBEA, 2016). Nitrous oxides can also be formed from reduced sulphates (Bates, 1998). While the amount of nitrous oxide released to the air is not relatively high, its global warming potential is 298 times higher than carbon dioxide (according to IPCC 2007), causing 9,7 g CO_2 eq/kWh in the ENA power plant.

Other contributors to the global warming impacts in the O&M phase are the fuel oil procurement and combustion (30% of O&M stage) and the use of ammonia (20% of O&M stage).

Water procurement and treatment causes 55% of the O&M impacts in eutrophication and 23% of carcinogenic human toxicity impacts, due to the release of phosphate and chromium VI in the water treatment process. The reducing agents in the SNCR and desulphurization systems (ammonia and caustic soda) are also responsible of between 30% and 40% of the impacts in eutrophication, toxicity and non-renewable CED categories, due to the manufacturing processes of such chemicals.

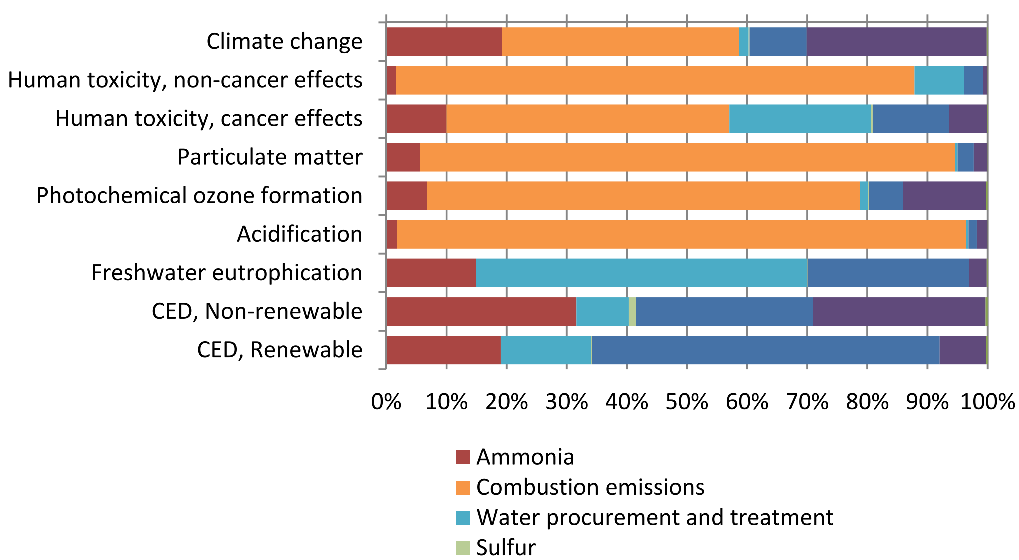


Figure 7 Characterized impacts associated with the O&M stage of the ENA baseline scenario per activity

The environmental impacts related to each fuel (forest residues and wood waste) are described in Table 11. Even though most of the feedstock in ENA is waste wood, most of the impacts in climate change, particulate matter, acidification, and non-renewable CED are associated with forest residues, due to the harvesting and chipping operations. However, waste wood has higher contribution than forest residues (around 60%) in the human toxicity categories due to the electricity consumption (Swedish electricity mix from the grid) for chipping.

Table 11 Characterized impacts of the fuel procurement stage per FU (1 kWh of electricity and 1 MJ of heat) in ENA baseline scenario, with share of impacts per fuel.

	Waste wood	Forest residues	**Electricity (kWh)**	**Heat (MJ)**	**U/FU**
Climate change	18%	82%	3,93	0,282	g CO_2 eq
Human toxicity, non-cancer effects	60%	40%	3,58E-10	2,57E-11	CTUh
Human toxicity, cancer effects	63%	37%	7,57E-11	5,42E-12	CTUh
Particulate matter	28%	72%	1,79E-06	1,28E-07	kg $PM_{2,5}$ eq
Acidification	19%	81%	1,95E-05	1,39E-06	molc H+ eq
Freshwater eutrophication	61%	39%	1,17E-07	8,40E-09	kg P eq
CED, Non renewable	37%	63%	0,121	0,009	MJ
CED, Renewable	94%	6%	9,21	0,660	MJ

3.3.3 Results low-cost additive scenario

Results of the low-cost additive scenario are very similar to the baseline scenario, since it is assumed that the only significant change in the inputs and outputs is the amount and nature of the additive. Table 12 describes the results obtained for the low cost additive scenario, and their relative difference compared to the baseline scenario. As observed in the table, the environmental benefits of using gypsum are minimal (decrease of maximum 1,2% of impacts in every category), since the avoided environmental impacts of not using commercial sulphur are very low (see also Figure 7).

