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Biofficiency

Environmental impact and resource efficiency of the developed technologies (D5.2)

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Abbreviations and Acronyms

CAPEX	Capital Expenditure
CHP	Cogeneration of Heat and Power
DCB	Dichlorobenzene
DH	District Heating
EC	European Commission
EFB	Empty Fruit Bunches
EU	European Union
FB	Fluidized Bed
FFB	Fresh Fruit Bunches
FCI	Fixed Capital Investment
GHG	Greenhouse Gas
GWP	Global Warming Potential
HHV	Higher Heating Value
HTC	Hydrothermal Carbonization
HV	High Voltage
H&C	Heating and Cooling
ILCD	International Reference Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Analysis / Assessment
LCI	Life Cycle Inventory
LHV	Lower Heating Value
MACRS	Modified Accelerated Cost Recovery System
NOx	Nitrogen Oxides
OPEX	Operational Expenditure
PM	Particulate Matter
PF	Pulverized Fuel
RED	Renewable Energy Directive
SE	Steam Explosion
SO2	Sulphur Dioxide
TCI	Total Cost of Investment
TPEC	Total Purchased Equipment Cost
TSP	Total Suspended Particles

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1. Introduction

Fossil fuels have been the main source of energy for human societies in the last centuries. However, in recent years, efforts have been made to reduce their usage and replace them with renewable fuels. Biomass, which is generally considered as one of the most widely deployed renewable energy sources in our times, has been used by humans as an energy source, mainly for heating, since prehistoric times. Even nowadays, in the developing countries more than a third of the energy demand is covered by biomass. Almost 3 billion people essentially depend on biomass to meet their heating, lighting and cooking needs [1]. Another attractive feature of biomass lies in the fact that it is more evenly spread over the earth compared to petroleum, which is a definite advantage from an energy independence and energy security perspective. However, due to the nature and the diversity of the biomass fuels, achieving high combustion efficiency and at the same time low combustion emissions is far more difficult for biomass than for fossil fuels [2].

This report provides an overview of the studied scenarios on next generation combined heat and power (CHP) combustion plants fueled by raw biomass feedstock, as well as a comparison of selected pretreatment technologies, in terms of environmental impact, cost performance and resource efficiency within the scope of the EU-funded Biofficiency project, after the first 18 months of the project. The report focuses on the emissions and carbon footprint of fluidized bed (FB) combustion and pulverized fuel (PF) combustion systems, depending on the selected feedstock and supply chain configuration.

The goal of this task is the assessment of both technologies (FB and PF) in terms of emissions, possible emission reductions when using different feedstocks, fuel and load flexibility and the development of a detailed Sankey diagram of the boiler. A plant with 15 to 200 MW thermal input is the objective due to the potential for high efficiencies, more effective flue gas cleaning systems in this size, as well as reduced specific plant capital costs. A life-cycle analysis is conducted including the fuel provision, pre-treatment and emissions of the power plant to evaluate and compare the equivalent carbon footprint among different cases. Central Europe (Hamburg area, Germany) was selected as the CHP plant location for all feedstock scenarios and a large-scale CHP plant (200 MW_{th}) was assumed.

The use of biomass as a fuel is rapidly spreading in the global energy production. Energy production accounted for 28.5% of the total greenhouse gas (GHG) emissions in 2015 [3], while heating and cooling represents half of the EU's current final energy consumption [4] and 75% of the EU's consumption in this sector is still fossil-based [5]. Direct biomass combustion is a mature technology applied to many active plants worldwide, with still limited energy efficiency and high operating and investment costs, factors that lead to low profitability. The main advantage of this technology is its adaptability to different types of fuel (agricultural, urban and industrial waste, energy crops), in units with installed capacities typically ranging between 2-50 MW_{el}. Mainly due to feedstock supply cost and availability issues, dedicated biomass power plants are typically of smaller size and lower electrical efficiency compared to coal power plants (30%-34% using dry biomass, and around 22% for municipal solid waste).

Moreover, CHP facilities are becoming more common, especially at smaller scales (see Fig. 1). Small facilities are more suited to producing heat as the primary product with power as the secondary product since electricity generation is not as efficient (normally around 10% electrical conversion). Larger CHP facilities (tens of megawatts) generally produce electricity as the primary product due to higher conversion efficiencies. For combined heat & power (CHP) plants the overall efficiency may reach 85 - 90% [6], although for biomass CHP plants the overall efficiency can be as low as 70% depending mainly on plant configuration and feedstock properties. Modern biomass fueled direct combustion plants achieve higher efficiencies by incorporating technologies such as flue gas coolers or condensers in their design, and utilize either grate firing (underfeed stoker, fixed or moving grate), fluidized bed (bubbling or circulating fluidized bed) or entrained flow boilers to generate heat and power from biomass. Boiler technology selection depends on various factors, such as the plant scale and desired technical characteristics, as well as the type and quantity of the biomass fuel available. Biomass pretreatment technologies such as torrefaction, hydrothermal carbonization, and steam explosion are being evaluated in the framework of Biofficiency to make the final product resemble the properties of fossil fuels, resulting in fuel efficiency comparable to that of fossil fuels, but with a smaller environmental impact.

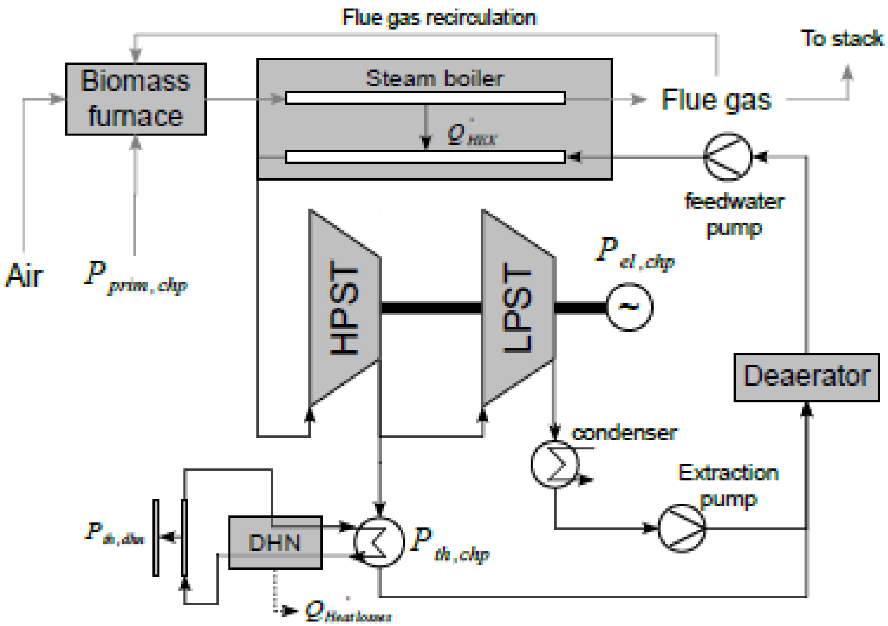


Figure 1: Typical configuration of a biomass CHP plant with DH network [2]

Concerning the Life Cycle Assessment of the biomass utilization for heat and power generation, different sub-processes and supply chain operations are to be considered. For the biomass cultivation stage, NTUA is applying available agricultural models in the literature to assess the fate of fertilizers used during the cultivation process. Available methodologies for each type of direct emissions arising from fertilizer and pesticides application during agricultural activities are applied. Direct and indirect field emissions arising from herbaceous plant growing activities (including emissions of greenhouse gases such as N_2O or CO_2, but also emissions of NH_3 and NO_x to the air, emissions of $NO_3^{2-}$and PO_4^{3-} in water, etc.) are generally significant contributors to the environmental impacts of biomass systems (more than 80%). These are compared to the forestry residues emissions.

A simplified logistic tool for calculation of total costs, energy consumption and CO_2 emissions from biomass supply chains is also being developed. The tool is able to handle different types of biomass with special care of the moisture content and biomass loss at each step of transportation, handling and storage. The models include modules for biomass processing such as hydrothermal carbonization (HTC), steam explosion and torrefaction. The LCA focuses on the following environmental impact categories: greenhouse gas emissions (carbon footprint), non-renewable primary energy use (energy footprint), water use (water footprint), but also on impacts on human health and impacts on the ecosystem. Particular attention is given to the efficient use of natural resources (incl. energy, minerals, water and land).

Literature data will be completed with results obtained from experimental campaigns performed by VAL, ORSTED and TUM and used as a basis for NTUA's final LCA, to be included in the Biofficiency final report. The goal is a comparison to existing coal-fired plants and the dissemination of the results to improve the reputation of biomass-fired combustion plants for renewable energy generation with low emissions and no threat to other utilization routes.

2. Overview of Relevant Literature: Environmental Assessment

Life Cycle Assessment (LCA) is considered to be the appropriate method to evaluate the GHG performance of bio-energy compared to that of fossil alternatives according to European legislation [5]. The GHG balance of bio-energy systems differs depending on the type of feedstock, carbon stock changes due to land use change, transport, processing of the feedstocks and the conversion technologies to produce heat or electricity. There is no single, universally accepted LCA methodology for the evaluation of bioenergy systems. Instead, there is a number of followed methodologies, each with its benefits and drawbacks. One methodology proposed by the EC for the GHG balance evaluation of biomass supply chains is the Fossil Fuel Comparator. Of course, LCA studies need to be compliant with the relevant ISO standards (ISO 14040:2006, ISO 14044:2006).

Methodological choices for LCA have an influence on the resulting environmental performance of bioenergy scenarios. It has to be noted that all LCAs display an innate degree of uncertainty due to assumptions, data limitations, and level of complexity [7]. There are two dominant methodologies for LCA studies, namely the attributional and the consequential LCA methodology. Attributional LCA describes the current environmentally relevant flows to and from a life cycle and its sub-systems, while a consequential LCA describes how environmentally relevant flows will change in response to possible future decisions [8]. The attributional modeling approach is used for compiling the life cycle inventories of all processes in the study, as in most bioenergy LCA studies [9-11], although some follow the consequential modeling approach [12], while the Cut – Off Unit process system model [13] was selected from the ecoinvent database.

In some processes multifunctionality issues arise. These are mainly the feedstock production processes. This issue is resolved in this study by performing economic allocation of the environmental burdens. The main disadvantage of this allocation method is the uncertainty of the biomass feedstock prices, as well as their variance according to location and time of the year [14], nevertheless its main advantage is the provision of financially interpretable results to policy makers.

Since the configuration under study produces two different products at the same time (electricity and heat), and since separation in individual processes in order to split the environmental burdens is not possible, a method of allocation needs to be applied on the environmental load between the two products. The ISO standards suggest to avoid allocation by expanding system boundaries, when possible [15]. When allocation is necessary, the method suggested by the European legislation [5] is that of exergy allocation, although some studies [16, 17] express their results on an end product (bioelectricity, bioheat, biocooling) energy allocation basis.

According to the International Reference Life Cycle Data System (ILCD) handbook, an LCA study consists of four phases, namely definition of Goal and Scope, Inventory, Impact Assessment and Interpretation of results [18]. Interpretation is the final stage of the LCA, however it is crucial in assessing the study's accuracy, uncertainty, limitations, and whether the goal and scope is achieved. When interpreting results, usually a sensitivity analysis is performed to evaluate the significance of the modeling assumptions. These four stages were also included in the analysis which was performed.

The functional unit is the basis for the quantification of the results of an LCA study. Common practice indicates that the functional unit should be selected in a way that corresponds to the purpose of the life cycle analysis as defined in the first step of the method. A functional unit of 1 MJ electricity, and 1 MJ of electricity and heat (exergy allocated, for purposes of compliance with the RED II standards) produced by the CHP plant was selected for this study, as this is a common practical selection in similar studies [5, 9, 13]. The selection of a mass or energy based functional unit provides a reference system that is independent of both the conversion process and the type of output, and can therefore be useful to compare alternative uses for a given feedstock [7]. For bioenergy studies, the functional unit should be directly correlated with the energy service delivered. Many researchers also express their findings based on electricity generation, using 1 kWh of electricity [17, 19] as a functional unit. However, numerous studies [10, 20] use a delivered feedstock unit (e.g. per MJ feedstock prior to densification or combustion process) so as to facilitate comparisons of intermediate products such as wood chips or raw pellets.

Similar to the functional unit, the definition of the system boundaries is a very important part of an LCA study. System boundary description determines which unit processes are included within the LCA study. Selection of different system boundaries alters the overall impact of the studied process on the environment, and hence the applicability of the results, while a comparison with similar processes may no longer be possible. In this study a cradle-to-grave system boundary was selected, including all stages from biomass feedstock cultivation up to the CHP combustion ash disposal.

The compilation of the **Life Cycle Inventories** (LCIs), along with the inventory analysis is considered the most critical stage, as this is the basis of the whole analysis [21]. The quality of the data used defines the accuracy of the final results [15]. For the compilation of the LCIs, both the ecoinvent database and available literature were used. For generic process datasets, such as transportation and waste disposal, the ecoinvent database was preferred whenever possible, as this source has a long learning experience and covers a particularly wide range of processes, thus it is used in numerous studies [13, 22]. Other LCI databases used in bioenergy studies are GEMIS 4.5 [13] Gabi Professional [9] and US-EI [19]. The implementation of the Life Cycle Inventory data has been conducted in SimaPro v8.5 software, as it is one of the most versatile and user friendly software applications for LCA, preferred by most researchers [12, 19]. Other bioenergy studies were conducted using the following software packages: CMLCA [16], Umberto [23] and GaBi [9, 22].

The LCA-type evaluation methodology described in the Renewable Energy Directive (RED) follows the entire energy chain from source to final energy product, i.e. in the case of transport the final fuel. In the case of solid and gaseous biomass used for electricity, heating and cooling, the final energy is not the fuel product; it is electricity, heat and cooling. To assess the GHG performance of biomass cogeneration, the RED methodology is extended so that conversion of the biomass fuel to electricity, heating or cooling is included in the GHG emissions calculations [5]. Cherubini et al. (2011) [8] stated that in the majority of LCA studies performed, replacing fossil energy with bioenergy results in a significant net reduction in GHG emissions.

Of course, apart from the GHG emissions, biopower and bioheat production is associated with other environmental impacts, such as eutrophication, resource depletion and acidification, therefore their environmental performance needs to be assessed by LCA methodologies (ISO 14040, ISO 14044) [24].

The recast RED provides greater flexibility to member states on the implementation choices concerning the transport mandate and sustainability criteria compared to the 2009 RED, while including the binding target to cut emissions in the Union by at least 40% below 1990 levels by 2030, in accordance with the Paris Agreement, and setting an overall renewable energy target of at least 27% for the Union by 2030 [5]. To minimise the administrative burden, the Union sustainability and greenhouse gas saving criteria should apply only to electricity and heating from biomass fuels produced in installations with a total rated thermal input equal or above to 20 MW. RED II states that the greenhouse gas emission saving from the use of biofuels, bioliquids and biomass fuels shall be at least 70 % for electricity, heating and cooling production from biomass fuels used in those installations starting operation after 1 January 2021 and 80 % for installations starting operation after 1 January 2026, compared to the EU average fossil fuel GHG emission comparator (183 g $CO_{2\text{-}eq}/MJ_{el}$ for electricity or 80 $CO_{2\text{-}eq}/MJ_{th}$ for heat, according to the latest available EU legislation values) [5], with a 1.3% annual increase target in the share of renewables in heating and cooling (H&C) for all 5 years – a target that, as EU associations representing renewable heating & cooling (RES-H&C) industries state, „lacks real ambition in a context where, under the right political impetus, renewables could deliver much more and reach a 100% renewable H&C sector in 2050“ [4]. All EU Member States must adopt the provisions from the RED II and transpose them into national legislation by 30 June 2021.

The analysis conducted herein is therefore in line with the RED II Directive, with **three main points of differentiation**: *first*, the economic allocation of cultivation burdens on the residual feedstocks (wood bark and empty fruit bunches), instead of considering the residues as totally burden-free up to the point of collection, as this part of the RED approach is a point of controversy among LCA practitioners [9, 14, 25], since the biomass residues are now being marketed and utilized as energy carriers in downstream processes, and therefore can no longer be considered as wastes according to LCA standards, but as by- or co-products. *Second*, the inclusion of the CHP plant infrastructure, so that the total impact of constructing and operating a large scale biomass fueled CHP plant in Europe can be evaluated and compared to the entire life cycle of large scale fossil CHP plants. Auxiliary equipment (e.g. tractors and trucks) and general infrastructure (e.g. roads and ports) construction impacts are not considered in the current study. *Third*, the GWP calculation is made using the most updated set of IPCC GWP CO_2 equivalence factors, instead of those included in the RED II Directive.

Concerns are expressed, however, over the potential of biomass feedstocks available as fuel for bioenergy plants in the European Union (EU). Studies provide a wide range of scenarios to estimate the biomass potential for energy under varying conditions, even beyond 2050. However, beyond 2030 there is very limited data available on biomass sources, potentials and costs [26]. Main summarized results regarding biomass potential fare shown in Fig. 2.

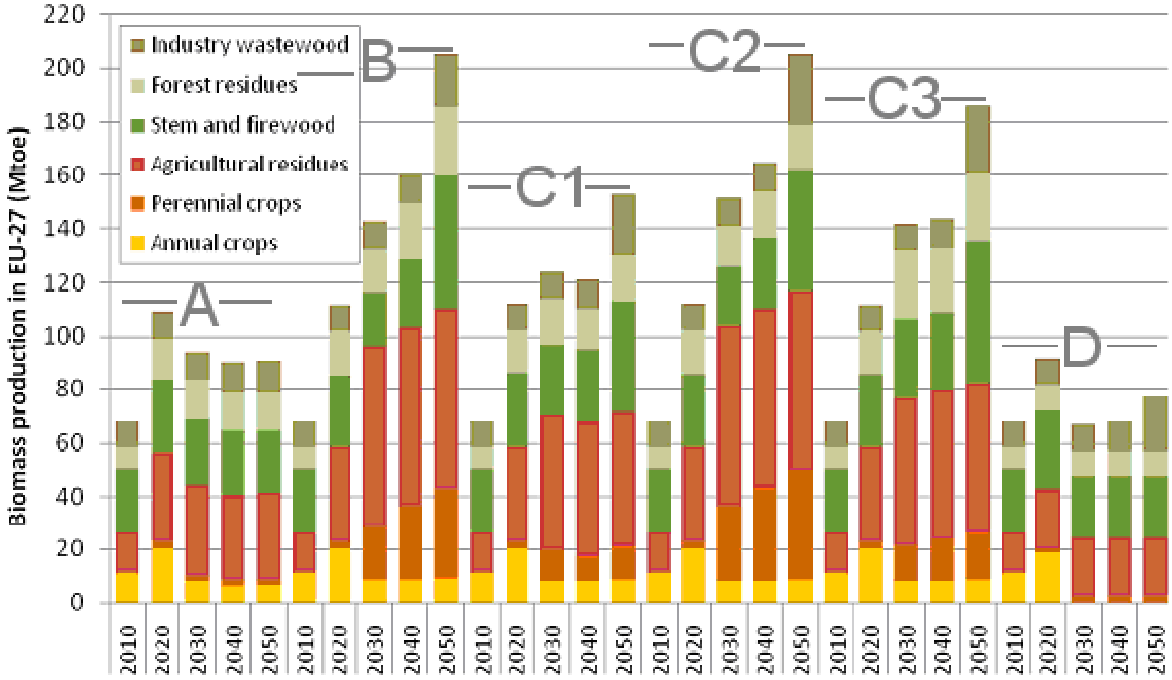


Figure 2: EU27 biomass potentials and sources for bioenergy from 2010 to 2050 under different scenarios [26]

In Canada there were 19 pellet plants operating in 2013 with a total production capacity of 1 million tonnes, however only 370,000 tonnes were sold (120,000 to Europe, 150,000 to the US, and 100,000 domestically) [27], leaving an unsold surplus of 630,000 tonnes. Summarized information on recent years' wood pellet production in North America is shown in Fig. 3.

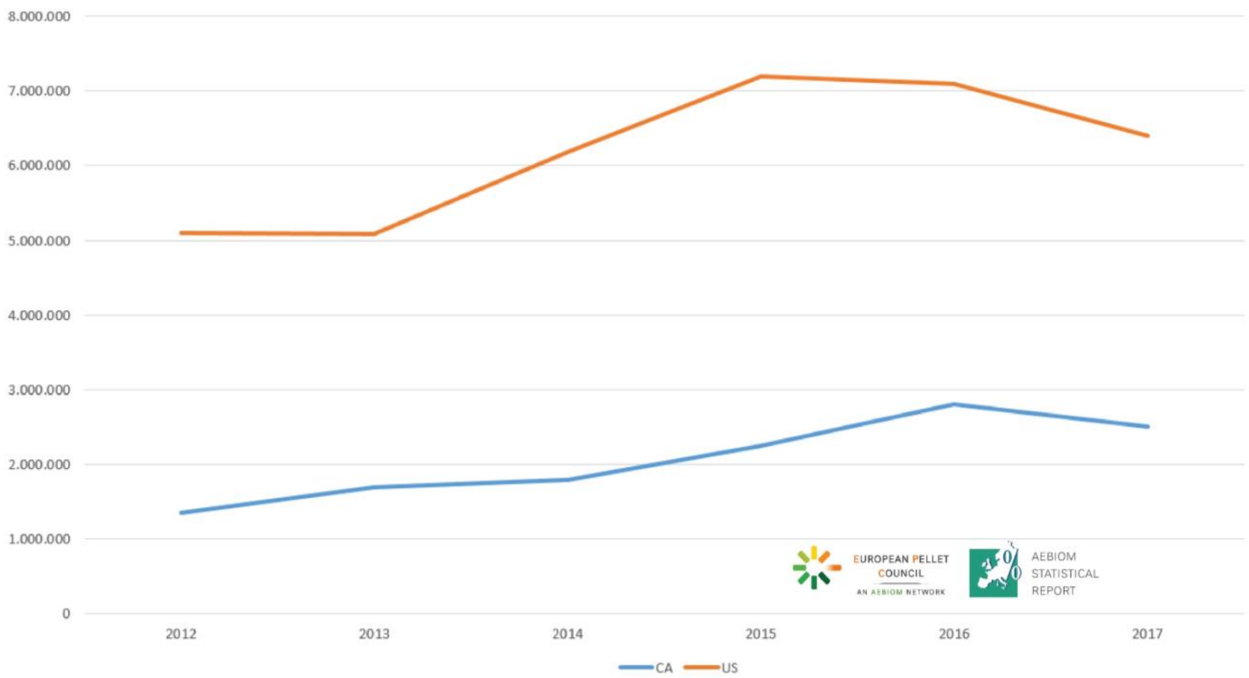


Figure 3: Wood pellet production in North America (tons) [28]

Biomass fuels can vary significantly in terms of ash content, chlorine, nitrogen and moisture content, causing variation in combustion emissions. For non-wood biomass fuels, sulfur content is also important. Different conversion technologies can result in largely different particulate matter (PM) emissions (prior to flue gas treatment). However, with the usual flue gas cleaning equipment, dust emissions are below 10mg/Nm³.

A comparative assessment concluded that CHP systems generally offer higher carbon savings than standard electricity production configurations, although CHP variants do not perform well in terms of economic parameters, either per unit of electricity produced or in terms of initial capital investment requirements. They are also the least likely systems to benefit from learning curve cost reductions [29]. For stationary gasification CHP plants, [13] concluded that there is no reason to discriminate between plant scales when estimating the environmental performance, as on a per energy unit basis, the impacts of all scales are in the same order of magnitude.

Furthermore, larger scale CHPs present a heavier impact in the globalized impact categories, such as global warming potential, mainly due to larger transportation distances, while smaller scale CHPs are higher in many localized impact categories, such as abiotic depletion and photochemical oxidation potential, presenting larger emission factors per amount of electricity produced. This happens because, for smaller units, the percentage of emissions generated from the unit operation itself (a single point source) is larger than in the case of a larger unit, where fuel processing and transport chains also have a large contribution to the total emissions. The most commonly utilized CHP technologies in Europe are presented in Fig. 4, as part of a study that collected and evaluated data for around 160 solid biomass commercial, demonstration, pilot and test scale CHP plants operating in Europe [30].

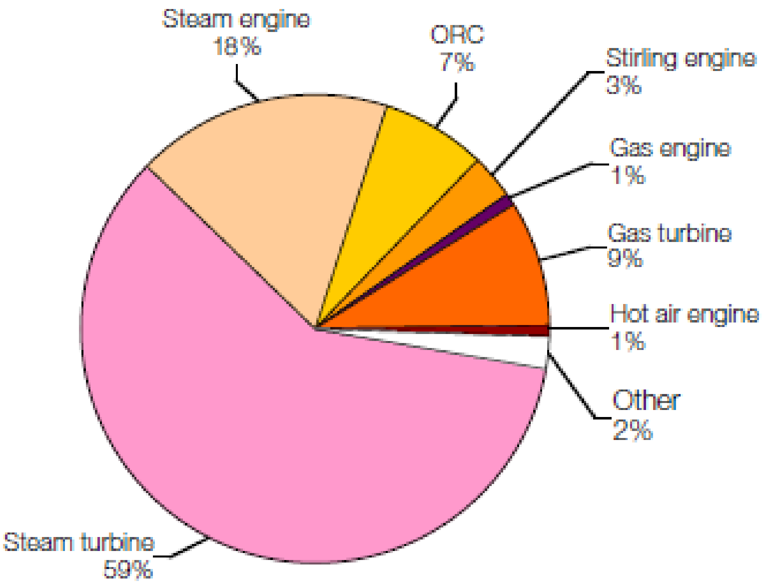


Figure 4: Main technologies of European biomass CHP plants [30]

All considered GHG emissions are typically converted to CO_2-equivalent (CO_{2-eq}) emissions using 100-year global warming potential (GWP) values from the Intergovernmental Panel on Climate Change (IPCC) [31], so that the various emissions can be combined and compared. It is important to note that there are alternative methods that could be used to evaluate climate impacts, and there is an ongoing debate regarding the use of the 100-year GWP to estimate climate impacts rather than one of other metrics (such as radiative forcing or global temperature change) [32]. The RED II provides a slightly different set of conversion factors for European studies, providing a methane conversion factor of 25 [5], although the IPCC method is still the standard method applied by the LCA community [32], therefore this is the method used in this study.

Part of the issue is that GWP values are only applicable for well-mixed greenhouse gases, which have a long lifetime. GWP does not include other anthropogenic factors that impact climate such as near-term climate forcers (e.g., ozone and aerosols, and their precursors), which have very short lifetimes, but still cause a near-term impact on climate warming over a period of several decades [33]. The Global Warming Potential is calculated according to the following characterization factors (Table 1).

Table 1: The Global Warming Potential of major Greenhouse Gases [34]

Global Warming Potential (GWP, kg CO_{2-eq}/kg emission)	
CO_2	1
CH_4	34
CH_4 (fossil)	36
N_2O	298

The utilization of biomass is not only beneficial due its reduced impact on the greenhouse effect, but also due to lower emissions of hazardous gases such as nitrogen oxides (NO_x) or sulphur dioxide (SO_2), which can exert a direct adverse effect on health of human beings and the environment. Concerning NO_x, the content of nitrogen within the fuel is an important aspect. This is not an issue when burning natural gas, as nitrogen only exists in trace amounts in natural gas. Among solid fuels, wood chips are preferable to coal, resulting in only half the amount of relevant emissions. Shifting a coal-fired CHP to a wood chip-fired CHP (assuming 100 MW capacity and 6000 full load hours) will thereby reduce NO_x emissions by 400 tons per year [35]. Regarding SO_2 emissions, biomass is beneficial as well, with wood chips producing nearly zero emissions and straw emitting only half of the amount of coal-fired plants. With small-scale plants fuelled with solid biomass, such as in the case of households, the main issue is that flue gas cleaning is usually absent and the quality of the combustion cannot be easily controlled.

Another hazardous component found in biomass plant emissions is fine particulate matter (PM), often referred to as aerosols. Aerosols do have an impact on climate, as they scatter and absorb solar and terrestrial radiation, but especially their effect on human health is severely harmful [36]. Fine particles can penetrate the respiratory tract and cause severe health problems and damage. There are estimates on cost and health problems due to these emissions. However, detailed recording and quantification of plant emissions are rare. According to regulations and BAT reports (BREFs), plant dust emissions in the EU must usually be below 10mg/Nm³. Often these particles are contaminated with heavy metal compounds. A reduction of fine particulate emissions is needed, which is achieved through pre-treatment and removal of aerosol forming elements, as well as through system optimization, improved maintenance and correct adjustment of excess air ratio, and especially flue gas cleaning [37].

The impact assessment of bioenergy production is not restricted to GWP impacts, although this is the main indicator required by the RED [5, 38], as there are many environmental indicators that are applicable. The following impact categories were selected as main indicators to evaluate the environmental profile of all scenarios: global warming, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, stratospheric ozone depletion, ozone formation, fine particulate matter formation, fossil and mineral resource depletion and land use, as these are among the most common categories reported in LCA studies of bioenergy systems [3, 8].

As far as the impact assessment methodology is concerned, ReCiPe 2016 Midpoint (Hierarchist, considering a fixed time horizon of 100 years) v. 1.02 impact assessment method [34] was selected to estimate the environmental impact of the proposed bioenergy system. As suggested, ReCiPe 2016 is the most updated method that provides a common framework in which both midpoint and endpoint indicators can be used, compared with similar methodologies to date [39]. In Fig. 5 the ReCiPe 2016 methodology is presented, providing both midpoint and endpoint level indicators and briefly describing the correlations between the two levels, while also demonstrating its suitability for single score evaluations.

Endpoint impact assessment is based on the combination and normalization of midpoint results. Whilst there is uncertainty with normalization, it is a useful process for selecting impact categories for further investigation. Results are analysed using the midpoint level categories, as these indicators are calculated directly from the inventory results and hence represent lower uncertainty levels. Midpoint results are also more convenient to interpret from an engineering and scientific point of view, and are directly comparable to other LCA and energy system assessments [10]. Apart from the RED methodology followed in many cases [40, 41], common impact assessment methods used in bioenergy life cycle assessments are CML 2001 [13], TRACI 2.1 [16, 19], IMPACT 2002+ v2.1 [42], EIO-LCA [17] and ReCiPe endpoint [10].

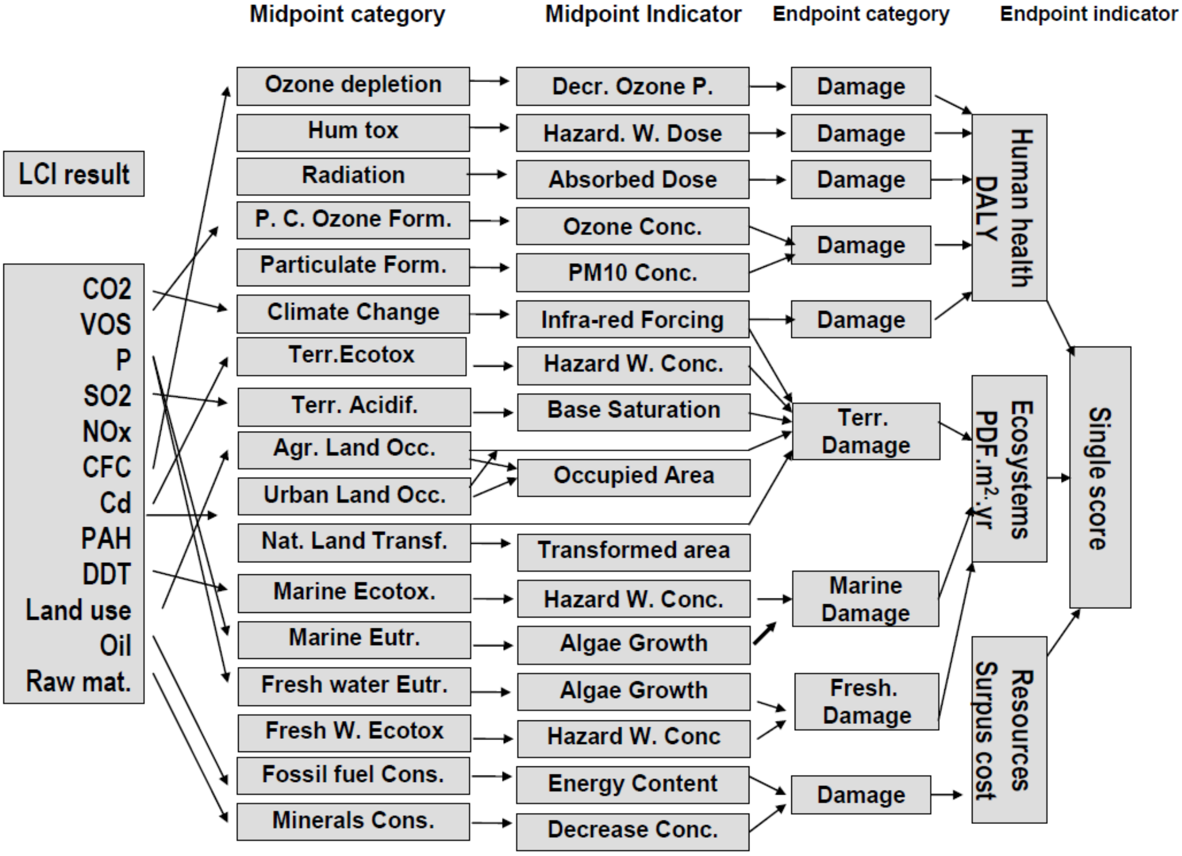


Figure 5: the ReCiPe 2016 impact assessment method [39]

During the reviewing of relevant literature on studies focused on biopower and/or bioheat production, the majority were found to be focused on either power or heat generation alone [9, 11, 24], instead of studying the cogeneration of heat and power. Numerous studies only focus solely on the life cycle of the biofuel production, not considering its use phase or waste treatment [10, 20]. Another difficulty faced was the fact that most LCA studies are limited to evaluating coal and biomass co-combustion scenarios [16, 43, 44], while numerous studies only focus on the GHG reduction, not considering the overall environmental impact of the bioenergy system under discussion [8, 11, 43]. Furthermore, most of the reviewed studies exclude fresh water depletion from their impact assessment [8, 10], as sufficient LCI data on process water consumption can be very difficult to compile. Lastly, very few studies have included indirect factors such as traffic impacts and transport disturbance of bioenergy in their impact assessment [29].

According to a review of numerous electricity generation technologies [45], the GHG emission factors of biomass conversion technologies varied greatly and ranged from 2.36 to 36.11 g CO_2-eq/MJ_{el} produced. Another study that compared micro, small and medium scale biomass cogeneration plants [13] resulted in a GHG impact of 8.8 - 10.5 g CO_2-eq/MJ_{el} for electricity production and 2.4 - 2.8 g CO_2-eq/MJ_{th} for district heat production from forest and sawmill residues at the CHP plant applying exergy allocation.

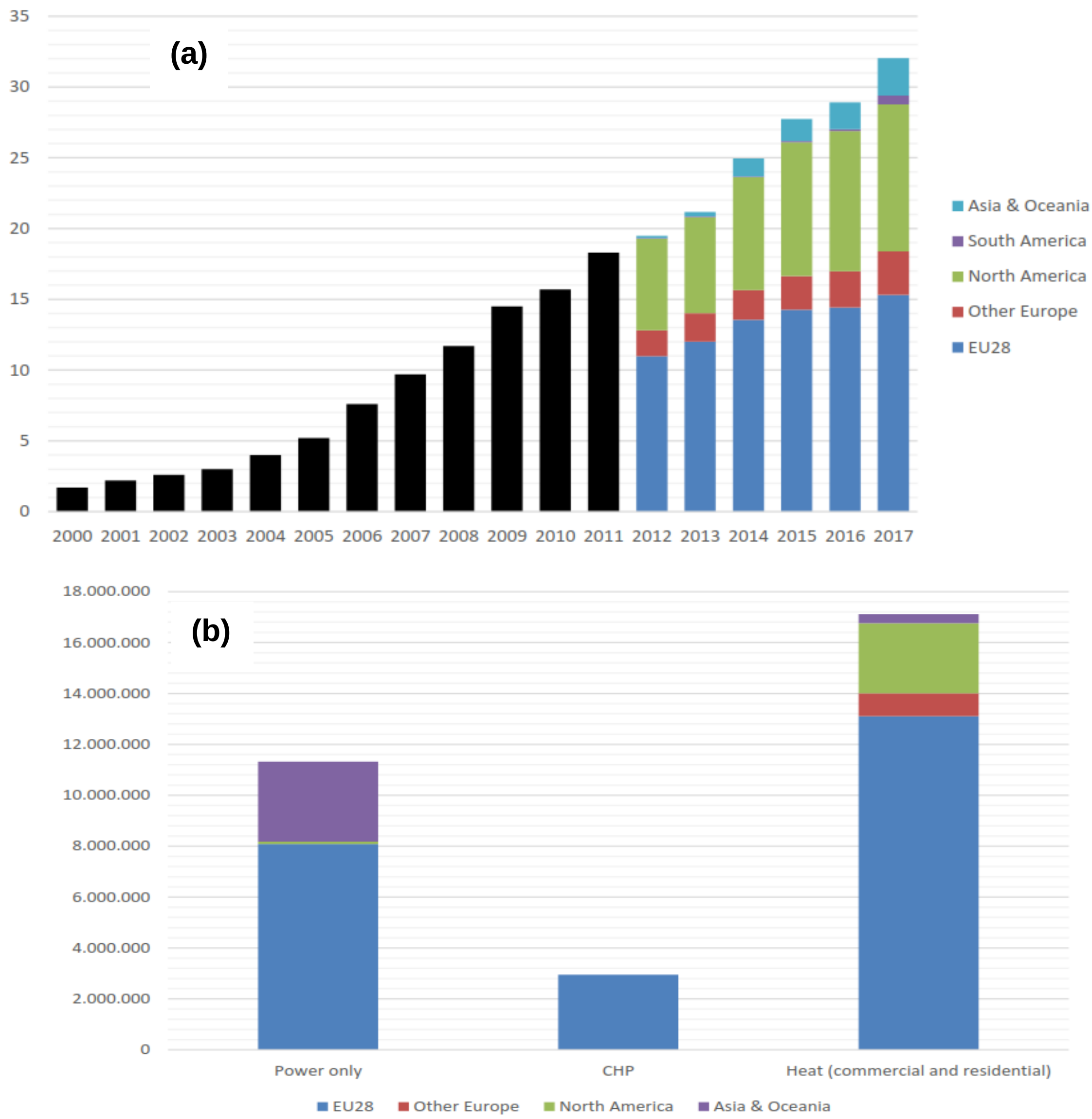
A paper found the GHG impact of electricity generation from forest residues as 26 g CO_2-eq/MJ_{el} [9] assuming a 80 MW_{el} biomass cogeneration plant, and 3.6 g CO_2-eq/MJ_{el} for electricity production from a 15 MW_{el} straw pellet fired plant, with the lower impact for straw resulting mainly from the avoided fossil electricity consumption for pellet drying.

Regarding the solid biomass CHP plant technology, most studies conducted were on biomass gasification [42, 46] and pyrolysis [29, 47]. On direct combustion technologies, a dedicated biomass cogeneration study compared the performance of moving grate versus fluidized bed boilers and found that the fluidized bed technology presents a smaller impact than the moving grate technology and can be a reasonable choice for implementation in new power plants [48]. Cambero et al. [42] concluded that boiler and steam turbine configuration CHP plants generated the largest non-biogenic carbon emission reductions.

Pretreated fuel life cycle emissions for commercial scale plants are not yet widely available, as these technologies are still under development. McNamee et al. [40] calculated the GHG impact of torrefied pellets as 29.4 g CO_2-eq/MJ_{el} when process heat is provided from combustion of wood chips and 43.1 g CO_2-eq/MJ_{el} when process heat is provided from combustion of natural gas, considering a process temperature of 250°C and a duration of 30 minutes. Stemann et al. [49] calculated the total supply chain emissions of empty fruit bunches (EFB) HTC coal production and road transport as 9.4–10.2 g CO_2-eq/MJ HHV of HTC EFB coal, which is in the same range as the supply chain emissions of bituminous coal, however infrastructure and shipping emissions were not included in the study. The net avoided CO_2 emissions amount to 67,400 t/a for a plant with a processing capacity of 40.0 kt/a EFB and 163,400 t/a for a plant of 96.7 kt/a EFB, of which 65% are related to the prevention of EFB dumping and the resultant CH_4 and N_2O emissions, while most of the remainder is due to the substitution of bituminous coal. For steam exploded wood pellets, a GHG impact of 21.67 g CO_2-eq/MJ_{el} produced [17] was calculated. Laborelec calculated a GHG impact of 36.4 g CO_2-eq/MJ_{el} for a pilot plant and 28.65 g CO_2-eq/MJ_{el} for a commercial scale plant producing steam exploded pellets for Arbaflame (Y. Ryckmans, personal communication, November 2018).

3. Overview of Relevant Literature: Economic Assessment

Nowadays, the most rapidly expanding solid biomass fuel market globally is the wood pellet market. Wood pellet production in 2006 was estimated at 6–7 Mt, it reached 14.3 Mt in 2010 and production surpassed 32 Mt in 2017 [28]. The EU 28 has the largest share in the global wood pellet demand, consuming 24.1 Mt in 2017, 62% of which was produced internally with the remaining 38% imported, mainly from North America and Russia. The majority of the EU pellet demand, 61%, (~14.7 Mt) was used for heating in the commercial and domestic sectors. This demand could be met by European pellet suppliers [50]. The remaining EU demand was used for electricity generation. This was met by imports from North America and Russia. Demand for wood pellets is expected to increase over the coming decade through continued, however slowing growth in Europe and the rapid growth in Asia. The USA is expected to continue as the largest producer of wood pellets. Throughout Europe the major growth market in the past has been the replacement of coal in the electricity sector [51]. The main producers and consumers of wood pellets are shown in Fig. 6.



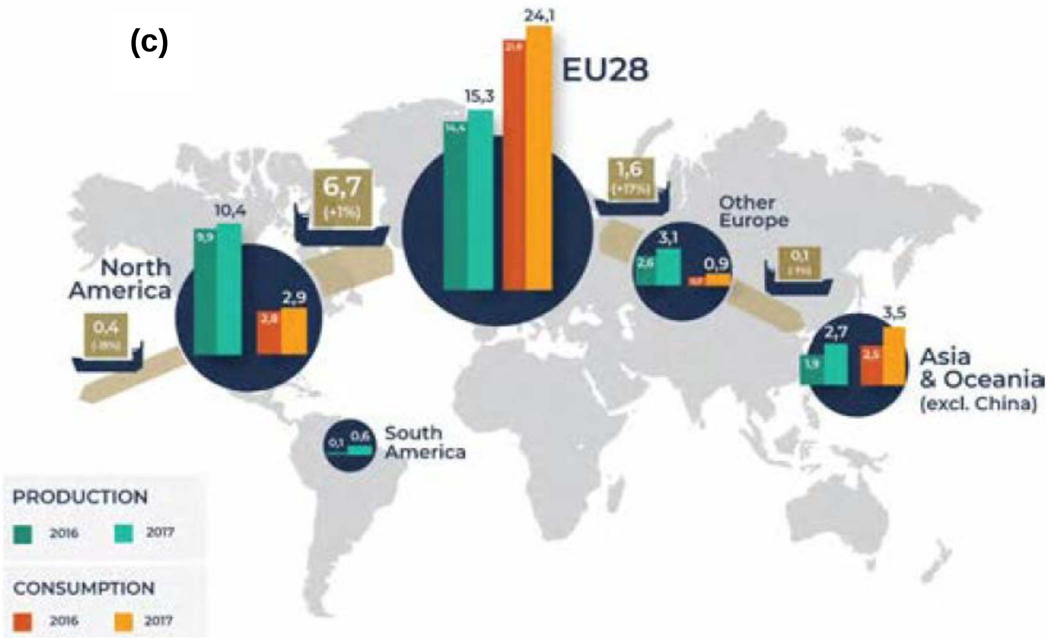


Figure 6: Main wood pellet producers (a), consumers (b) and trade (c) [28]

Biomass pellet price per unit of primary energy produced is generally lower than that of fossil fuels in the contemporary EU CHP market, such as natural gas (e.g. 36.55 €/MWh versus 55.9 €/MWh [2] for natural gas, according to Eurostat 2013 prices). Projected biomass fuel provision costs in the EU based on expected feedstock availability in 2030 (assuming 2010 prices) are shown in Fig. 7 [26].

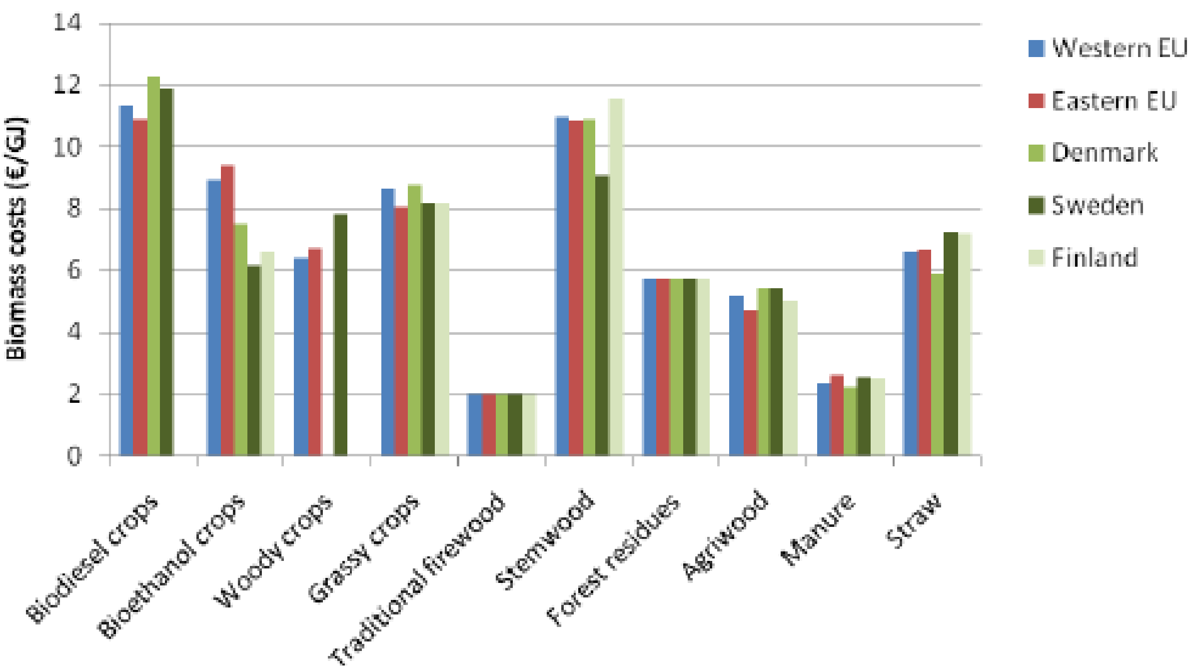


Figure 7: Average EU27 biomass provision costs per source for bioenergy and region for 2030 [26]

As discussed before, due to the versatility of biomass feedstocks, the initial investment cost of a biomass CHP plant can be significantly higher than that of a corresponding fossil fuel CHP plant [2]. A specific investment cost reported for a 5 MW_{el} steam turbine CHP plant was 2400 €/kW_{el}, resulting in a specific electricity generation cost of 0.13 €/kWh_{el} [52], while according to another European study the specific investment costs for steam cycle based biomass combustion and gasification technologies were in the range of 5000 to 8000 €/kW_{el} [30].

For plants of similar configuration and location, the specific costs are generally expected to decrease with increasing plant capacity due to economies of scale, hence the targeting for large scale units. Back-pressure turbines delivering all exhaust steam as a heat source for industrial process will reduce the need for cooling towers or air coolers compared to condensing plants designed for dedicated electricity generation. Adding steam extraction for supply of industrial process heat or district heat may add investment costs compared to a condensing plant for power production only [53].

A comparative analysis of CO_2 saving cost per MWh_{el} generated and per technology studied biomass co-firing, dedicated biomass firing, large scale PVs and offshore wind is given in [51]. According to the study's findings, although potential CO_2 emission cost savings are largely site-specific and therefore cannot be easily quantified in a more generalized approach, all the renewable technologies assessed (not including the co-firing scenarios) show CO_2 emission reduction mean costs in the range of 82–89 US$/$tCO_2$. In the same study, large scale solar PV electricity generation showed the lowest minimum CO_2 saving cost (5 US$/$tCO_2$), while a 10% biomass cofiring scenario presented the highest maximum CO_2 saving cost (199 US$/$tCO_2$). Regarding the plant technology, combustion based technologies were evaluated as more profitable over their life cycle than gasification and pyrolysis based on electricity production, despite higher operating costs. Capital costs for direct combustion were found in the range of 1708–3250 €/kW_{el} using 2005 reference prices [54]. Cambero et al. [42] concluded that the boiler and steam turbine configurations provide the lowest electricity production costs, considering a 5 MW_{el} plant size.

Considering transportation costs, short-distance transportation takes place by trucks. The clear economic benefit of pelletization can be demonstrated when taking into account that the highest economic viability limit for truck transportation of wood chips is limited to approximately 50 km for fresh biomass. For wood pellets this maximum limit is 150 km, and together with necessary storage this accounts for more than 50% of the total fuel cost [55]. For raw wood pellets produced in Eastern Canada, the combined impacts of low EU pellet prices, high wood costs owing to the cyclical low in sawmill residue production, and long supply chains have hindered this being a viable supply chain. However, the sawmilling industry is now recovering and this supply chain could prove extremely fruitful, exporting through the ports of Quebec, Trois Rivières and Montreal [27].

Regarding the overall profitability of biomass CHP systems, Trømborg et al. [56] studied the Norwegian market and concluded that CHP investments based on forest biomass fuels would demand a 50% reduction in investment costs and nearly a 100% increase in electricity prices to be profitable with 2007 biomass prices. To improve the economics of biomass cogeneration plants, the fuel cost is the most important factor. Considering the use of straw (assuming pellet price around 15 €/MWh) instead of wood pellets, the price for electricity generation could be decreased by around 40% [57]. Of course this analysis would be more accurate if the specific costs for the boiler retrofit necessary for straw combustion (higher quality alloys are needed, due to higher corrosion rates) were more thoroughly documented. Another aspect is the improvement of the plant efficiency. A total fuel utilization efficiency of 100% (EU target) would result in a decrease of around 18% in electricity generation costs, and therefore improve the economy of the plant significantly.

With regards to the pretreated pellet cost, there is little information on commercial scale pretreatment plants, as the technologies under discussion are still developing. The pretreatment with the highest current commercialization potential is torrefaction [58]. Regarding torrefied fuel pellets, they have been found to develop a hydrophobic nature and improved grindability characteristics compared to raw biomass [59].

A sensitivity analysis [60] has shown that capital investment cost and low heating value are the main barriers to economic feasibility of state-of-the-art torrefied pellets. The annual cost of torrefied pellet production calculated in same study is less (6.11M€) than for conventional pellets (7.05 M€). The specific costs, however, were greater for torrefied pellets (95.54 €/t), compared to 88.09 €/t for conventional wood pellets. The specific costs per unit of thermal fuel energy were 5.22 €/GJ and 5.58 €/GJ for torrefied and conventional pellets respectively. When pellet transportation was ignored, the specific costs of thermal fuel energy for torrefied pellet production were calculated at 3.02 €/GJ, compared to 2.23 €/GJ for conventional wood pellets. This shows the importance of the shipping distance used in the analysis to evaluate the economic benefit of torrefaction (based on energy cost) because at the production site, the cost of the produced fuel energy is much lower for conventional pellets.

For the other pretreatments there is few data available on commercial plant investment and product cost. The total cost of the HTC EFB coal pellets according to [49], including shipping to Europe, amounted to 9.67 €/GJ_{HHV} for the smaller plant with a capacity of processing 5.7 t/h EFB and 7.94 €/GJ_{HHV} for the larger plant with a 13.8 t/h processing capacity. This was compared to industrial wood pellets which ranged between 114 and 140 €/t between 2007 and 2010, corresponding to 6.54 – 7.96 €/GJ_{HHV}.

A case study of electricity generation from steam exploded wood pellets in Ontario, Canada, concluded that on an energy basis steam exploded pellets have a slightly higher production cost ($10.2/GJ) than conventional wood pellets ($9.9/GJ) [17]. The study was conducted for a pellet plant production capacity of 150,000 oven dry tons per year supplied to a large-scale, retrofitted power plant with a net capacity of 150 MW_{el}. Another feasibility study resulted in a reference fuel cost of 33 €/MWh for black pellets, considering a biorefinery with a production capacity of 80-160 kt/a black pellets [61]. The higher cost for steam-treated pellets arises primarily due to greater capital requirements associated with the steam treatment reactor and ancillary equipment, which increases capital financing costs by approximately 50%. In general, pelletized solid biofuel prices are usually in the range of 90 – 135 €/t [60]. FutureMetrics concludes on a cost of 126 $/t for steam exploded pellets from Arbaflame with a LHV of 18.64 GJ/t, versus 150 $/t for white wood pellets (fob) in North America with a LHV of 17.40 GJ/t, but their model is based on offering steam exploded pellets at a price equivalent to white pellets on an energy equivalent basis (Y. Ryckmans, personal communication, October 2018).

4. Methodology

a. LCA scenario evaluation

The attributional modelling approach is applied in this study. Where multifunctionality issues arise, allocation was the selected method for attribution of the responding environmental burdens. In most cases, allocation is only applied to the main products generated from the process, not to waste products. In our study we treated waste biomass species such as agricultural or forestry residues as byproducts, driven by their increasing economic value during recent years, therefore a part of the environmental burdens from their production processes was assigned to them via economic allocation, as suggested in [62].

The assumptions underlying this analysis were to a great extent documented through other studies [16, 63, 64]. The processing of the collected Life Cycle Inventory data was conducted in SimaPro v8.5 software. The life cycle inventories were compiled using data from the ecoinvent database version 3.4 [65], as well as datasets from relevant literature. The four phases of the LCA study (Goal and Scope definition, Inventory, Impact Assessment and Interpretation of results) are now presented.

- Goal and Scope Definition

The scope of this study is to determine the environmental impact of biomass fueled cogeneration plants and to perform a comparison with existing coal plants. The possibility of further reducing the plants’ carbon footprint is also investigated through combustion of different types of fuel (therefore development of different supply chain scenarios) and different pretreatment technologies.

Given that the full life cycle is being studied, from the cultivation and collection of biomass to be utilized as fuel to ash management resulting from combustion, this study belongs to the category of "cradle-to-grave" analyses.

- Functional Unit

When the LCA method is applied in the field of bioelectricity generation, as in the present study, the choice of **one produced megajoule of electricity (1 MJ_{el})** and **one produced megajoule of heat (1 MJ_{h})** respectively are considered suitable functional units, as they facilitate comparison between different power and heat generation systems. Since electricity is the main product (the one offering higher revenues), the results of this report are presented with respect to the electricity production of each scenario, therefore per megajoule of produced electricity. The MJ is preferred to the MWh to facilitate compatibility with the RED methodology and comparability with the electrical EU Fossil Fuel Comparator.

- System Boundaries

For this study, which deals with life cycle analysis of cogeneration of electricity and heat from biomass, the system boundaries include the collection and transportation of the biomass to the pretreatment plant, the pretreatment process itself, the transportation to the cogeneration unit, the transport, processing and disposal of pretreatment waste (upstream processes), the utilization of the fuel at the cogeneration plant (direct processes) as well as the transportation, treatment and final recovery or disposal of combustion residues (downstream processes). The pretreatment and CHP plant construction and decommissioning stages are included in the system boundaries for all scenarios. The transfer of electric and thermal energy to the end users is not considered within the boundaries of the studied system. Carbon capture and storage technologies were not considered as part of the plant configuration, as this would render the results not comparable to the majority of relevant bioenergy studies.

Environmental issues considered in the study include effects on human health (e.g. toxicity, particulates), ecosystems (e.g. acidification, eutrophication), land use, resource (mineral, water and fossil) depletion and climate change. As per the RED II guideline, apart from the building infrastructure, no equipment or machinery manufacturing was taken into account when compiling the LCIs [5]. A graphic representation of the system boundaries and the main process steps of all studied scenarios is shown in Fig. 8.

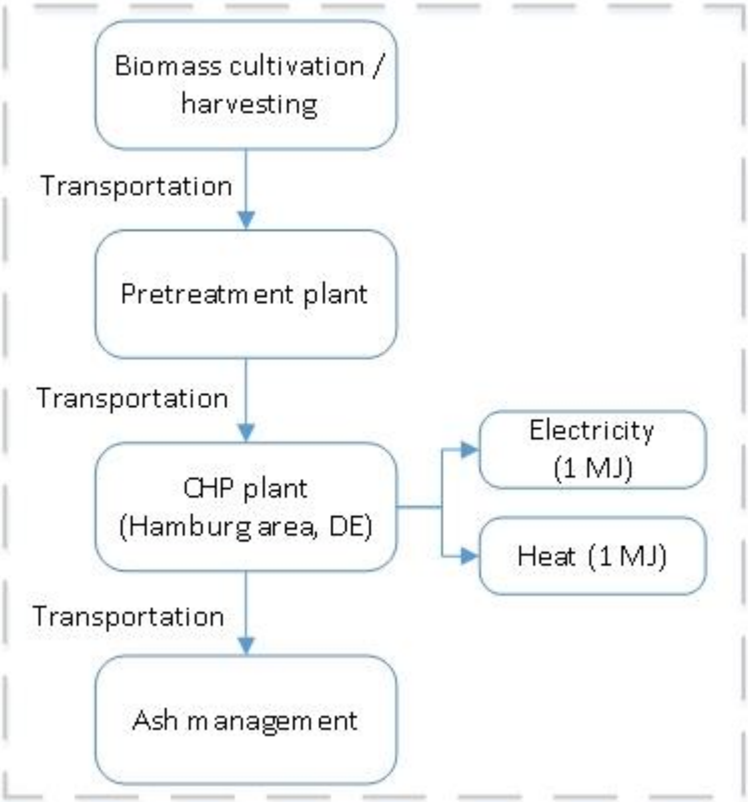


Figure 8: System boundaries and main process stages of the studied scenarios

- Impact Assessment

ReCiPe 2016 Midpoint (H) v. 1.02 impact assessment method [34] was applied to estimate the environmental impact of the proposed bioenergy system. The following impact categories were selected as main indicators to evaluate the environmental profile of all scenarios: global warming, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, stratospheric ozone depletion, ozone formation, fine particulate matter formation, fossil and mineral resource depletion and land use.

Regarding the biomass plant operation, the CHP plant resource efficiency is calculated according to:

$$\eta_{resource} = (GWh_{out}/year) \,/\, (GWh_{in}/year) \quad (1)$$

The resource efficiency is used to compare how well the different sub scenarios utilize the resources. A resource efficiency of 1 would mean that the energy input is equal to the energy output, i.e. no losses. This is an indicator that would require more detailed modeling to provide realistic results and will be evaluated later on in the project, along with the construction of the Sankey diagrams of the boilers.

According to the recommendations made by the European Commission [5], the GHG emissions (carbon footprint) from the production and use of solid biomass fuels shall be calculated as:

$$E = e_{ec} + e_{l} + e_{p} + e_{td} + e_{u} - e_{sca} - e_{ccs} - e_{ccr} \quad (2)$$

Where:

E	= total emissions from the production of the fuel before energy conversion, g CO_2eq/MJ
e_{ec}	= emissions from extraction or cultivation of raw materials, g CO_2eq/MJ
e_l	= annualized emissions from carbon stock changes caused by land use change, g CO_2eq/MJ
e_p	= emissions from processing, g CO_2eq/MJ
e_{td}	= emissions from transport and distribution, g CO_2eq/MJ
e_u	= emissions from the fuel in use (greenhouse gases emitted during the combustion of solid biomass), g CO_2eq/MJ
e_{sca}	= emission savings from soil carbon accumulation via improved agricultural management, g CO_2eq/MJ
e_{ccs}	= emission savings from carbon capture and storage, g CO_2eq/MJ
e_{ccr}	= emission savings from carbon capture and replacement, g CO_2eq/MJ

The emission factors used for this study were either retrieved from ecoinvent or from other relevant literature, expressed in terms of units of mass per kg of fuel consumed. Due to the extreme variability of emissions according to the chemical and physical characteristics of biomass, as well as the type of combustion facility and installed emission control systems, a collection of experimental data from the combustion of the selected feedstock types in commercial or pilot scale boilers resembling the selected technical and operational specifications would be the preferred method.

According to the European Commission, the emissions for combined heat and power plants shall be allocated to the electricity and heat based on the fraction of exergy of each product. The life cycle GHG emissions of biomass energy utilization must be compared to average electricity production mix carbon footprint values, such as the average EU Fossil Fuel Comparator for electricity (183 g CO_2eq/MJ electricity produced, or 212 g CO_2eq/MJ electricity for the outermost regions, as defined in the COM 10308/18, Annex V, Art. 19 [5] or 441 g CO_2eq/kWh according to the 2014 ELCD database [66]) and heat (80 g CO_2eq/MJ heat according to COM 10308/18, Annex V, Art. 19 [5]), in order to calculate emission savings. Of course, the definition of the fossil reference system at this point has a major influence on the resulting savings calculation. The emissions from electricity production EC_{el} shall therefore be calculated using the total fuel emissions E as:

$$EC_{el} = (E/\eta_{el})(C_{el} \cdot \eta_{el}/(C_{el} \cdot \eta_{el} + C_h \cdot \eta_h)) \quad (3)$$

And the emissions from heat production EC_h shall be calculated as:

$$EC_h = (E/\eta_h)(C_h \cdot \eta_h/(C_{el} \cdot \eta_{el} + C_h \cdot \eta_h)) \quad (4)$$

Where:

C_{el} = Fraction of exergy in the electricity, set to 100 %, C_{el} = 1

C_h = Carnot efficiency (fraction of exergy in the useful heat). For temperatures lower than 150°C, the C_h is defined as Carnot efficiency in heat at 150°C, which is 0.3546

η_{el} = The electrical efficiency, defined as the annual electricity produced divided by the annual energy input (34% in our case)

η_h = The thermal efficiency, defined as the annual useful heat output divided by the annual energy input (51% in our case)

The relative GHG emission savings from biomass consumption in energy production instead of fossil fuels is calculated as follows:

$$SAVING = (EC_F - EC_B)/EC_F \quad (5)$$

Where EC_F is the total emissions from the fossil fuel comparator and EC_B total emissions from the biomass based scenario [5]. For the electricity scenarios, a 80% demand for emission saving, along with a fossil fuel comparator of 183 g CO_{2eq}/MJ electricity means that the acceptable scenarios shall have a GHG impact of up to **36.6 g CO_{2eq}/MJ** electricity produced.

b. Economic evaluation methodology

A number of preliminary economic assessments have been conducted for some of the cases under study in the Biofficiency project.

The analysis was based on the following raw feedstock prices: 12.75 €/t for spruce bark from Sweden (with 18.5 t/ha estimated yield) [67], 12.75 €/t for wheat straw from Germany (assuming 2.65 t/ha yield) [68], 3 €/t for EFB from Malaysia (considering a 4.25 t/ha yield) and 34 €/t for miscanthus from France (assumed yield: 22.5 t/ha).

For the collection, a cultivation area was calculated using the equation:

$$\bar{R} = \frac{2}{3}\sqrt{\frac{n}{\varphi}}\sqrt{\frac{\dot{m}_{(torr/HTC/SE)}}{yield}} \quad (6)$$

With n=8, φ=0.4.

The TCI calculation was performed as per [69], as a percentage of the TPEC, while the equipment cost was estimated using a scaling factor for the equipment costing of 0.6 and time-adjusted according to the CEPCI 2017 index. The indirect costs were evaluated as 128% of the TPEC. The fixed operating costs were calculated as: 7% of the FCI for maintenance and repairs, 2% of the FCI for insurance, 2% of the FCI for taxation and 15% of labour cost for general expenses. The average wage in the EU was taken by Eurostat's public records [70]. Depreciation was evaluated following the MACRS method, assuming a 7 year depreciation period.

The electricity production cost is calculated from equation 7 [71]:

$$C_{el} = CAPEX + OPEX - (Heat_{sale,yr}) \quad (7)$$

Where CAPEX, OPEX and heat sales are expressed in €/a in equation (7).

The heat sale price was estimated in a range from 30 to 40 €/MWh, based on substitution of natural gas – derived district heat assuming 95% boiler efficiency, while the sanitary landfill tax for the ash is taken as 50 €/t ash disposed [63]. The TCI for the CHP plant was estimated as 250 M€, assuming a specific investment cost of 4200 €/kW$_{el}$ [72].

In general, for a biomass CHP scenario to be considered economically viable, the resulting electricity production cost must not exceed 100 €/MWh [73].

For the scenarios evaluated in the context of the present study, the following transportation scenarios have been selected to calculate the cost of each biofuel supply chain: all transportation from the harvesting locations to the pelletization / pretreatment plants was considered as 50 km distance by a 40-ton truck, while the transportation to the CHP plant was considered as described in Table 2.

Table 2: Transportation to large scale CHP plant located in Hamburg, Germany - all fuel supply chains (economic evaluation)

Transportation	***Wheat straw***	***Miscanthus***	***Empty fruit bunches***	***Spruce bark***
		Distance (km)		
Train	150	1000	150	250
Ship	0	0	17100	0

5. Description of studied LCA scenarios

Available experimental data for PF and FB combustion technologies will be implemented in the final LCA models from the relevant pilot and large scale plant tests, as foreseen in the task description based on the T5.1 database. For the present preliminary evaluation of the comparative cradle-to-grave scenarios, one simplified emissions dataset for fuel combustion at the CHP plant level is used, based on the PF combustion of a single fuel (raw wood pellets) in a CHP plant in Germany (Hamburg area).
All pretreatment processes (including pelletization) have been considered to take place in the vicinity of the biomass collection / harvesting location, as in any other case the feedstock would be more sensitive to degradation due to higher moisture content. Of course, the transportation of pretreated fuel is also economically preferable to the transportation of raw feedstock.

- Transportation

Transportation emissions are estimated using the ecoinvent database entries for ship, truck and train cargo transportation. Regarding train transportation, the possibilities for lowering supply-chain emissions through train transportation depend on local biomass availability and the development of the local road network around the plants. In general, the poorer these conditions are in the plants' surrounding area, the more GHG savings train transportation may offer. As feedstock demand grows and distances become larger, the emission savings by train transportation are expected to rise even further [74]. The trucks are assumed to be EURO 4 compliant, while the maximum feedstock mass loss during transportation and storage is estimated at 3% [75].

In all cases the maximum losses during the transportation and storage of the fuel were considered as 3% of the dry biomass weight [76]. The collected ash is assumed to be initially delivered for landfilling in all scenarios, before extending the study to include ash valorization in industrial or agricultural applications in WP6. All resulting biomass ashes are considered to be disposed of in a sanitary landfill, including a transportation step of 30 km up to the landfill site, using a 16-ton lorry transport dataset from ecoinvent. The biomass ash is modeled as waste wood ash using the relevant ecoinvent waste treatment dataset.

- Combustion and CHP plant operation

The modeled biomass CHP plant must be compared with the average fossil EU comparator, when following the revised RED methodology, otherwise it needs to be compared with the fuel and the technology it will most probably replace in the energy mix. This was assessed as a lignite CHP plant located in Germany, as the LHV of lignite is within the same range as those of the studied pelletized fuels, while lignite is still one of the main fossil fuels used in Germany [77]. For facilitating comparison, the biomass CHP plant is considered to provide the same electricity and heat generation as the lignite reference CHP plant, having similar construction and operational characteristics. The lignite CHP plant is used for basic load with 6000 hours of operation at full capacity per year. The reference lignite CHP plant is assumed to operate for 200000 hours during its lifetime. The biomass CHP plant under discussion has a lifetime of 40 years, with a basic load operation of up to 8000 hours at full capacity annually. This enhanced plant capacity factor and lifetime can be justified by improved operation strategies arising from tackling corrosion issues, as also investigated through this project (material investigation, new mixtures of additives, etc.). Electricity transformation requirements were not included in the LCI datasets.

The combustion LCI (used as reference dataset) is the same for all processes (based on ecoinvent dataset: Electricity, high voltage {RoW}| electricity production, lignite | Cut-off, U).

This includes water consumption, combustion emissions and waste treatment. Combustion additive inputs, as well as bed material flows for the fluidized bed scenario, are neglected at this stage of the study. The feedstock provision is modeled separately to represent the change in feedstock demand according to the variance of the fuel LHV. The ash by-product is corrected for each fuel according to the fuel composition. The LCI for wood combustion is shown in Table 3.

It is stressed that this dataset is based on an ecoinvent copyrighted process, so the initial values are not to be publicly demonstrated. These values are to be refined, however, according to industrial experts' estimations and process modeling results, to reflect the actual material and energy flows inside large scale biomass plants. Combustion additives such as coal fly ash are not included in the LCI datasets in this stage, as there are no sufficient data regarding their origin and the quantity required from each for a large scale, continuous operation biomass CHP plant. The main additives to be added in the combustion LCI datasets are sand, kaolin, olivine or other relevant bed materials for the BF combustion dataset, as well as coal fly ash for the PF combustion dataset.

Table 3: Combustion LCI for all scenarios, for production of 1 MJ_{el} (based on ecoinvent dataset: Electricity, high voltage {RoW}| electricity production, lignite¸ emissions adapted from [78])

Inputs: materials / fuels / resources	
Fuel pellets	mass varies with LHV
Water, cooling	0,166 m^3
Wood ash transport, lorry 7.5-16 metric ton, EURO4	mass varies with ash content
CHP plant construction infrastructure	2,518E-12 p
SO_x retained in FGD	1,453E-6 kg
NO_x retained in SCR	8,120E-5 kg
Water, decarbonized	0,4655 kg
Water, completely softened	0,0186 kg
Chlorine, gaseous	3,103E-5 kg
Emissions & Waste treatment	**kg/MJ_{el} (energy allocated)**
Dinitrogen monoxide	2.353E-6
Mercury	1.176E-9
TSP	2.941E-5
Nitrogen oxides	2.382E-4
Zinc	6.765E-9
Sulfur dioxide	5.588E-6
Water/m3	1.580E-06
PAH, polycyclic aromatic hydrocarbons	3.824E-11
NMVOC, non-methane volatile organic compounds	1.500E-5
Methane, biogenic	9.118E-6
Carbon monoxide, biogenic	2.647E-4
Cadmium	7.941E-10
Dioxins	4.118E-14
Naphthalene	6.806E-9
Residue from cooling tower	1.552E-5
Wood ash, sanitary landfill	5.61E-4

Due to lack of experimental combustion data for PF and FB technology at this scale for all investigated raw and pretreated fuels, an initial combustion process was set up using the same utilities demand and combustion emissions dataset for all fuels. This dataset was based on ecoinvent's electricity production from lignite cogeneration plant dataset, assuming negligible differences in plant infrastructure and operation, supplemented with biomass combustion emissions taken from Energinet's study on wood fired decentralized CHP generation ([78], Table 5.4) regarding the flue gas emissions. At this point it is reminded that, as IPCC Guidelines clearly state, the emission factor of wood can vary considerably, and therefore contribute to inherent uncertainty [31]. The emissions were expressed on a per output unit basis assuming an electrical efficiency of 34% and a thermal efficiency of 51% (thus assuming 85% overall cogeneration or fuel utilization efficiency).

The steam consumption for the drying of pellets is taken as 3 MJ/kg H_2O evaporated. All pretreatment processes are considered to take place in an integrated pretreatment and CHP plant, so that the electricity required for the pretreatment is generated in the CHP unit, lowering the environmental impact of the pretreatment step. Furthermore, drying of biomass after thermal treatment can be to a large extent covered by heat from a flue gas cooler when considering an integrated CHP and fuel pretreatment plant. This can have a significant impact on overall fuel utilization (biomass to heat, power and pellets). The volatiles from the pretreatment processes are also considered to be combusted in the biomass boiler, lowering the electricity demand even further. For the torrefied wood pellets, the torrefaction step is modeled as prior to the pelletization stage. For the empty fruit bunches, mechanical dewatering precedes the pelletization step.

The feedstock scenarios, both for raw and pretreated fuels, analyzed for the complete cradle-to-grave analysis are as follows:

- Wood pellet scenario: In this scenario (see Figure 9), wood pellets are produced in Canada and transported to Germany to be used in a large scale CHP plant. Since this is recognized as a typical transportation route for wood pellets, the impact of torrefaction (conducted in Canada, prior to shipping to Europe) on main environmental and economic indexes is discussed.

Figure 9: Graphic illustration of the wood pellet scenario.

- EFB pellet scenario: In this scenario (Figure 10), EFB is collected from palm oil mills in Indonesia and Malaysia. It is either dried and pelletized at the processing plant in Malaysia to be transported to Germany, or pretreated by HTC, pelletized at the processing plant in Malaysia and then transported to the CHP plant in Germany. Treatment of EFB with HTC is considered an appropriate pathway for upgrading this waste biomass due to its high moisture content.

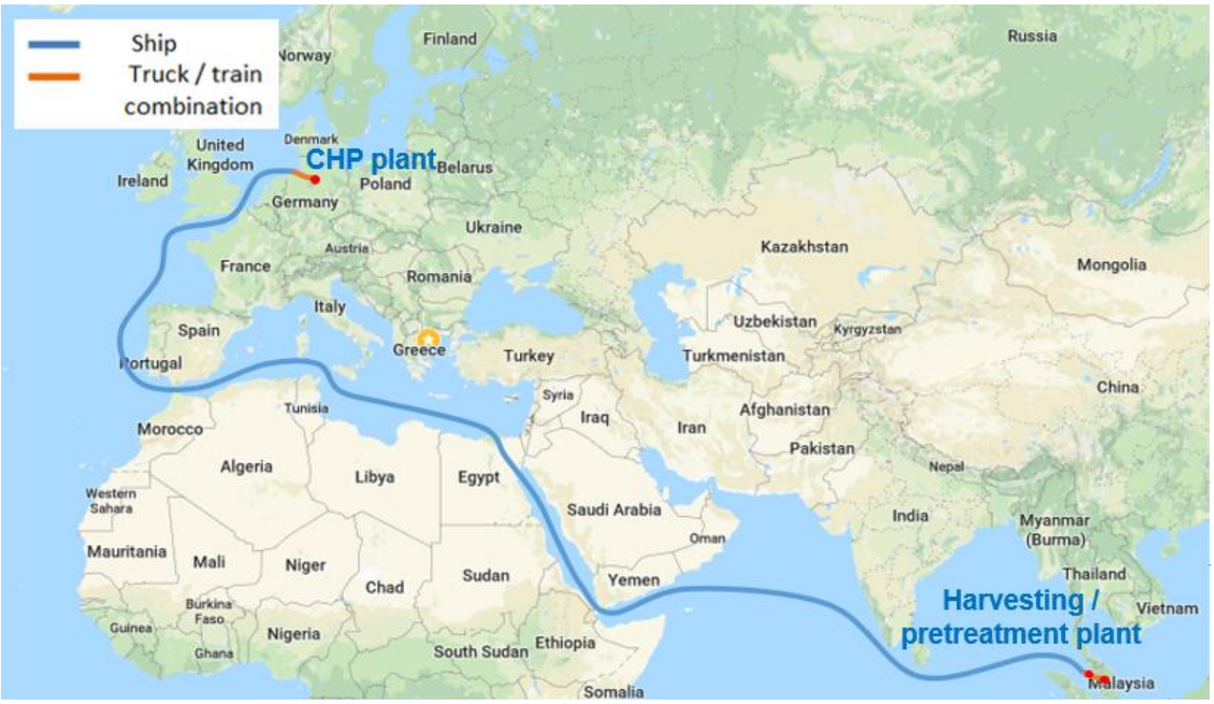


Figure 10: Graphic illustration of EFB pellet scenario.

- Bark pellet scenario: In this scenario (Figure 11), the use of bark pellets from Finland for the CHP plant is evaluated. It is assumed that the fuel comprises of bark and wood residues which is either dried and pelletized or pretreated and pelletized at Metsä Fibre's Bioproduct Mill. Steam explosion is the considered pretreatment process, since it is also of particular interest for bark upgrading also for the pulp and paper industry. Additional wood residues are considered due to insufficient bark quantities for large scale CHP operation.

Figure 11: Graphic illustration of bark pellet scenario.

1a. Wood pellet scenario – raw, from Canada

For all subprocesses of wood pellet production, feedstock production emissions are assessed through the ecoinvent database (modified ecoinvent process: Wood pellet, measured as dry mass {Ca-QC}| wood pellet production | Alloc Rec, U), assuming the production plant is located in Quebec region, Canada. The process heat consumed is obtained by burning residual material in an integrated on site biomass boiler, as a standard pellet mill practice (ecoinvent process: Heat, district or industrial, other than natural gas {CA-QC}| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Cut-off, U), while electricity is assumed to be supplied from the local grid (ecoinvent process: Electricity, high voltage {CA-QC}| production mix | Cut-off, U).

Transportation is assumed to be carried out via truck (for 50+150 = 200 km in total, assuming similar road and vehicle conditions in Quebec and Hamburg areas) and transoceanic shipping (for 3430 nautical miles or 5500 km), resulting in 3% dry mass loss, or 3.3% pellet mass loss. The wood pellet LHV was assumed to be 17.88 MJ/kg and the moisture content (5.2%) and elemental composition were taken from Phyllis2 database [79]. The combustion emissions dataset has already been presented in Table 3. The wood chip moisture prior to pelletization was taken as 28.6% [80].

1b. Wood pellet scenario - torrefied, from Canada

Torrefied wood pellet data were retrieved from [16], [81]. The feedstock is assumed to be torrefied and afterwards pelletized. The torrefied wood pellet LHV is taken as 20.2 MJ/kg (source: Phyllis2 database, spruce pellets, #3525) and pellet moisture is taken as 4.1% [16]. The torrefaction process conditions selected were a temperature of 250 °C and a time duration of 30 min. An average mass yield of 80% for wood was assumed according to [63]. For the utility boiler's biomass ashes a transportation step of 30 km up to the sanitary landfill site is considered, using a EURO 4 3,5-7,5 ton lorry transportation dataset from ecoinvent.

Transportation is assumed to be carried out via truck (for 50+150 = 200 km in total, assuming similar road and vehicle conditions in Quebec and Hamburg areas) and transoceanic shipping (for 3430 nautical miles or 5500 km), resulting in 3% dry mass loss, or 3.3% pellet mass loss.

The process heat requirement is estimated at 1.1 MJ/kg torrefied pellet product [82], while the pellet drying heat consumption at 3 MJ/kg H_2O evap. [83]. The energy demand of the torrefaction process is partially met by surplus heat from the integrated torrefaction and pellet plant's biomass boiler, which is used to dry the wood, and the rest of the heat demand is met by combustion of the torrefaction gas product, torgas, which is released during the torrefaction process, while the electricity for the conveyors and chipping line, dryer, reactor & motors and the densification is supplied from the electricity grid [64]. The torrefaction LCI used is shown in Table 4. The biomass utility boiler emissions are retrieved from Energinet's study [78].

Table 4: Wood torrefaction LCI per kg of pellet product (4% moisture)

INPUTS	VALUE	UNIT
Wood Chips, Raw	1.536	kg
Transport Of Ashes, Lorry 3.5-7.5 Metric Tons, Euro4	1.037e-05	tkm
Heat Consumption From Biomass CHP Unit	1.395	MJ
Electricity Consumption From Biomass CHP Unit	0.354	kWh
Diesel Consumption	0.069	MJ
EMISSIONS		
Carbon Dioxide, Biogenic	0.2494	kg
Carbon Monoxide, Biogenic	6.92E-06	kg
Methane, Biogenic	2.38E-07	kg
Sulfur Dioxide	1.46E-07	kg
UHC, Unburnt Hydrocarbons	4.69E-07	kg
Nitrogen Dioxide	6.23E-06	kg
Particulates, < 10 Um	7.69E-07	kg
NMVOC, Non-Methane Volatile Organic Compounds	3.02e-07	kg
Dinitrogen Monoxide	6.15E-08	kg
Cadmium	2.08E-11	kg
Mercury	3.07E-11	kg
Zinc	1.77E-10	kg
PCDD-F	1.08E-15	kg
PAHS	0.000538	kg
Naphthalene	1.78E-10	kg
Wood Ash To Sanitary Landfill	0.0005	kg
Water Removed From Feedstock	0.189	kg

2a. EFB pellet scenario - raw

For the EFB pellets, harvesting and processing is assumed to take place in Malaysia, as this is the largest producer of oil palm biomass [84], while feedstock production emissions are assessed using data from available literature records [85] for the processes, utilizing the ecoinvent database for any missing information. The fresh fruit bunch (FFB) plantation lifetime is taken as 25 years. Transportation to the CHP plant in Hamburg was assumed to be carried out via a 32-ton EURO4 truck for a distance of 200 km (ecoinvent dataset: Transport, freight, lorry >32 metric ton, EURO4 {RoW}| transport, freight, lorry >32 metric ton, EURO4 | Cut-off, U) and via transoceanic ship for 17005 km (ecoinvent dataset: Transport, freight, sea, transoceanic ship {GLO}| processing | Cut-off, U). Transportation from the palm oil mill (POM) to the pellet plant was assumed to be carried out by a 7.5 ton EURO4 truck for 25 km (ecoinvent dataset: Transport, freight, lorry 7.5-16 metric ton, EURO4 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO4 | Cut-off, U).

In general, the EFB production is considered as 22.5% w/w of the FFB production. The economic allocation factors for the crude palm oil (multifunctional) production process in a POM were considered as follows [86]:

- 67% for crude palm oil
- 31.7% for palm kernel oil
- 1.3% for EFB

The LCI for FFB processing, using a reference unit of 1 ton FFB, utilized as a basis for the EFB production LCI, is presented in Table 5. Palm oil mill effluent (POME) commercial value is considered negligible thus it is excluded from economic allocation.

Table 5: LCI dataset for the processing of 1 t FFB

		VALUE	UNIT
PRODUCTS / COPRODUCTS	EFB	225	kg
	Palm oil	199.8	kg
RESOURCE CONSUMPTION	FFB	1000	kg
	Water	0.72	m^3
	Electricity	73	MJ
	Vehicle diesel consumption	7.6	MJ
EMISSIONS	CH_4	8.744	gr
	NOx	272	gr
	SO_2	2.4	gr
	CO	671	gr
	Particulates < 2.5 um	151	gr
	Acetaldehyde	0.116	gr
	Ammonia	42.4	gr
	Arsenic	$1.9 \cdot 10^{-3}$	gr
	Benzene	1.734	gr
	Benzene, ethyl-	$5.72 \cdot 10^{-2}$	gr
	Benzene, hexachloro-	$1.37 \cdot 10^{-8}$	gr
	Benzo(a)pyrene	$9.52 \cdot 10^{-4}$	gr
	Cadmium	$1.33 \cdot 10^{-3}$	gr
	Chlorine	$3.42 \cdot 10^{-1}$	gr
	Chromium	$7.54 \cdot 10^{-3}$	gr
	Chromium VI	$7.62 \cdot 10^{-5}$	gr
	Copper	$4.20 \cdot 10^{-2}$	gr
	Dinitrogen monoxide	6.81	gr
	Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	$5.90 \cdot 10^{-8}$	gr
	Formaldehyde	$2.48 \cdot 10^{-1}$	gr
	Hydrocarbons, aliphatic, alkanes	1.73	gr
	Hydrocarbons, aliphatic	6	gr
	Hydrogen sulphide	58	gr
	Lead	$4.76 \cdot 10^{-2}$	gr
	m-Xylene	$2.28 \cdot 10^{-1}$	gr
	Manganese	$3.24 \cdot 10^{-1}$	gr
	Mercury	$5.72 \cdot 10^{-4}$	gr
	Nickel	$1.14 \cdot 10^{-2}$	gr
	NMVOC	1.71	gr
	PAH	$2.12 \cdot 10^{-2}$	gr
	Phenol, pentachloro-	$1.54 \cdot 10^{-5}$	gr
	Phosphorus	$5.72 \cdot 10^{-1}$	gr
	Toluene	$5.72 \cdot 10^{-1}$	gr
	Zinc	$5.72 \cdot 10^{-1}$	gr

The EFB is assumed to arrive at the pelletization plant at a moisture content of 60% [85]. The maximum acceptable moisture content for pelletization is 15% [87], therefore a mechanical dewatering step is required, with an electricity demand of 0.31 kWh / kg H_2O until the moisture content reaches 48% [88]. The thermal drying of the feedstock follows, while process electricity and heat demands were assumed to be met by a 6667 kW (fuel input) capacity onsite wood chip cogeneration unit (ecoinvent dataset: electricity, high voltage - heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 – FI). Afterwards the pelletization stage has a power consumption of 0.1065 kWh/kg final pellet product. Mass loss is taken as 4% [89], while final pellet moisture is assumed as 12% [90]. The electricity production LCI includes biomass ash transportation to sanitary landfill by a EURO4 16 ton lorry (transportation dataset from ecoinvent). The raw EFB pellet LHV is taken as 17.46 MJ/kg according to the fuel analysis performed at TUM.

2b. EFB pellet scenario - HTC – treated

The process conditions assumed for temperature and treatment duration for the hydrothermal treatment of EFB were set to 230 °C and 4 hours duration, respectively. A water to biomass ratio of 5 and a mass yield of 59% (considering partial recovery of the wastewater) were selected, as common in the literature [49]. The HTC process LCI was calculated based on process modeling results [63]. The composition and LHV value (25.56 MJ/kg) were taken from experimental measurements performed in TUM. No additional building infrastructure was considered for the HTC equipment, since sufficient LCI data on a commercial, continuous operation HTC plant could not be found, however the ecoinvent wood pellet plant dataset selected already for the pretreatment stage has a large environmental impact on the final product. For comparison purposes, it can be reminded here that no infrastructure emissions are taken into account in the RED calculations methodology. The electricity demand was set to 0.1426 kWh/kg HTC-treated biomass, as a total value for the integrated HTC and pelletization plant [63].

Transportation to the CHP plant in Hamburg was assumed to be carried out via a 32-ton EURO4 truck for 200 km and via transoceanic ship for 17005 km. Transportation from the POM to the HTC pretreatment and pelletization plant was assumed to be carried out by a 7.5 ton EURO4 truck for 25 km (ecoinvent dataset: Transport, freight, lorry 7.5-16 metric ton, EURO4 {RER}| transport, freight, lorry 7.5-16 metric ton, EURO4 | Cut-off, U).

The emissions for auxiliary biomass combustion in the medium size utility biomass boiler are estimated according to the straw combustion emissions dataset from Energinet [78], adding the calculated emissions from the HTC-gas combustion. The emissions from HTC-gas combustion in the utility boiler were calculated based on the HTC-gas composition by [63], assuming 99% conversion of the existing H_2S to SO_x and 1% unburned H_2S at flue gas exit. NO_x emissions were neglected for the HTC-gas, as there were no nitrous compounds in the off-gas and the temperature in the biomass boiler is too low to allow for thermal NO_x generation [37].

The wastewater treatment model was based on an available ecoinvent dataset for the treatment of potato starch wastewater, as the wastewater composition was assumed to be more representative of the studied case of uncatalyzed hydrothermal treatment, multiplying the dataset with a correction factor of 0.004 (estimated wastewater flow for our process, based on the HTC mass balance by [63]: $4 \cdot 10^7$ L/a, ecoinvent facility capacity: $1 \cdot 10^{10}$ L/a). No co-treatment with POME effluents was considered in this scenario due to lack of relevant information. The LCI dataset used in the study is shown in Table 6.

Table 6: LCI dataset for 1 kg of HTC treated EFB pellets

Materials / fuels / resources	Value	Unit
efb extraction from integr. mill	4.69	kg
efb (raw) integr. Pelletization	1	kg
Water consumption	4.691	kg
Electricity / heat		
Electricity, high voltage, CHP, wood chips, MY, 6667 kW	0.143	kWh
Emissions		
TSP	0.007	kg
Carbon dioxide, biogenic	0.505	kg
Water	0.718	kg
Particulates, < 10 um	0.0002	kg
Carbon monoxide, biogenic	0.110	kg
Methane, biogenic	0.0009	kg
Hydrogen chloride	0.081	kg
Nitrogen dioxide	0.228	kg
Sulfur dioxide	0.083	kg
Wastewater to treatment	3.638	kg

For the electricity generation LCI, an input of 0.119 kg HTC-treated pellets was calculated per MJ of electricity produced, which in turn would require an input of 0.483 kg of raw EFB to the integrated oil mill / biorefinery in Malaysia.