Table 12 Characterized impacts of the low-cost additive scenario and changes with respect to the baseline scenario

Impact categories	**Baseline (sulfur)**	**Low-cost additive (gypsum)**	**Difference**	**U/kWh**
Climate change	37,6	37,5	-0,13%	g CO_2 eq
Human toxicity, non-cancer effects	1,68E-08	1,68E-08	-0,03%	CTUh
Human toxicity, cancer effects	3,98E-10	3,97E-10	-0,15%	CTUh
Particulate matter	8,74E-05	8,73E-05	-0,04%	kg $PM_{2.5}$ eq
Acidification	1,10E-03	1,10E-03	-0,05%	molc H+ eq
Freshwater eutrophication	1,29E-06	1,29E-06	-0,06%	kg P eq
CED, Non renewable	0,527	0,521	-1,21%	MJ
CED, Renewable	11,60	11,60	-0,00%	MJ

3.4 Life cycle interpretation

This section contains the interpretation of the results obtained in the environmental impact evaluation with respect to the goal of the project. Sensitivity analysis are performed in the most relevant parameters while recommendations and limitations are pointed out.

3.4.1 Sensitivity analysis on allocation between energy and heat.

The baseline scenario allocates the environmental burdens of energy generation to heat and electricity by considering the exergy content of each energy carrier. In the sensitivity analysis, the allocation factors are based on the energy content instead of exergy content, as described in section 3.2.2. As observed in Table 13, when applying energy allocation, the environmental impacts per kWh of electricity are less than half than the same impacts when applying exergy allocation. Conversely, the environmental impacts per MJ of heat are 1,5 times higher when applying energy allocation. This is due to the higher value allocated to1 MJ heat in the energy allocation method than in the exergy allocation method. Still, more impacts are allocated to electricity because there is more energy generated in the form of electricity than in the form of heat.

Table 13 Sensitivity on the losses of dry matter in the supply chain (changes for the low range and high range assumptions with respect to the baseline scenario)

	EXERGY ALLOCATION		ENERGY ALLOCATION		
Impact categories	FU= $1kWh_e$	FU= $1MJ_{th}$	FU= $1kWh_e$	FU= $1MJ_{th}$	U/FU
Climate change	37,6	2,69	15,3	4,26	g CO_2 eq
Human toxicity, non-cancer effects	1,68E-08	1,21E-09	6,86E-09	1,90E-09	CTUh
Human toxicity, cancer effects	3,98E-10	2,85E-11	1,62E-10	4,50E-11	CTUh
Particulate matter	8,74E-05	6,26E-06	3,56E-05	9,89E-06	kg $PM_{2.5}$ eq
Acidification	1,10E-03	7,92E-05	4,50E-04	1,25E-04	molc H+ eq
Freshwater eutrophication	1,29E-06	9,26E-08	5,27E-07	1,46E-07	kg P eq
CED, Non renewable	0,527	0,038	0,215	0,060	MJ
CED, Renewable	11,60	0,831	4,73	1,313	MJ

3.4.2 Results interpretation

The results of the environmental assessment indicated that the highest impacts of the power plant's life cycle are coming from the O&M phase, due mainly to the flue gas emissions. This activity contributes to a range of 30%-85% of impacts in the categories of human toxicity, particulate matter, and acidification. Climate change impacts are mainly caused by the nitrous oxide emissions produced in the desulphurization process

(36% of total impact in climate change) and the fuel oil combustion for start-up operations (26% of total impact).

The low contribution of impacts from the fuel procurement phase is highly influenced by the cut-off allocation method used to model the use of waste, that allocates 0% of the wood impacts to the waste wood, freeing this feedstock of any burden. If we were to consider an alternative allocation method, such as system expansion, the results would depend on the expected avoided treatment for the wood waste. If the wood waste would have sent to a landfill, the impacts of the fuel procurement phase would have been even lower, since landfilling would have been avoided.

When looking at the fuel procurement step, a sensitivity analysis on the impacts of chipping waste wood with respect to the total impacts revealed a high contribution form the electricity consumed for chipping. In order to refine the results of the study, the original dataset "Wood chipping, industrial residual wood, stationary electric chipper {RER}| processing | Alloc Rec, U " was adapted to the case under study by using the Swedish electricity mix instead of the European mix. Changing this parameter reduced the eutrophication impacts by 36% and the climate change impacts by 13%. Other impacts decreased in a range of 1-3%.

3.4.3 Conclusions, limitations and recommendations

Since the ENA power plant already used elemental sulphur as additive before starting the REFAwood project, the inventory data was collected accordingly, and the results obtained in this analysis are only relevant to compare the performance of low-cost additives with that of commercial additives (baseline scenario). The results indicated that replacing sulphur by gypsum does not affect significantly the environmental impacts of producing electricity and heat, since the environmental impacts are clearly dominated by the fuel gas emissions, which are not affected by the change of additive.

Nevertheless, the results from this analysis could give a qualitative evaluation of the differences on the environmental impacts of using additives with respect to a no-additives scenario. Results from the trials with additives in the ENA power plant performed in WP3 suggested that the use of additives would increase the net energy efficiency of the ENA power plant in 0,5% with respect to a no-additives scenario. The use of additives would not change significantly the combustion emissions (only a slight decrease of CO emissions), due to the increased use of NaOH to compensate the higher SO_2 emissions generated by the additive. Since the expected increase in energy efficiency is not very high, and the use of NaOH does not have a high contribution to the total environmental impacts of producing heat and electricity in the ENA power plant (see section 3.3.2), the environmental profile of the ENA power plant with or without additives would remain quite similar.

As stated through the report, the main limitation of this study is the short duration of the trial tests, which does not give clear indications of the effects of additives on the long term performance in energy efficiency. Additionally, inventory data on emissions was limited, and the low-cost additive scenario is modelled considering same amount of emissions than with commercial sulphur. However, even though emissions are expected to be similar, small changes are likely to occur.

It should be noted that the obtained results are relative to the data provided and do not forecast impacts in endpoints, or the exceedance of predefined levels and safety margins. Environmental risks associated with impacts are not included.

4. LCC: ENA POWER PLANT

The methodology as described in paragraph 1.2 was applied for ENA in Sweden (see figure 8), a 70 MW_{th} power plant. Tests were performed with gypsum.

Figure 8: The ENA powerplant in Sweden (left) and the gypsum additive used in ENA

4.1 Baseline scenario

The gathered data for the baseline scenario of ENA is based on data from 2015 which was a regular and representative year of operation. The data is given in table 16.

Table 14: Plant data from Egger from 2015 as set for the baseline scenario of the CBA

Parameter	Value	Unit
Depreciation period	25	year
Total project costs	103.000.000	€
Net environmental subsidy	0	€
Purchasing cost wet wood chips	13	€/ton
Revenue for heat delivered	1,90	€ct/kWh
Revenue from electricity feed	2,90	€ct/kWh
Exploitation and insurance costs	6.919.603	€/year
Maximum electricity production	22.000	kWe
Maximum heat production	45.000	kWth
Thermal supply of wood chips	71.000	kWth
Heating value of biomass	12,3	MJ/kg
Biomass use on a yearly basis	87.901	ton/year
Operational (full load) hours of boiler	4.230	hours/year
Operational (full load) hours of steam turbine	2.240	hours/year
Net heat production	190.350	MWh/year
Net electricity production	49.280	MWh/year

Price inflation (yearly basis)	1,5	%

4.2 Gypsum additives scenario (high)

Full scale trials in the ENA power plant were performed in 2018. The tests were performed using 0,5 wt% of gypsum (see figure 9) as additive.

Figure 9: Gypsum additive used in the ENA power plant, mixed with demolition wood

Based on the trials, estimations were made for certain parameters, given in table 17.

Table 15: Parameters and costs for gypsum additives scenario (high)

Parameter	**Value**	**Unit**
Downtime reduction	50	hours/year
Increased total plant efficiency	1	%
Increased lifetime superheater	6	years
Costs of additive	8.420	€/year
Investment in gypsum dosing equipment	50.000	€
Additional cost for fluegas desulphurization	5.000	€/year
Additional (ash and gypsum) disposal costs	0	€/year
Cost reduction due to decreased downtime	300.000	€/year

Cost reduction due to increased lifetime superheater	16.667	€/year

As shown in table 17, the downtime of the powerplant could be reduced with 50 hours per year due to the use of 1 wt% of gypsum. Next to that, the increased total plant efficiency is expected to raise by 1% and the superheaters' lifetime would be extended with 6 years, from 12 to 18 years.