3a. Bark and wood residue pellet scenario - raw

For the bark and energy wood pellets, feedstock production emissions are calculated based on Swedish forest operations from [91], coupled with data from ecoinvent database, while supplementary data is retrieved from Metsä Fibre's recent studies and its available data records. The final version of this LCI will be representative of Metsä Fibre's target bark pellet production operation and current forest operations in Finland.

The LCI used as a basis for the siviculture and harvesting calculations (mass allocated) for 1 kg of bark is presented in Table 7, assuming the following mass allocation factors for tree parts [92]:

- 78% roundwood
- 10% bark
- 8% tops & branches
- 4% foliage

Table 7: The LCI dataset for the siviculture and harvesting operations per kg raw bark

		Value	Unit
Seed production and cultivation of seedlings	Land occupation	8.30	m^2
	Diesel consumption	$3.9 \cdot 10^{-4}$	L
	Gasoline consumption	$2.4 \cdot 10^{-6}$	L
	Electricity	$1.4 \cdot 10^{-3}$	kWh
Soil scarification	Diesel consumption	$1.8 \cdot 10^{-4}$	L
	Engine oil consumption	$1.8 \cdot 10^{-6}$	L
Cleaning (motor manual)	Gasoline consumption	$5.6 \cdot 10^{-5}$	L
	Engine oil consumption	$1.1 \cdot 10^{-6}$	L
Cleaning (mechanized)	Diesel consumption	$2.4 \cdot 10^{-5}$	L
	Engine oil consumption	$2.4 \cdot 10^{-7}$	L
Fertilization	Urea -CH_4N_2O-	$7.1 \cdot 10^{-4}$	kg
	Ammonium sulfate -$(NH_4)_2SO_4$-	$6.0 \cdot 10^{-4}$	kg
	Air jet fuel consumption	$7.1 \cdot 10^{-5}$	L
	Diesel consumption	$5.5 \cdot 10^{-6}$	L
	Engine oil consumption	$8.5 \cdot 10^{-7}$	L
Other consumptions	Diesel consumption	$3.5 \cdot 10^{-4}$	L
	Gasoline consumption	$2.8 \cdot 10^{-4}$	L
	Engine oil consumption	$4.6 \cdot 10^{-6}$	L
Logging	Diesel consumption	$4.0 \cdot 10^{-3}$	L
	Engine oil consumption	$1.3 \cdot 10^{-4}$	L
Truck loading	Diesel consumption	$1.9 \cdot 10^{-3}$	L
	Engine oil consumption	$3.4 \cdot 10^{-5}$	L
Emissions to air	N_2O	$6.1 \cdot 10^{-6}$	kg
	NH_3	$4.5 \cdot 10^{-5}$	kg
	NO_x	$3.2 \cdot 10^{-6}$	kg
	CH_4	$4.6 \cdot 10^{-6}$	kg
Emissions to water	NO^{3-}	$1.4 \cdot 10^{-4}$	kg
Emissions to soil	As	$1.6 \cdot 10^{-4}$	mg
	Cd	$1.4 \cdot 10^{-4}$	mg
	Cr	$2.7 \cdot 10^{-3}$	mg
	Co	$5.4 \cdot 10^{-4}$	mg
	Cu	$6.7 \cdot 10^{-3}$	mg
	Hg	$5.4 \cdot 10^{-5}$	mg
	Mo	$4.7 \cdot 10^{-4}$	mg
	Ni	$1.1 \cdot 10^{-3}$	mg
	Pb	$6.1 \cdot 10^{-4}$	mg
	Se	$1.6 \cdot 10^{-4}$	mg
	Zn	$2.2 \cdot 10^{-2}$	mg
Emissions from fossil fuel consumption	CO	$6.5 \cdot 10^{-2}$	g
	HC	$1.3 \cdot 10^{-2}$	g
	CH_4	$1.2 \cdot 10^{-3}$	g
	N_2O	$1.4 \cdot 10^{-3}$	g
	NO_x	0.2	g
	Particles	$1.1 \cdot 10^{-3}$	g
	SO_2	$1.2 \cdot 10^{-3}$	g
	CO_2	$1.5 \cdot 10^{-2}$	g

For the raw feedstock transportation distance (by a 32-ton EURO4 truck) to the bioproduct mill for debarking and sawing, a 200 km radius is selected after Metsä Fibre's suggestion. Transportation to the CHP plant in Hamburg is carried out by truck for 200 km in total using a 32 ton EURO4 truck (assuming similar vehicle and road conditions for Finland and Germany), by train for 275 km (to the port of Helsinki) and by ship for 1100 km.

The available bark on site at Metsä Fibre's bioproduct plant is estimated at 110.000 tons/year (dry basis) with a 60% moisture content (K. Kemppainen, Metsä Fibre, personal communication, 19/4/18), while the yearly large scale CHP plant feedstock pellet demand is calculated at 334,108.1 metric tons/year based on the assumed pellet LHV of 17.24 MJ/kg (fuel analysis conducted by TUM). It was estimated that the available bark for upgrading accounts for 44.16% of the yearly pellet CHP demand. The remaining 55.84% was assumed to be covered by energy wood (spruce) chips from sustainable forest management (ecoinvent dataset: wood chips, softwood, spruce, sustainable forest management – RER), which is classified as energy wood in Swiss forest management archives [80]. A 1% maximum mass loss is assumed [75] during the pelletization stage, while the final pellet moisture is estimated at 8% [87].

The electricity demand for sawmill operation and pelletization is assumed to be met by a 6667 kW (fuel input) capacity onsite wood chip cogeneration unit (ecoinvent dataset: electricity, high voltage - heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 – FI). The electricity required for debarking is estimated at 0.104 kWh/kg softwood over bark [93], while for the pelletization stage the electricity consumption is taken as 0.118 kWh/kg. Pellet drying heat consumption is taken as 3 MJ/kg H_2O evaporated, which is produced from the integrated biomass cogeneration unit.

3b. Bark and wood residue pellet scenario - SE – treated

The fuel properties are considered the same as the pure bark pellet properties for simplification of the model calculations. The composition and LHV (18.42 MJ/kg) are taken from experimental measurements performed in TUM. The annual steam exploded pellet demand was calculated at 312,755.4 tons, considering 8% pellet moisture content. The effect of steam explosion on fuel properties was investigated utilizing data provided from Valmet [61]. The process conditions are the following: temperature 204 °C, residence time: 5 min, maximum pressure: 17 bar. Under these conditions the mass yield is estimated at 92 % (dry basis) [94]. The steam to biomass weight ratio inside the reactor is 0.22 [95].

The steam production from waste biomass is taken as 0.24 kWh/kg final pellet product (data from Valmet's steam explosion reactor report usage of 0.5 kg steam consumption per kg dry pellet product, but no steam quality information were found to translate this into MJ of heat consumption – however, this number is in good agreement with NTUA calculation 0.47 kg steam demand / kg final pellet). The electricity consumption of the steam explosion process is taken as 0.13 kWh/kg final pellet product [96]. The assumed final pellet moisture was 8% (w/w) [61]. The electricity and heat demand was assumed to be met by a 6667 kW (fuel input) capacity onsite wood chip cogeneration unit (ecoinvent dataset: electricity, high voltage - heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 – FI). The fresh bark is considered to arrive at the plant at 60% moisture, while pre-drying of the bark chips occurs first by air and afterwards by exposing the chips to the steam explosion reactor blow steam. This way the bark chips are considered to enter the pretreatment reactor at 8% moisture.

Transportation to the bioproduct mill was conducted by a 32 ton EURO4 truck for 200 km. Transportation to the CHP plant in Hamburg is carried out by truck for 200 km in total using a 32 ton EURO4 truck (assuming similar vehicle and road conditions for Finland and Germany), by train for 275 km (to the port of Helsinki) and by ship for 1100 km. Wastewater treatment is modeled as a standard treatment process of average wastewater from ecoinvent. No co-treatment with other Metsä Fibre's plant condensates or effluents was considered for this scenario due to absence of relevant data. The LCI used for the evaluation of steam exploded bark is shown in Table 8.

Table 8: The LCI dataset for one kg of steam exploded spruce bark/energy wood pellets

Resources / materials / fuels	**Value**	**Unit**
Water, unspecified natural origin/kg	0.239	kg
Wood pellet factory, RER production	0.00000002	p
Bark chips	0.079	kg
Wood chips	0.140	kg
Electricity/heat		
Electricity, HV, CHP, wood chips, 6667 kW, FI, state-of-the-art 2014	0.13	kWh
Heat, industrial, FI, CHP, wood chips, 6667 kW, state-of-the-art 2014	0.857	MJ
Emissions		
TSP	0.42	g
Particulates, < 10 um	0.393	g
Particulates, < 2.5 um	0.393	g
Carbon monoxide	2.342	g
Sulfur dioxide	0.0578	g
Nitrogen oxides	0.141	g
Dinitrogen monoxide	0.011	g
Methane	0.039	g
NMVOCs	0.203	g
Wastewater, average {Europe without Switzerland} treatment	5.022E-06	kg

6. Results and Discussion

a. LCA results and interpretation for the discussed scenarios

The detailed impact assessment results based on ReCiPe 2016 midpoint analysis are presented in Tables 10-15 and Figures 13-18. Stratospheric ozone depletion was omitted from the comparative graphic representations, as it was found to be of minor importance for the studied case scenarios. Freshwater eutrophication and marine eutrophication indicators were also omitted from a number of scenarios' comparative charts for the same reason. However, all results presented here may change when incorporating the experimental results from the Biofficiency combustion tests for each fuel. For the exergetic allocation of GHG emissions between electricity and heat produced, the exergetic factors calculated from equations (3) and (4) were E_{el} = 0.6528 for electricity and E_{th} = 0.3472 for heat.

According to the revised **RED II target** of **80%** emission savings based on the current fossil fuel comparator for units commencing operation in 2021 [5], the GHG footprint threshold for acceptable bioelectricity production is only **36.6 g CO_2-eq/MJ$_{el}$**. Application of this criterion means that the only acceptable fuels are the raw wood pellets from Canada (15.3 g CO_2-eq/MJ$_{el}$) with 91.63% emission savings, the torrefied wood pellets from Canada (20.8 g CO_2-eq/MJ$_{el}$) with 88.63% emission savings. The lower performing fuels were the EFB pellets, both raw (with 82.89 g CO_2-eq/MJ$_{el}$) and HTC-treated (with 79.98 g CO_2-eq/MJ$_{el}$), mainly due to the very large transportation distances included in the supply chain. This specific supply chain can largely benefit from the commercialization of marine transport biofuels, that will lower the marine transportation impact. However, the environmental benefit of the combined hydrothermal pretreatment and pelletization is clear, resulting in 2.91 g CO_2-eq/MJ$_{el}$ /MJ$_{el}$ of carbon footprint reduction compared to the raw EFB case when including building infrastructure and an 8.21 g CO_2-eq/MJ$_{el}$ for the exclusion of building infrastructure from the LCI.

For January 1st 2026, the revised RED emissions saving target is determined as **85%** based on the current EU fossil fuel comparator, so the GHG footprint threshold reaches **27.5 g CO_2-eq/MJ$_{el}$**, allowing only the usage of raw and torrefied wood pellets from Canada (scenarios 1a, 1b) when building infrastructure is included. In the alternate GHG calculations set, where **building infrastructure is excluded** following the RED methodology, two more acceptable scenarios are identified apart from the wood pellets: both the raw and steam exploded bark and wood residues scenarios (3a and 3b, 92.4% savings for both).

Until January 1st 2021, the **current RED [38]** sets a target for GHG savings of at least **60%** for biofuel production based on an average fossil fuel comparator of 198 g CO_2-eq/MJ$_{el}$. There are no specific thresholds applying for the production of renewable electricity and heat from solid biomass fuels.

The environmental benefit of the applied steam explosion pretreatment is not as clear as in the HTC-treated EFB pellet scenario in comparison with the raw EFB pellets, mainly due to the relatively small transportation distance – as transportation distance increases, the benefit from steam explosion is expected to increase as well, mainly due to its higher mass yield compared to that of HTC. The carbon footprint of each scenario based on energy and exergy allocation is shown in Table 9, including the carbon footprint of a second version for each scenario, excluding building infrastructure from the LCIs, to ensure comparability with the RED methodology.

Table 9: Comparison of GHG footprint evaluation methodologies

Large Scale Biomass CHP Scenario (CHP located in Germany for all scenarios) - Electricity, energy allocation	**GWP impact (infrastructure included) g CO_2-eq/MJel**	**GWP impact (infrastructure NOT included) g CO_2-eq/MJel**
1a: Wood pellets, Canada, raw	23.46	22.45
1b: Wood pellets, Canada, torrefied	31.87	24.16
2a: EFB pellets, Malaysia, raw	126.98	105.09
2b: EFB pellets, Malaysia, HTC-treated	122.52	92.52
3a: Bark pellets, Finland, raw	43.27	21.31
3b: Bark pellets, Finland, steam exploded	43.79	21.31
Large Scale Biomass CHP Scenario (CHP located in Germany for all scenarios) - Electricity, exergy allocation	**GWP impact (infrastructure included) g CO_2-eq/MJel**	**GWP impact (infrastructure NOT included) g CO_2-eq/MJel**
1a: Wood pellets, Canada, raw	15.31	14.66
1b: Wood pellets, Canada, torrefied	20.80	15.77
2a: EFB pellets, Malaysia, raw	82.89	68.60
2b: EFB pellets, Malaysia, HTC-treated	79.98	60.40
3a: Bark pellets, Finland, raw	28.25	13.91
3b: Bark pellets, Finland, steam exploded	28.59	13.91

As observed from Table 9, the inclusion of building infrastructure has a notable GHG impact on all scenarios, with the impact being even larger for the pretreated fuel scenarios and for short transportation distances. For instance, when applying energy allocation, the impact of building infrastructure is only 4.33% of the overall GHG impact for scenario 1a (raw wood pellets from Canada to Germany), whereas it rises to 51.16% for scenario 3b (steam exploded bark and wood residue pellets from Finland to Germany), driving the bark pellet GWP impact lower than that of the raw wood pellets when infrastructure is excluded. The comparative results for electricity and heat cogeneration (based on exergy allocation) along with the RED II minimum acceptable GHG savings for the forthcoming years can be seen in Fig. 12. As already discussed, the exclusion of building infrastructure leads to 4 acceptable scenarios out of 6, whereas the inclusion of building infrastructure leads to raw (and torrefied, in the case of electricity) wood pellets from Canada being the only fuels acceptable from 2026 onwards, according to RED II limitations. The inclusion of biomass cultivation emissions in the LCI is a minor contributor to the cradle-to-grave LCAs conducted. The cultivation impact, of course, usually appears far greater in cradle-to-gate LCA studies, where not all life cycle stages (i.e. no final energy conversion –use phase- and waste treatment) are included.

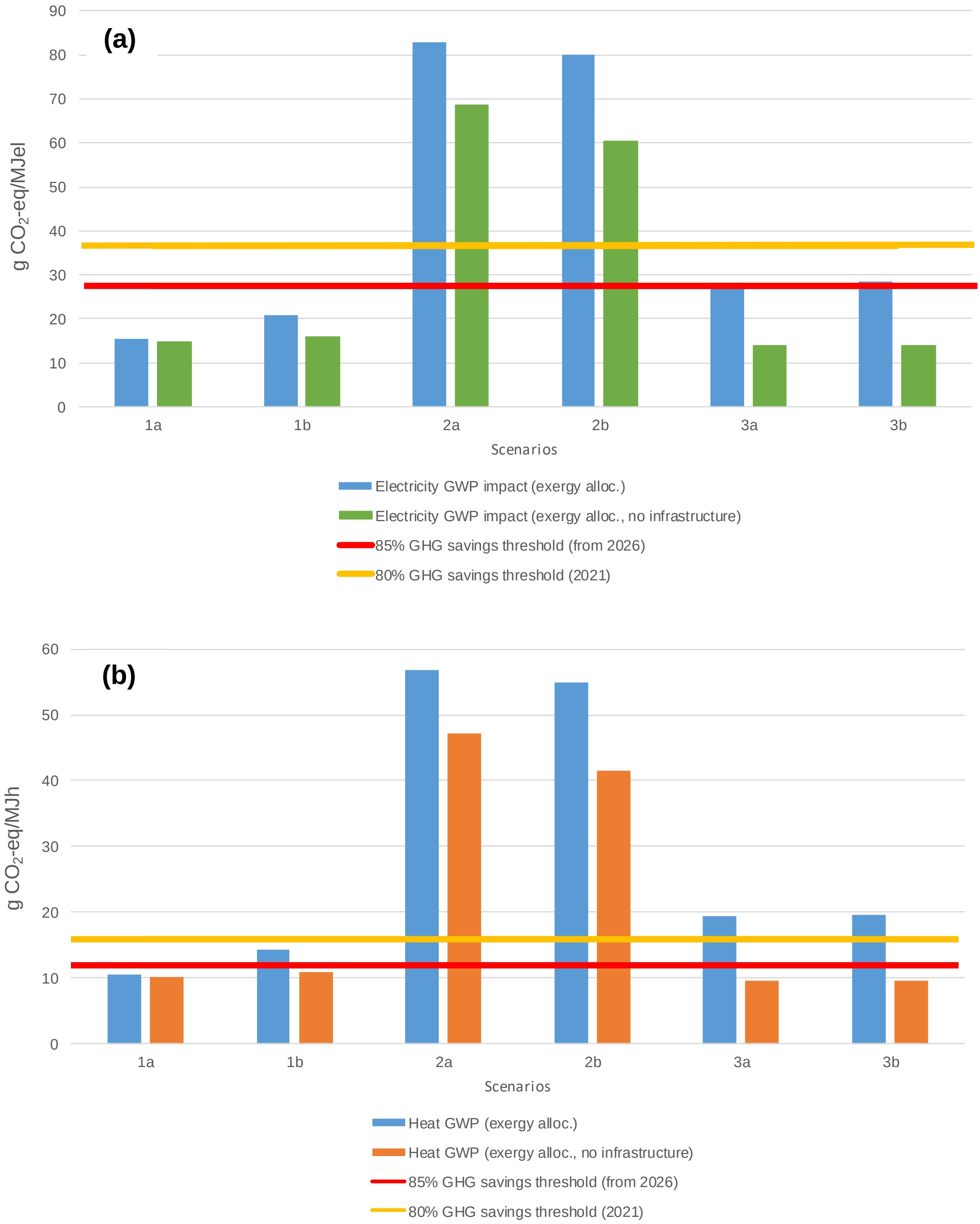


Figure 12: GHG impact assessment per MJ produced electricity (a) and heat (b), all studied scenarios (exergy allocation)

In the case that the RED fossil fuel comparator is not used as an evaluation criterion, the German lignite CHP carbon footprint was selected as a suitable baseline indicator to allow GHG footprint comparison, as this is the most environmentally preferable cogeneration technology to be substituted by the studied biomass CHP plant scenario in Germany. The unit's GHG impact was calculated from the ecoinvent database (dataset: Electricity, high voltage {DE}| heat and power co-generation, lignite | Cut-off, U) as **323 g CO_2-eq/MJ_{el}** (energy allocation). Based on this value, the following emission savings were calculated for energy allocation of produced electricity: 92.74% for raw wood pellets from Canada, 90.13% for torrefied wood pellets from Canada, 60.69% for raw EFB pellets from Malaysia, 62.07% for HTC-treated EFB pellets from Malaysia, 86.6% for raw bark and wood residue pellets from Finland and 86.44% for steam exploded bark and wood residue pellets from Finland. For exergy allocation of produced electricity, the saving percentages are as follows: 95.26% for scenario 1a, 93.56% for 1b, 74.34% for 2a, 75.24% for 2b, 91.26% for 3a and 91.15% for 3b. Both the reference lignite dataset and the studied models include building infrastructure, to facilitate comparability.

A preliminary discussion of some interesting findings on other impact indicators, calculated via energy allocation, follows. All scenarios ranked very low in stratospheric ozone depletion, so this factor was not taken into consideration for the interpretation of all scenarios' impact assessment results. Regarding the water footprint of the studied scenarios, the electricity production from steam exploded bark and wood residue pellets was the least water-intensive option with only $4.79 \cdot 10^{-3}$ m^3 H_2O/MJ_{el}. The highest water demand was calculated for electricity production from HTC-treated EFB pellets at $6.06 \cdot 10^{-3}$ m^3 H_2O/MJ_{el}. It needs to be stressed at this point that the water consumption per MJ of produced electricity is to a great (more than 80% for all scenarios) extent due to the water - steam cycle operation, therefore the obtained results are quite different than those obtained on a per fuel mass evaluation. A more detailed analysis of water mass balances for the fuel pretreatment scenarios would assist in further validating the calculated results.

Regarding particulate emissions, the feedstock with the highest fine particulate matter formation impact was the HTC-treated EFB pellets with $6.25 \cdot 10^{-3}$ kg $PM_{2.5}$ eq/MJ_{el}, while the lowest were the raw wood pellets with $1.11 \cdot 10^{-4}$ kg $PM_{2.5}$ eq/MJ_{el}. The highest land use was calculated for raw EFB pellets (1.21 m^2a crop eq/MJ_{el}), while the lowest for raw wood pellets ($7.1 \cdot 10^{-2}$ m^2a crop eq/MJ_{el}).

To summarize, a few preliminary conclusions are presented. First, as demonstrated from most of the studied scenarios, when the electricity and heat demand is met by renewable heat and electricity, the resulting impact is lower than for the scenarios of utilizing electricity and heat from the grid or from fossil resources in general. It was also verified by all scenario results that the building infrastructure, and mainly the pretreatment and pelletization plant construction is responsible for a large part of the environmental burdens of the whole life cycle impact.

In the case that the studied residual feedstocks are considered wastes, and as such enter the system burden-free up to the point of collection according to the revised RED, the overall GHG emissions are expected to drop. The impact assessment as a whole, however, is expected to appear significantly different, due to the impact of biomass cultivation and forestry operations on the ecosystems, but mainly on water and land use. Another issue that arises from the bark pellet LCA is the heavy impact of forestry operations assumed for the supplementary demand for wood chips to meet the large CHP plant's annual fuel demand. A larger bark production potential, leading to a larger percentage of bark content in the final pellet, is expected to further reduce the GHG footprint of the bark pellets. What needs to be examined is either a combination of neighboring suppliers to satisfy the large annual bark demand, or the selection of plantations of softwood varieties with larger bark percentage, in the case that the bark is retrieved from sustainably managed forests that agree to provide their residual materials as biofuel feedstock.

Avoided emissions from biomass dumping can further reduce the GHG footprint of all scenarios, especially for the EFB scenarios. since according to [63] these can amount to 65% of the whole EFB life cycle net avoided CO_2 emissions. However, these were not taken into account for our study, as there is no explicit consent for including the alternate fate of residues or any other future projections in the revised RED, therefore the inclusion of such information would incur a risk of loss in comparability with other RED-compliant studies [5].

For the raw wood pellet scenarios, the following observations were made. First, for scenario (1a) the GHG impact calculated for raw wood pellets from Quebec, Canada is 9.62% lower than the one reported in [9] for a CHP unit with a similar electrical output (23.5 versus 26 g CO_2-eq/MJ_{el}), even though the transportation from Canada to Germany is much more GHG-intensive (3430 nautical miles by ship and 200 km in total by truck in our scenario, versus 100 km in total by truck estimated by Giuntoli et al., 2016). This could be due to the higher fuel utilization efficiency of the proposed CHP configuration, as opposed to standard bioelectricity production units.

Agar et al. [41] assumed a transportation of 781 km by rail and 15500 km by ship for the transportation from Vancouver, Canada to La Coruna, Spain, resulting in a total GHG footprint of 52 g CO_2-eq/MJ_{el} both for raw and torrefied wood pellets. A shorter transport route from Finland was also assessed in the aforementioned study, consisting of 178 km by truck and 3361 km by ship, with a calculated GHG footprint of 43 g CO_2-eq/MJ_{el} for raw pellets and 45 g CO_2-eq/MJ_{el} for torrefied pellets, all per dry mass, considering a moisture content of 10% for raw pellets and 4% for torrefied ones. Both studies mentioned, however, are about systems producing heat as their main product, therefore both their electrical and their overall efficiencies are expected to be low compared to the Biofficiency proposed concept. As efficiencies vary, so shall the energy and exergy allocation factors for the electricity and heat produced by the CHP unit under study.

Table 10: Impact assessment of CHP plant burning raw wood pellets from Quebec, Canada (Method: ReCiPe 2016 Midpoint (H))

Impact Category	Unit	Total	Wood Pellet {Ca-Qc} Production	Electricity, HV, CHP, Wood Pellets	Raw Wood Pellets Transport To CHP
Global Warming	kg CO_2 eq	2.35E-02	7.97E-03	1.77E-03	1.37E-02
Stratospheric Ozone Depletion	kg CFC_{11} eq	3.72E-08	4.79E-09	2.61E-08	6.30E-09
Ionizing Radiation	kBq Co-60 eq	1.07E-03	5.35E-04	2.45E-05	5.15E-04
Ozone Formation, Human Health	kg NO_x eq	4.30E-04	3.64E-05	2.43E-04	1.51E-04
Fine Particulate Matter Formation	kg $PM_{2.5}$ eq	1.11E-04	1.92E-05	2.96E-05	6.22E-05
Ozone Formation, Terrestrial Ecosystems	kg NO_x eq	4.35E-04	3.77E-05	2.45E-04	1.52E-04
Terrestrial Acidification	kg SO_2 eq	3.15E-04	3.29E-05	9.54E-05	1.87E-04
Freshwater Eutrophication	kg P eq	4.93E-06	2.79E-06	5.68E-07	1.57E-06
Marine Eutrophication	kg N eq	3.60E-07	2.25E-07	2.37E-08	1.12E-07
Terrestrial Ecotoxicity	kg 1,4-DCB	1.29E-01	4.33E-02	1.01E-02	7.52E-02
Freshwater Ecotoxicity	kg 1,4-DCB	9.87E-04	2.82E-04	5.94E-04	1.10E-04
Marine Ecotoxicity	kg 1,4-DCB	1.42E-03	3.98E-04	8.33E-04	1.89E-04
Human Carcinogenic Toxicity	kg 1,4-DCB	8.45E-04	4.15E-04	1.60E-04	2.70E-04
Human Non-Carcinogenic Toxicity	kg 1,4-DCB	3.15E-02	7.49E-03	2.07E-02	3.27E-03
Land Use	m^2a crop eq	7.10E-02	7.06E-02	2.46E-05	3.05E-04
Mineral Resource Scarcity	kg Cu eq	6.90E-05	3.43E-05	1.67E-05	1.80E-05
Fossil Resource Scarcity	kg oil eq	6.77E-03	2.13E-03	1.88E-04	4.45E-03
Water Consumption	m^3	5.44E-03	4.04E-04	4.99E-03	4.05E-05

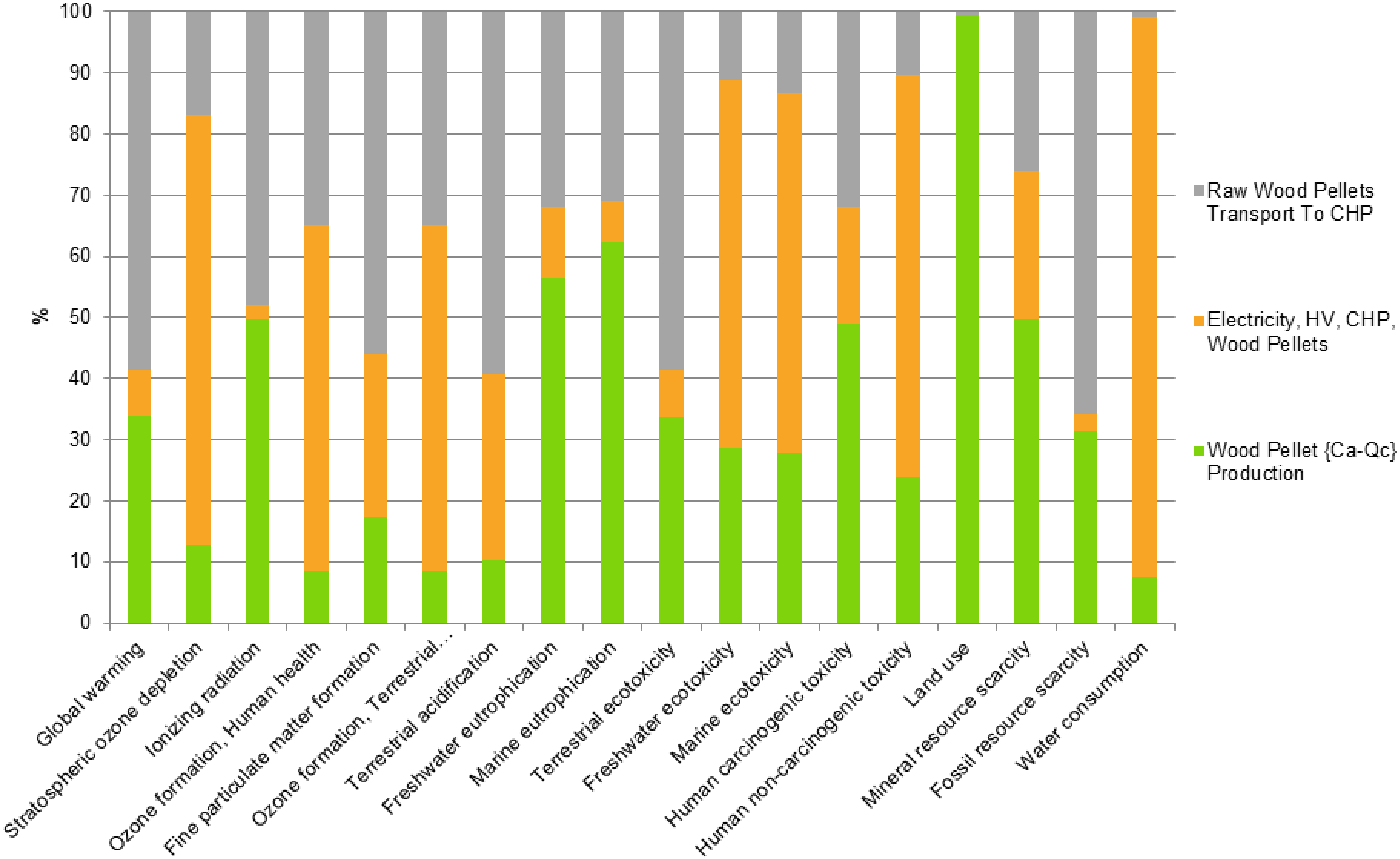


Figure 13: Impact assessment (comparative) of CHP plant burning raw wood pellets from Quebec, Canada (Method: ReCiPe 2016 Midpoint (H))

Table 11: Impact assessment of CHP plant burning torrefied wood pellets from Quebec, Canada (Method: ReCiPe 2016 Midpoint (H))

Impact category	Unit	Total	Electricity, HV, CHP, torrefied wood pellets	Torr. wood pellets transport to CHP plant	Wood pelletization & torrefaction
Global warming	kg CO_2 eq	3.19E-02	1.88E-03	1.21E-02	1.78E-02
Stratospheric ozone depletion	kg CFC_{11} eq	6.83E-08	2.62E-08	5.58E-09	3.66E-08
Ionizing radiation	kBq Co-60 eq	1.20E-03	2.80E-05	4.56E-04	7.14E-04
Ozone formation, Human health	kg NO_x eq	5.81E-04	2.44E-04	1.33E-04	2.03E-04
Fine particulate matter formation	kg $PM_{2.5}$ eq	1.53E-04	2.98E-05	5.50E-05	6.78E-05
Ozone formation, Terrestrial ecosystems	kg NO_x eq	5.87E-04	2.46E-04	1.35E-04	2.07E-04
Terrestrial acidification	kg SO_2 eq	4.23E-04	9.61E-05	1.66E-04	1.61E-04
Freshwater eutrophication	kg P eq	6.18E-06	9.18E-07	1.39E-06	3.88E-06
Marine eutrophication	kg N eq	4.47E-07	2.48E-08	9.87E-08	3.24E-07
Terrestrial ecotoxicity	kg 1,4-DCB	2.73E-01	1.05E-02	6.65E-02	1.96E-01
Freshwater ecotoxicity	kg 1,4-DCB	2.70E-03	1.99E-03	9.77E-05	6.06E-04
Marine ecotoxicity	kg 1,4-DCB	4.55E-03	2.79E-03	1.67E-04	1.59E-03
Human carcinogenic toxicity	kg 1,4-DCB	4.04E-03	2.00E-04	2.39E-04	3.60E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	1.11E-01	7.02E-02	2.89E-03	3.83E-02
Land use	m^2a crop eq	1.43E-01	3.91E-05	2.70E-04	1.42E-01
Mineral resource scarcity	kg Cu eq	1.16E-04	1.69E-05	1.59E-05	8.27E-05
Fossil resource scarcity	kg oil eq	9.28E-03	2.24E-04	3.94E-03	5.12E-03
Water consumption	m^3	5.58E-03	4.99E-03	3.58E-05	5.51E-04

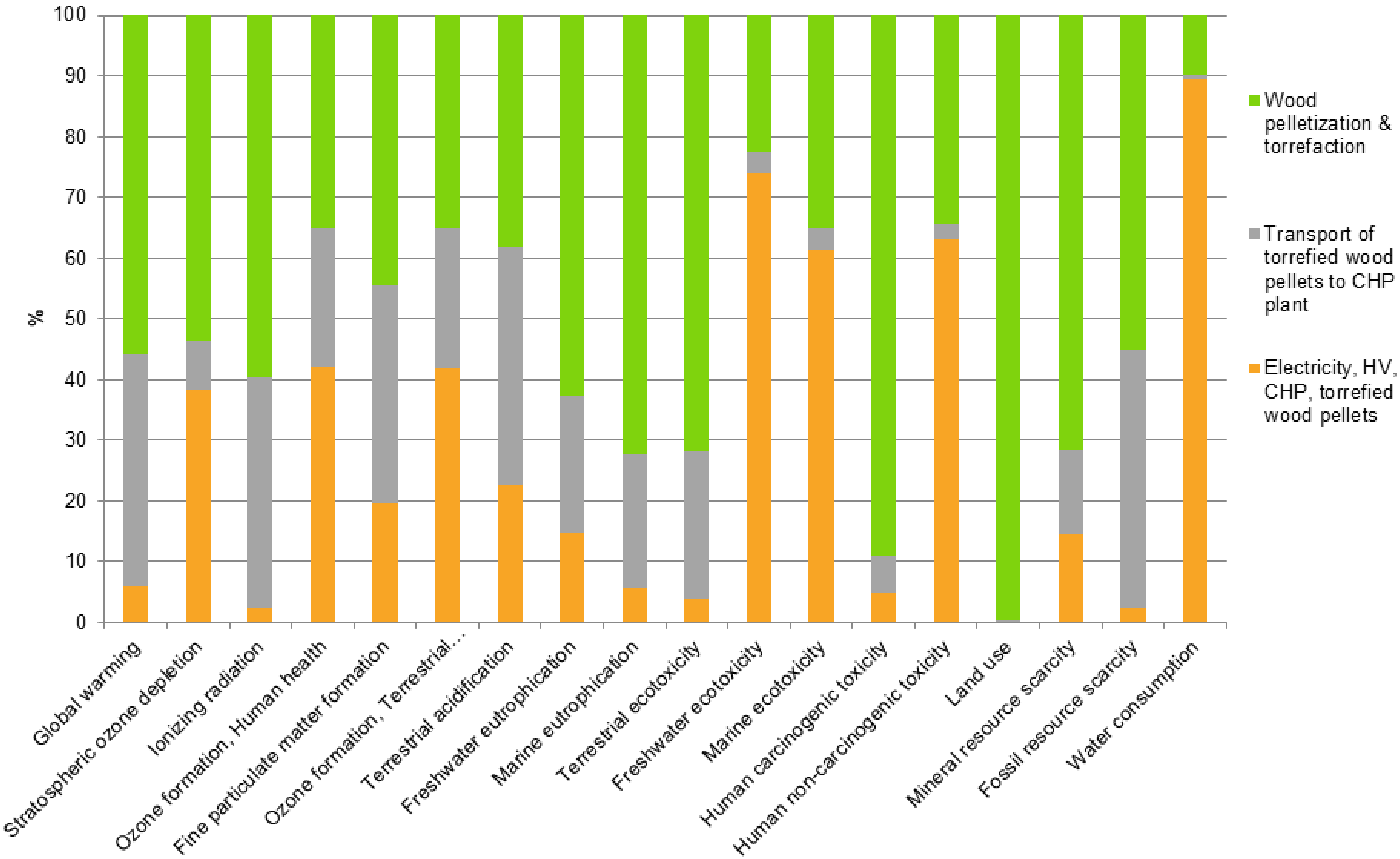


Figure 14: Impact assessment (comparative) of CHP plant burning torrefied wood pellets from Quebec, Canada (Method: ReCiPe 2016 Midpoint (H))

Table 12: Impact assessment of CHP plant burning raw EFB pellets from Malaysia (Method: ReCiPe 2016 Midpoint (H))

Impact category	Unit	Total	EFB extraction from integr. mill	Raw EFB pelletization	EFB transport to integr. mill	raw EFB pellet transport to CHP	Electricity, HV, CHP, raw EFB pellets
Global warming	kg CO_2 eq	1.27E-01	5.32E-02	2.37E-02	1.12E-02	3.70E-02	1.86E-03
Stratospheric ozone depletion	kg CFC_{11} eq	6.46E-07	5.36E-07	6.24E-08	4.89E-09	1.70E-08	2.62E-08
Ionizing radiation	kBq Co-60 eq	2.69E-03	1.64E-04	8.11E-04	2.71E-04	1.42E-03	2.74E-05
Ozone formation, Human health	kg NO_x eq	7.82E-04	6.81E-05	1.86E-04	4.64E-05	4.46E-04	3.51E-05
Fine particulate matter formation	kg $PM_{2.5}$ eq	4.73E-04	5.23E-05	2.13E-04	1.33E-05	1.88E-04	6.84E-06
Ozone formation, Terrestrial ecosystems	kg NO_x eq	7.98E-04	6.86E-05	1.95E-04	4.73E-05	4.50E-04	3.68E-05
Terrestrial acidification	kg SO_2 eq	1.05E-03	2.20E-04	2.07E-04	3.25E-05	5.72E-04	2.08E-05
Freshwater eutrophication	kg P eq	4.07E-05	9.80E-06	2.45E-05	9.65E-07	4.55E-06	8.62E-07
Marine eutrophication	kg N eq	1.15E-04	1.13E-04	1.71E-06	7.47E-08	3.17E-07	2.46E-08
Terrestrial ecotoxicity	kg 1,4-DCB	8.89E-01	6.37E-02	5.74E-01	1.22E-01	1.19E-01	1.04E-02
Freshwater ecotoxicity	kg 1,4-DCB	3.77E-02	3.07E-02	4.72E-03	2.11E-04	2.59E-04	1.77E-03
Marine ecotoxicity	kg 1,4-DCB	1.80E-02	8.06E-03	6.65E-03	3.48E-04	4.21E-04	2.47E-03
Human carcinogenic toxicity	kg 1,4-DCB	5.75E-03	3.35E-04	4.21E-03	2.76E-04	7.41E-04	1.93E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	2.33E-01	1.07E-02	1.46E-01	7.47E-03	7.13E-03	6.22E-02
Land use	m^2a crop eq	1.21E+00	1.19E+00	2.27E-02	4.04E-04	4.61E-04	3.68E-05
Mineral resource scarcity	kg Cu eq	9.35E-04	6.02E-05	7.85E-04	2.63E-05	4.63E-05	1.69E-05
Fossil resource scarcity	kg oil eq	2.23E-02	1.49E-03	4.98E-03	3.82E-03	1.18E-02	2.18E-04
Water consumption	m^3	5.49E-03	1.94E-04	1.67E-04	3.22E-05	1.06E-04	4.99E-03

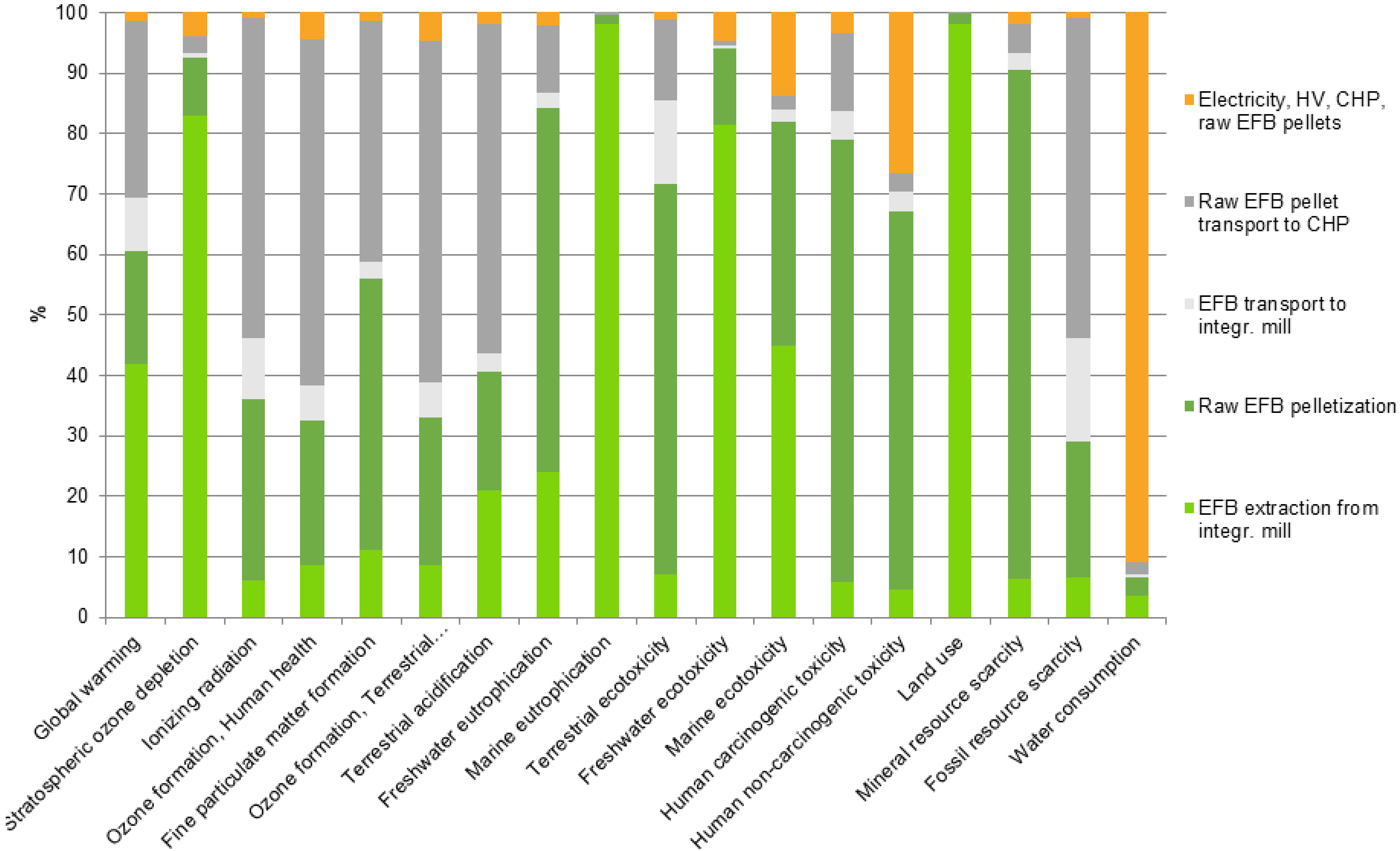


Figure 15: Impact assessment (comparative) of CHP plant burning raw EFB pellets from Malaysia (Method: ReCiPe 2016 Midpoint (H))

Table 13: Impact assessment of CHP plant burning HTC-treated EFB pellets from Malaysia (Method: ReCiPe 2016 Midpoint (H))

Impact category	Unit	Total	EFB transport to integr. mill	HTC EFB pellets transport to CHP	Electricity, HV, CHP, HTC EFB pellets	EFB HTC & pelletization
Global warming	kg CO2 eq	1.23E-01	1.04E-02	2.53E-02	1.98E-03	8.49E-02
Stratospheric ozone depletion	kg CFC11 eq	6.02E-07	4.55E-09	1.16E-08	2.62E-08	5.59E-07
Ionizing radiation	kBq Co-60 eq	2.53E-03	2.53E-04	9.69E-04	3.09E-05	1.28E-03
Ozone formation, Human health	kg NOx eq	8.72E-04	4.32E-05	3.05E-04	2.44E-04	2.79E-04
Fine particulate matter formation	kg PM2.5 eq	6.25E-03	1.23E-05	1.28E-04	3.00E-05	6.08E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	8.85E-04	4.40E-05	3.07E-04	2.46E-04	2.88E-04
Terrestrial acidification	kg SO2 eq	2.05E-02	3.02E-05	3.90E-04	9.66E-05	2.00E-02
Freshwater eutrophication	kg P eq	4.83E-05	8.98E-07	3.11E-06	1.21E-06	4.31E-05
Marine eutrophication	kg N eq	1.07E-04	6.95E-08	2.17E-07	2.57E-08	1.07E-04
Terrestrial ecotoxicity	kg 1,4-DCB	1.06E+00	1.13E-01	8.14E-02	1.08E-02	8.52E-01
Freshwater ecotoxicity	kg 1,4-DCB	3.87E-02	1.96E-04	1.77E-04	3.15E-03	3.51E-02
Marine ecotoxicity	kg 1,4-DCB	2.17E-02	3.24E-04	2.88E-04	4.41E-03	1.67E-02
Human carcinogenic toxicity	kg 1,4-DCB	7.13E-03	2.57E-04	5.06E-04	2.32E-04	6.14E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	3.35E-01	6.95E-03	4.87E-03	1.11E-01	2.12E-01
Land use	m2a crop eq	1.13E+00	3.76E-04	3.15E-04	5.12E-05	1.13E+00
Mineral resource scarcity	kg Cu eq	1.22E-03	2.45E-05	3.16E-05	1.71E-05	1.14E-03
Fossil resource scarcity	kg oil eq	2.01E-02	3.55E-03	8.03E-03	2.54E-04	8.28E-03
Water consumption	m3	6.06E-03	3.00E-05	7.25E-05	4.99E-03	9.66E-04

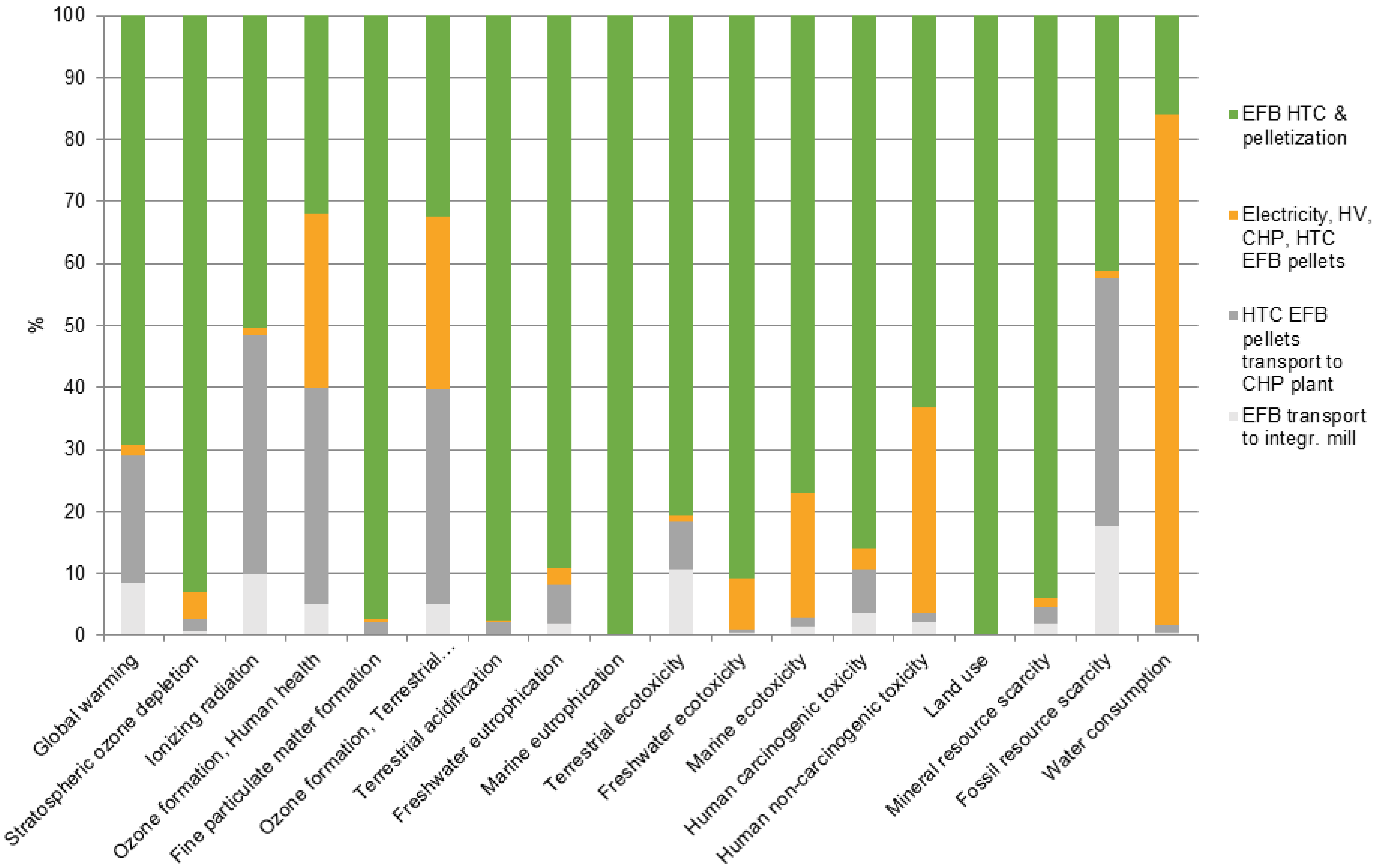


Figure 16: Impact assessment (comparative) of CHP plant burning HTC-treated EFB pellets from Malaysia (Method: ReCiPe 2016 Midpoint (H))

Table 14: Impact assessment of CHP plant burning raw bark pellets from Finland (Method: ReCiPe 2016 Midpoint (H))

Impact category	Unit	Total	Bark sawmill & pelletization	Silviculture & harvest	Spruce chips, sust. forest mgmt	Raw pellet transport to CHP	Roundwood transport to sawmill	Electricity, HV, CHP, raw bark pellets
Global warming	kg CO2 eq	4.33E-02	2.34E-02	1.69E-04	2.83E-03	7.72E-03	7.22E-03	1.88E-03
Stratospheric ozone depletion	kg CFC11 eq	8.31E-08	4.64E-08	1.82E-09	1.84E-09	3.54E-09	3.30E-09	2.62E-08
Ionizing radiation	kBq Co-60 eq	1.86E-03	8.26E-04	7.81E-06	4.78E-05	7.15E-04	2.38E-04	2.80E-05
Ozone formation, Human health	kg NOx eq	4.78E-04	1.30E-04	4.11E-06	8.77E-06	5.73E-05	3.31E-05	2.44E-04
Fine particulate matter formation	kg PM2.5 eq	2.12E-04	1.49E-04	9.35E-07	2.92E-06	2.07E-05	9.48E-06	2.99E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.88E-04	1.37E-04	4.14E-06	8.99E-06	5.81E-05	3.40E-05	2.46E-04
Terrestrial acidification	kg SO2 eq	3.82E-04	1.96E-04	4.02E-06	7.02E-06	5.78E-05	2.15E-05	9.61E-05
Freshwater eutrophication	kg P eq	2.83E-05	2.49E-05	1.92E-08	2.36E-07	1.73E-06	4.68E-07	9.21E-07
Marine eutrophication	kg N eq	2.16E-06	1.74E-06	2.11E-07	1.72E-08	1.19E-07	4.02E-08	2.48E-08
Terrestrial ecotoxicity	kg 1,4-DCB	8.01E-01	5.80E-01	3.44E-04	7.21E-03	6.66E-02	1.36E-01	1.05E-02
Freshwater ecotoxicity	kg 1,4-DCB	7.05E-03	4.80E-03	1.82E-06	2.46E-05	1.19E-04	1.03E-04	2.00E-03
Marine ecotoxicity	kg 1,4-DCB	1.00E-02	6.77E-03	2.92E-06	3.73E-05	1.94E-04	2.01E-04	2.80E-03
Human carcinogenic toxicity	kg 1,4-DCB	4.96E-03	4.27E-03	2.89E-06	4.46E-05	3.16E-04	1.29E-04	2.00E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	2.26E-01	1.47E-01	6.69E-05	6.32E-04	3.69E-03	3.68E-03	7.05E-02
Land use	m2a crop eq	1.66E-01	2.19E-02	2.48E-05	1.43E-01	3.82E-04	5.77E-04	3.92E-05
Mineral resource scarcity	kg Cu eq	8.55E-04	7.97E-04	2.96E-07	6.30E-06	2.17E-05	1.21E-05	1.69E-05
Fossil resource scarcity	kg oil eq	1.15E-02	5.06E-03	1.87E-04	9.09E-04	2.46E-03	2.63E-03	2.24E-04
Water consumption	m3	5.23E-03	1.71E-04	2.32E-06	6.29E-06	3.51E-05	2.48E-05	4.99E-03

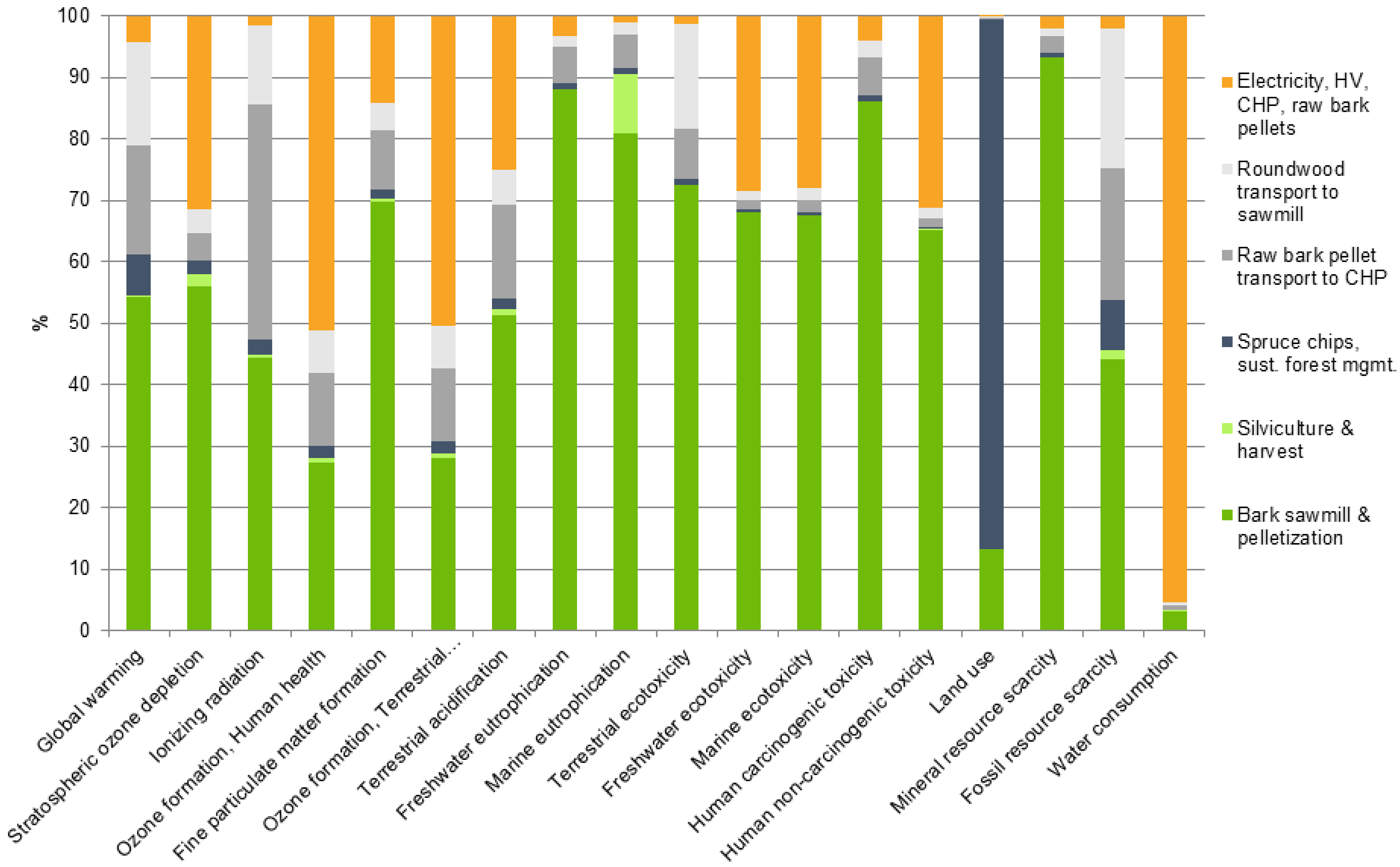


Figure 17: Impact assessment (comparative) of CHP plant burning raw bark pellets from Finland (Method: ReCiPe 2016 Midpoint (H))

Table 15: Impact assessment of CHP plant burning steam exploded bark pellets from Finland (Method: ReCiPe 2016 Midpoint (H))

Impact category	Unit	Total	Bark sawmill, SE & pelletization	Silviculture & harvest	Spruce chips (sfm)	SE pellet transport to CHP	Roundwood transport to sawmill	Electricity, HV, CHP, SE pellets
Global warming	kg CO2 eq	4.38E-02	2.24E-02	1.58E-04	5.46E-03	7.23E-03	6.76E-03	1.77E-03
Stratospheric ozone depletion	kg CFC11 eq	8.37E-08	4.59E-08	1.71E-09	3.53E-09	3.31E-09	3.09E-09	2.61E-08
Ionizing radiation	kBq Co-60 eq	1.83E-03	8.08E-04	7.33E-06	9.84E-05	6.69E-04	2.23E-04	2.41E-05
Ozone formation, Human health	kg NOx eq	4.89E-04	1.29E-04	3.86E-06	2.81E-05	5.36E-05	3.10E-05	2.43E-04
Fine particulate matter formation	kg PM2.5 eq	2.07E-04	1.41E-04	8.78E-07	7.26E-06	1.94E-05	8.87E-06	2.96E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	5.00E-04	1.35E-04	3.89E-06	2.93E-05	5.44E-05	3.18E-05	2.45E-04
Terrestrial acidification	kg SO2 eq	3.80E-04	1.90E-04	3.78E-06	1.71E-05	5.41E-05	2.01E-05	9.54E-05
Freshwater eutrophication	kg P eq	2.69E-05	2.40E-05	1.80E-08	4.52E-07	1.62E-06	4.38E-07	4.54E-07
Marine eutrophication	kg N eq	5.24E-06	4.76E-06	1.98E-07	1.09E-07	1.12E-07	3.76E-08	2.36E-08
Terrestrial ecotoxicity	kg 1,4-DCB	7.64E-01	5.49E-01	3.23E-04	1.41E-02	6.23E-02	1.27E-01	1.03E-02
Freshwater ecotoxicity	kg 1,4-DCB	4.91E-03	4.53E-03	1.71E-06	4.74E-05	1.11E-04	9.61E-05	1.26E-04
Marine ecotoxicity	kg 1,4-DCB	7.00E-03	6.38E-03	2.74E-06	7.19E-05	1.82E-04	1.88E-04	1.79E-04
Human carcinogenic toxicity	kg 1,4-DCB	4.73E-03	4.06E-03	2.71E-06	1.05E-04	2.96E-04	1.21E-04	1.48E-04
Human non-carcinogenic toxicity	kg 1,4-DCB	1.53E-01	1.41E-01	6.28E-05	1.25E-03	3.46E-03	3.45E-03	4.13E-03
Land use	m2a crop eq	1.58E-01	2.33E-02	2.33E-05	1.34E-01	3.58E-04	5.40E-04	2.11E-05
Mineral resource scarcity	kg Cu eq	8.16E-04	7.53E-04	2.78E-07	1.44E-05	2.03E-05	1.13E-05	1.67E-05
Fossil resource scarcity	kg oil eq	1.17E-02	4.85E-03	1.76E-04	1.76E-03	2.31E-03	2.46E-03	1.89E-04
Water consumption	m3	4.79E-03	-2.81E-04	2.17E-06	1.60E-05	3.28E-05	2.32E-05	4.99E-03

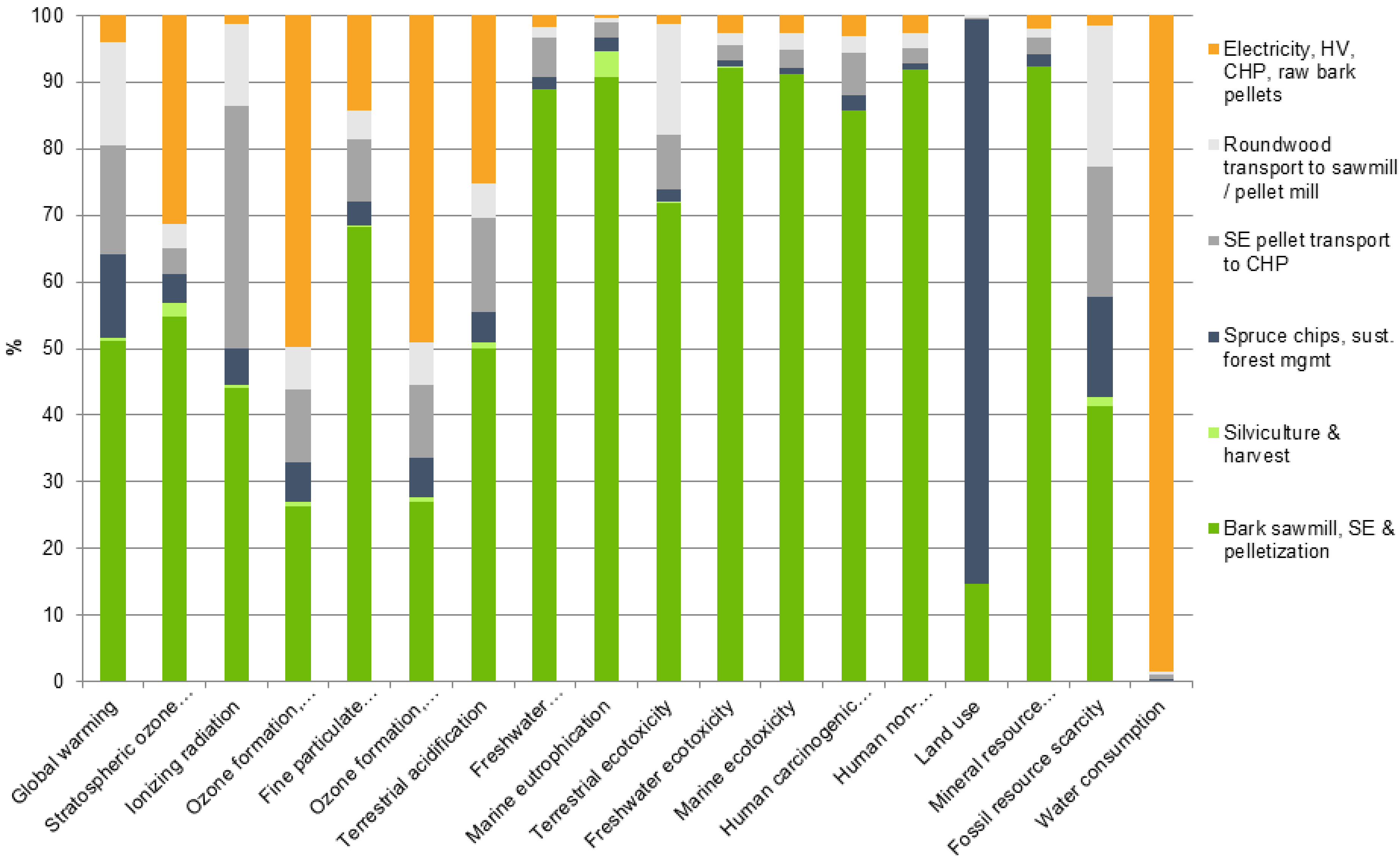


Figure 18: Impact assessment (comparative) of CHP plant burning steam exploded bark pellets from Finland (Method: ReCiPe 2016 Midpoint (H))

Sensitivity analysis

Apart from the initial sensitivity analysis regarding the effect of energy and exergy allocation on the GHG footprint of the produced bioelectricity, as well as that of building infrastructure inclusion in the LCI of all scenarios, which is presented in Table 9, a preliminary sensitivity analysis was performed for the supply of raw wood pellets from Canada (scenario 1a), assuming the electricity demand for pelletisation is supplied from a nearby river hydropower unit (ecoinvent process: Electricity, high voltage {CA-QC} electricity production, hydro, run-of-river | Cut-off, U). The results are slightly in favor of the hydro-powered wood pellet plant (see Table 16). For instance, the GHG impact was 23.3 g CO_2-eq/MJ_{el} versus 23.5 g CO_2-eq/MJ_{el} for the Quebec grid powered pellet plant scenario. All comparative indicator results were within a 0-2% range, with the largest difference calculated for freshwater ecotoxicity ($9.67 \cdot 10^{-4}$ kg 1,4-DCB versus $9.87 \cdot 10^{-4}$ kg 1,4-DCB for grid supplied electricity). This result was anticipated, given that electricity generation in the Quebec region is dominated (by 96.1%) by hydroelectric plants [97].

A sensitivity analysis examining the effect of ship transportation distance was also performed for wood pellets (assuming grid supplied electricity), by varying the shipping distance by ±30%. For a 30% increase, there was a 12.2% raise of the scenario's carbon footprint (26.36 g CO_2-eq/MJ_{el} or 25.69 g CO_2-eq/MJ_{el} excluding building infrastructure), while for the 30% decrease, a 15.36% decrease in the carbon footprint was calculated (19.89 g CO_2-eq/MJ_{el} or 19.22 g CO_2-eq/MJ_{el} excluding building infrastructure). For the raw EFB pellets from Malaysia, varying the shipping distance by ±30% resulted in an 8.05% increase (137.2 g CO_2-eq/MJ_{el}) and an 8.65% decrease (116 g CO_2-eq/MJ_{el}) respectively.

When test scenarios were evaluated for other feedstocks, where pretreatment electricity was assumed to be supplied from the local grid, results varied. This is due to the large differences between electricity production mixes for each country/region and the known problems with feedstock supply chain development, as well as low overall efficiency issues of medium scale biomass cogeneration. Assuming a scenario of grid electricity consumption for bark/energy wood raw pellets with train and ship transportation, a GHG impact of 48.1 g CO_2-eq/MJ_{el}, raised by 11.16% was calculated. When land transportation in Finland was assumed to be carried out only by truck, with a wood chip fueled CHP for covering the electricity and heat loads, the impact rose to 47.67 g CO_2-eq/MJ_{el}, a 10.17% raise. For raw EFB pellets, the carbon footprint calculated for the Malaysian grid electricity consumption scenario equals to 148.71 g CO_2-eq/MJ_{el}, a 17.11% raise.

b. Economic evaluation results for a number of scenarios

An example of the methodology used for calculating the electricity production cost for all studied fuels is presented. For a torrefied wheat straw biomass pellet total fuel cost of 22.93 €/MWh, including purchasing and transportation costs, the following cost analysis was performed, resulting in a production cost of electricity of 82.45 €/MWh. The results are shown in Table 16.

Table 16: Preliminary economic evaluation of biomass CHP plant with 22.93 €/MWh cost of fuel

Fixed Cost		**12.5435**	**€/MWh**
Total investment cost	C	250000000	€
Fixed cost of operation, maintenance, administration	U_{fix}	5500000	€/a
Thermal power of the CHP plant	$Pi_{th,CHP}$	200	MW
Availability factor of the plant		8000	h/yr
Variable Cost		**47.4523**	**€/MWh**
Cost of fuel	y_f	22.93	€/MWh
thermal efficiency	$n_{th,CHP}$	0.55	-
electrical efficiency	$n_{el,CHP}$	0.3	
Variable cost of operation, maintenance and repair	u_{var}	5.76	€/MWh
Yearly income from heat sale		26400000	€/year
Heat price		40	€/MWh
Heat sale availability factor		6000	h/a
Yearly cost of electricity		39578043.23	€/a,electr
cost of electricity per MWh		82.45	€/MWh
Annuity factor	ψ	0.058278	-
Discount rate per year %	D	0.05	
Plant lifetime	N	40	A

ash disposal		
ash percentage	7.40%	%
ash disposal price	50	€/t ash
t of ash per year	24464.55	t ash/a
cost of ash treatment per year	1223227.27	€/a
cost of ash per MWh	0.76	€/MWh

The comparative torrefied fuel cost evaluation is shown in Fig. 19, expressed in €/MWh of fuel produced, while the comparative torrefaction pretreatment plant TCI for all studied feedstocks is in Fig. 20.

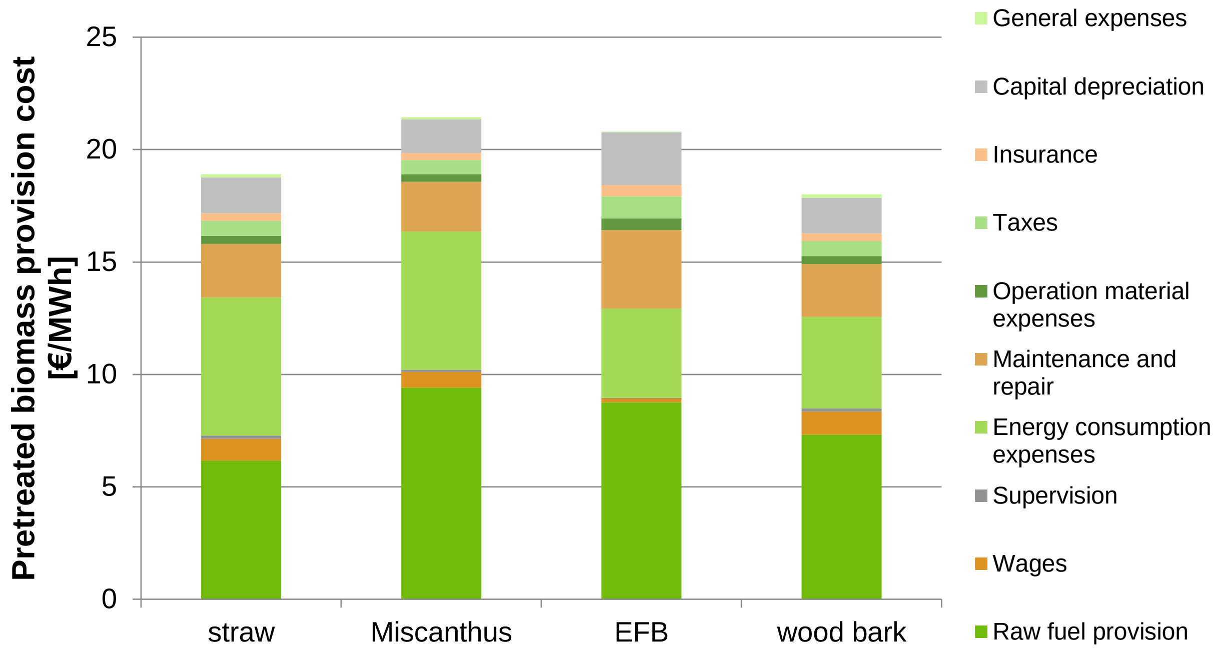


Figure 19: Comparative cost evaluation of selected torrefied fuels

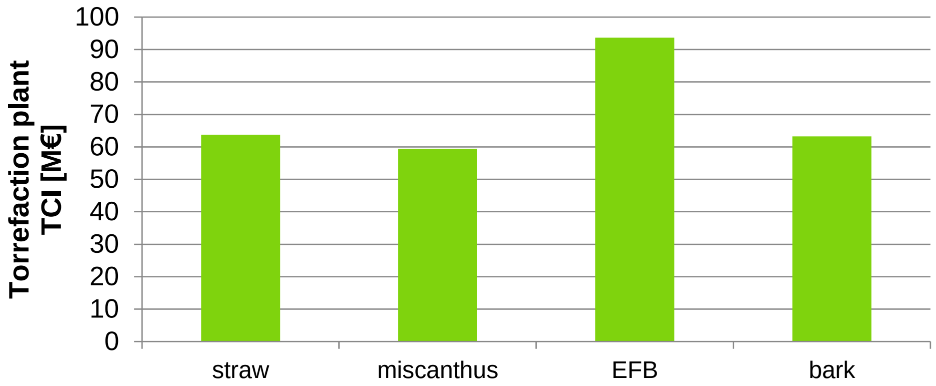


Figure 20: Comparative TCI evaluation for torrefaction plants of selected feedstocks

The comparative HTC fuel cost evaluation is shown in Fig. 21 and the comparative HTC pretreatment plant TCI for all studied feedstocks is in Fig.22.

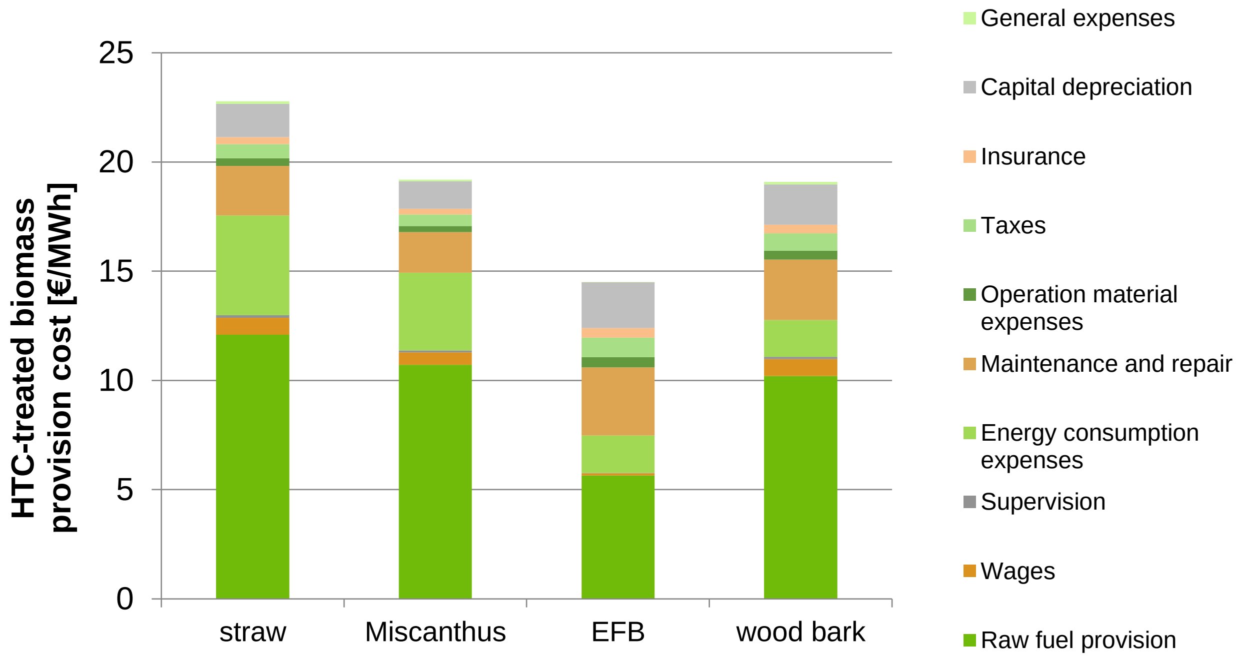


Figure 21: Comparative cost evaluation of selected HTC-treated fuels

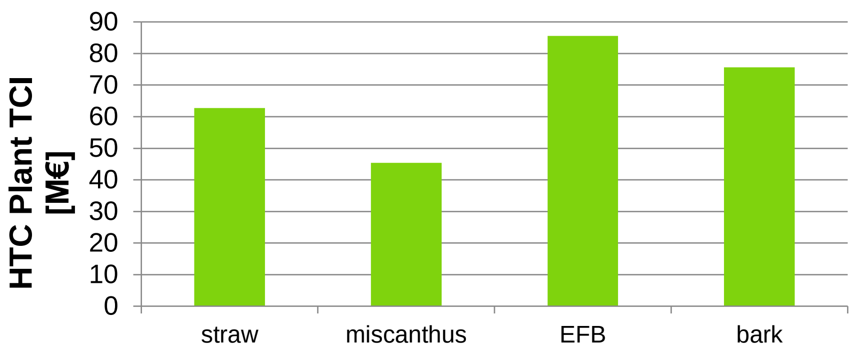


Figure 22: Comparative TCI evaluation for HTC plants of selected feedstocks

The impact of heat sale price on the electricity generation costs is shown in Fig. 23 for torrefied fuels and in Fig. 24 for HTC-treated fuels. Comparative results of the best performing feedstock for each treatment scenario are shown in Fig. 25, along with the calculated costs for the steam explosion treatment of wood bark. The feedstocks that result in the lowest electricity production cost were found to be torrefied wheat straw and bark pellets, followed by HTC-treated wood bark. Empty fruit bunches were found to be the least cost-effective feedstock, mainly due to high transportation costs. The miscanthus HTC treatment plant was the least expensive standalone plant. The steam explosion plant was found to be expensive in our preliminary evaluation (100 M€ TCI for a processing plant of a 72.2 dry input tons/h capacity, calculations adapted from 1990 prices), however, it is usually considered as a concept to be built as an integrated processing plant in wood processing units (pulp/paper mills, sawmills etc.) instead of a standalone configuration, which was the NTUA base case for the economic evaluation. Integrated steam explosion biorefineries in existing pulp and paper mills benefit from the unit's existing infrastructure, readily available residual feedstocks and excess heat and this results in much lower both investment and operational costs.

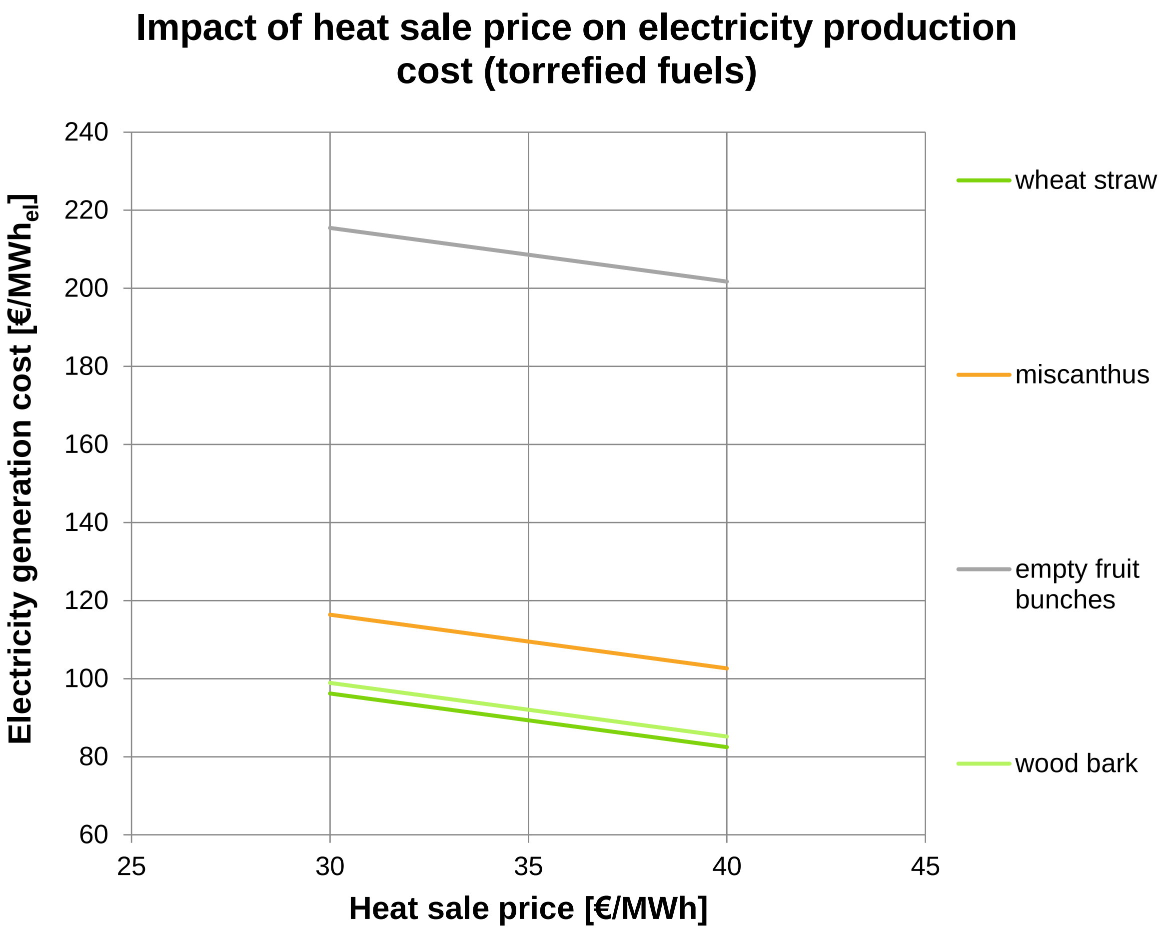


Figure 23: Comparative assessment of the effect of the heat sale price on various torrefied fuels

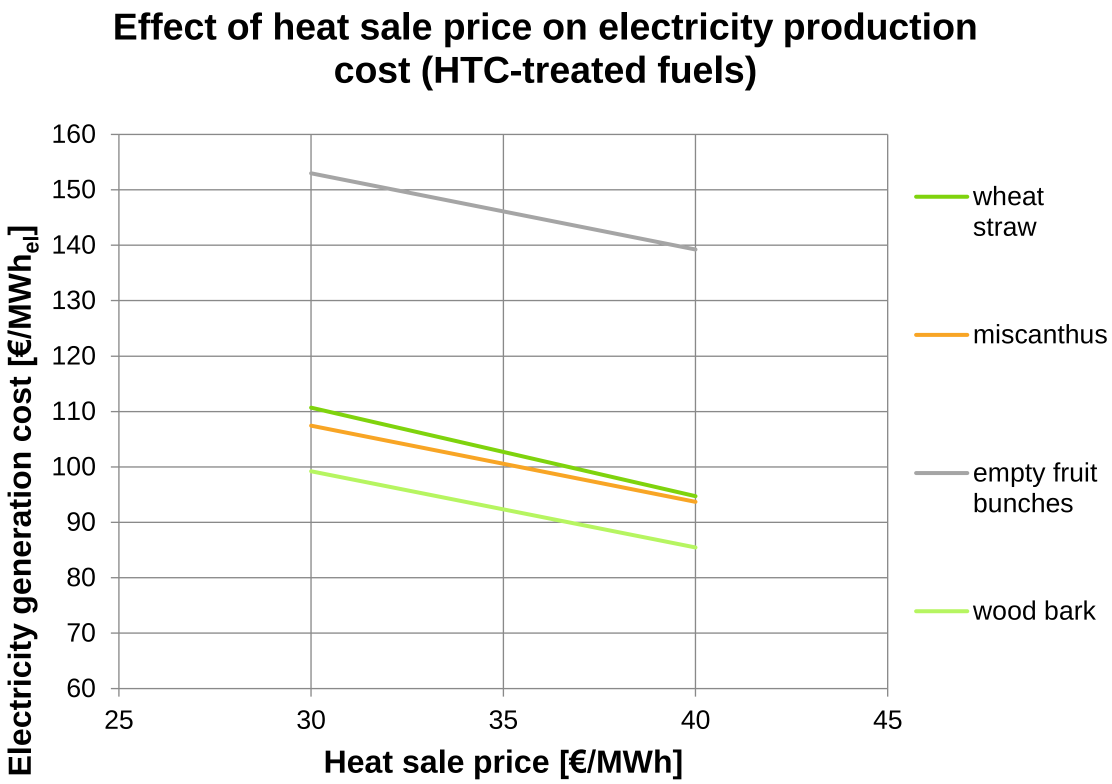


Figure 24: Comparative assessment of the effect of the heat sale price on various HTC-treated fuels

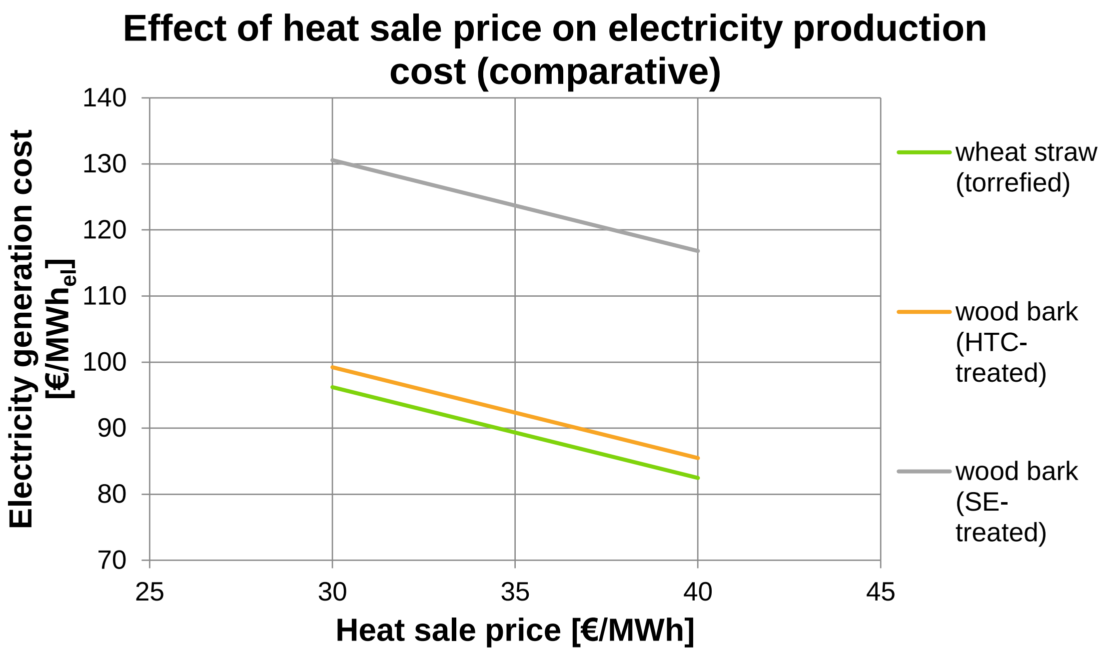


Figure 25: Comparative assessment of the effect of the heat sale price on the most cost-effective pretreated fuels

7. Conclusions and Outlook

As stated in the Introduction section, this document provides an interim, preliminary evaluation of some of the scenarios under study in the Biofficiency project, based mainly on literature and other publicly available sources. The final report shall contain the complete assessment of the specific scenarios under study, utilizing the feedback on this interim report from the partners (both industrial and academic) and providing an insight to the specific biomass production, pretreatment and utilization routes. The effect of biomass ash recycling and various valorization options shall also be considered, e.g. use in geopolymers and as fertilizer.

Some of the investigated scenarios have already been proven not feasible, either financially, environmentally or both, mainly due to large transportation distances, technology limitations and pretreatment facility investment costs. However, following exergy allocation and excluding infrastructure emissions, GHG savings between 62% and 92% were calculated for the studied scenarios. Technology advances and changes in environmental legislation, as well as green financing solutions can result in further improved impacts in the following years. One technology option to be considered, especially for fuels containing significant amounts of chlorine and sulfur, is the installation of a flue gas condensing system, to achieve optimal heat recovery and remove HCl and SO_2 from the flue gases [22]. These preliminary results will be refined according to industrial and academic partners' feedback, while the final results will be presented in the Biofficiency project final report. Main areas to be refined in order to be more representative of the Biofficiency concept scenarios are the following:

- Feedstock pretreatment life cycle inventories: expert estimations on the performance characteristics of **continuous operation, large scale integrated pretreatment and pelletization plants** (specific feedstock consumption, specific energy consumption, specific water consumption, auxiliary biomass boiler emission factors and specific biomass fuel consumption, machinery and infrastructure specific data, wastewater treatment utility specific demands etc., preferably for the production of 1 kg fuel as a functional unit).
- Expert estimations on **large scale biomass CHP plant** performance data (general arrangement, equipment cost data for the refining of the techno-economic assessment, specific combustion emission factors for PF and FB systems, electrical and overall system efficiencies for each studied fuel, specific water consumption per water quality used, combustion additives (origin and specific consumption), SCR and FGD specific consumption, expected system full load operational hours per year, other infrastructure specific data, wastewater treatment utility specific demands etc., preferably per MJ electricity produced by the CHP plant as a functional unit). This way the impact of CHP load flexibility on the life cycle emissions can be evaluated. Cost