The costs related to this gypsum additives scenario (high) are also given in table 17. For a full year of operation, about 421 tons of gypsum would be necessary by the costs of €20 per ton. To be able to apply this gypsum, an investment of €50.000 would have to be done for gypsum dosing equipment. Additional costs for fluegas desulphurization were set at €5.000 per year whereas no additional disposal costs would apply.

Next to the costs and investments, also some cost reductions apply. For ENA, the downtime costs are €6.000 per hour. Based on a reduction of 50 downtime hours per year, this would save €300.000 per year due to the decrease in downtime. The lifetime of the heat exchanger, which costs €600.000, would be extended from 12 to 18 years resulting in saving €16.667 per year.

The total plant efficiency is increased by 1% which is modelled as a decrease in thermal supply of wood chips, thus less biomass use on yearly basis.

As result, for using 1 wt% gypsum additive in the ENA power plant, calculated through a discounted cashflow, the cost reduction (before interest and corporate tax) for a full year of operation is €334.000 per year.

4.3 Gypsum additives scenario (low)

Since the data for the cost reductions and the increase in boiler efficiency were estimated values, another scenario has been calculated in which the benefits of the gypsum additives scenario (high) are all only half of the estimated values. This affects the estimation for the decrease in downtime hours, the increased boiler efficiency and the increased lifetime of the superheater. Table 18 shows the parameters and costs for the gypsum additives scenario (low). The amount of additives will stay the same (1 wt% of gypsum).

Table 16: Parameters and costs for gypsum additives scenario (low)

Parameter	**Value**	**Unit**
Downtime reduction	25	hours/year
Increased total plant efficiency	0,5	%
Increased lifetime superheater	3	years
Costs of additive	8.420	€/year
Investment in gypsum dosing equipment	50.000	€
Additional cost for fluegas desulphurization	5.000	€/year
Additional (ash and gypsum) disposal costs	0	€/year
Cost reduction due to decreased downtime	150.000	€/year
Cost reduction due to increased lifetime superheater	10.000	€/year

The affected benefits, which are reduced by 50%, results in less cost reductions (due to the decreased amount of downtime hours and the increased lifetime of the superheater). Contrary, the costs and investments stay equal to the gypsum additives scenario (high). As result, calculated through a discounted cashflow, the cost reduction (before interest and corporate tax) for a full year of operation is €134.000 per year.

4.4 Conclusion

As a final result, for 70 MW_{th} plant ENA, a yearly cost reduction between €134.000 and €334.000 (before interest and corporate tax) could be realised by applying 1 wt% gypsum within the fuel mix, see figure 10.

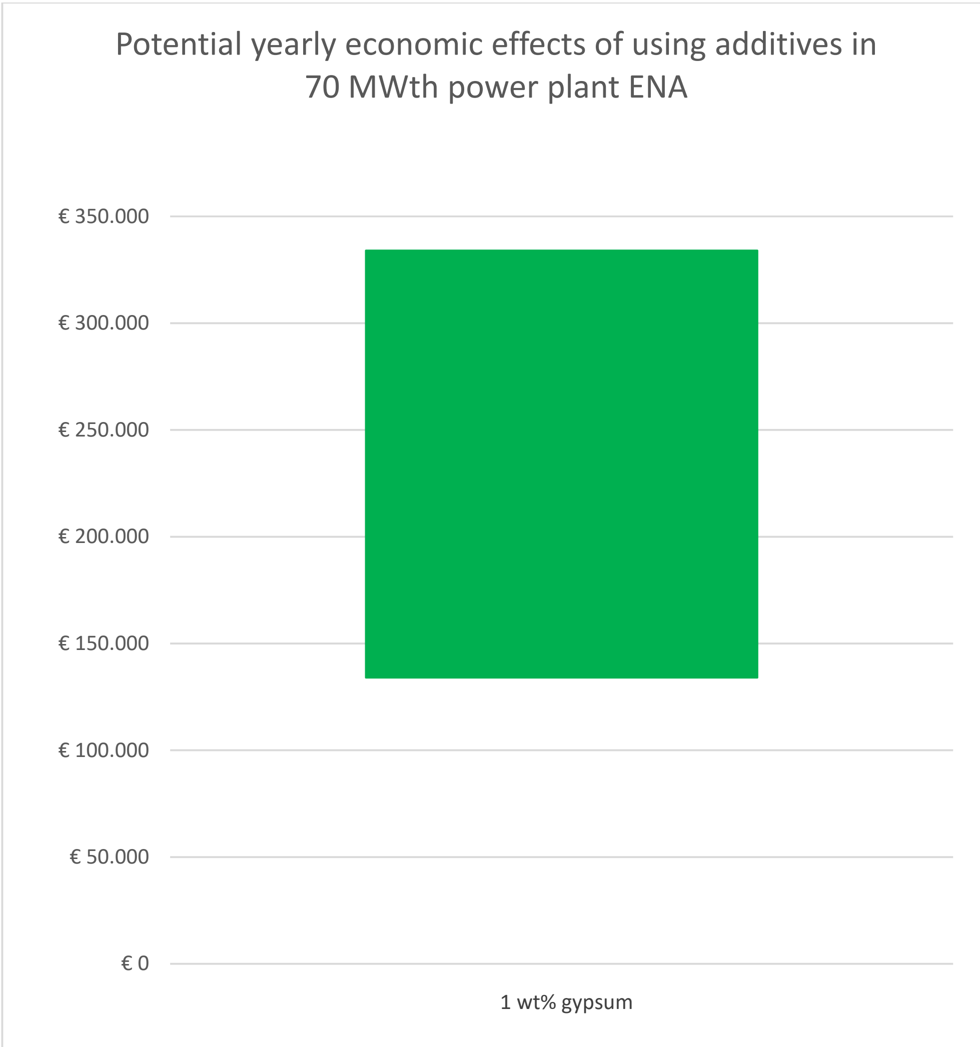


Figure 10: Conclusion of the cost benefit analysis (CBA) for the ENA power plant in Sweden

5. References

Astrup, T.F., Tonini, D., Turconi, R., Boldrin, A., 2015. Life cycle assessment of thermal Waste-to-Energy technologies: Review and recommendations. Waste Manage., 104-115

Bates, J., 1998. Options to reduce nitrous oxide emissions (Final Report). AEA Technology Report AEAT-4180 Issue

Black-Samuelsson, S., 2012. First National Report on Forest Genetic Resources. Country report: Sweden. FAO. FAO first state of the world's forest genetic resources for food and agriculture

Cherubini, F., Strømman, A.H., 2011. Life cycle assessment of bioenergy systems: State of the art and future challenges. Bioresour. Technol. 2, 437-451

EC, 2016. Proposal for a Directive of the European Parliament and the Council on the promotion of the use of energy from renewable sources (recast) COM(2016) 767 final/2

EC, 2009. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, 2009

EMEP/EEA, 2016a. EMEP/EEA air pollutant emission inventory guidebook 2016. European Environment Agency, Copenhagen

EMEP/EEA, 2016b. EMEP/EEA air pollutant emission inventory guidebook 2016 - Emission factors. European Environment Agency, Copenhagen. 07/25

Hasler, P., Nussbaumer, T., 1998. Particle size distribution of the fly ash from biomass combustion, 8-11

IrBEA, 2016. Project report for biomass combustion emissions study. Irish Bioenergy Association (IrBEA), 1-87

Muench, S., Guenther, E., 2013. A systematic review of bioenergy life cycle assessments. Appl. Energy, 257-273

Tiwari, M., Sahu, S.K., Bhangare, R.C., Yousaf, A., Pandit, G.G., 2014. Particle size distributions of ultrafine combustion aerosols generated from household fuels. Atmospheric Pollution Research. 1, 145-150

Weidema, B.P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C., Wernet, G., 2013. The ecoinvent database: Overview and methodology, Data quality guideline for the ecoinvent database version 3, www.ecoinvent.org

Weidema, B.P., Wesnæs, M.S., 1996. Data quality management for life cycle inventories—an example of using data quality indicators. J. Clean. Prod. 3–4, 167-174

Wolf, M., Chomkhamsri, K., Brandao, M., Pant, R., Ardente, F., Pennington, D.W., Manfredi, S., de Camillis, C., Goralczyk, M., 2010. ILCD Handbook-General Guide for Life Cycle Assessment-Detailed Guidance

.

Utrecht University and Avans University of Applied Sciences
Address
Phone: 010-516 50 00
Email: info@ri.se, Internet: www.ri.se

Report :
ISBN: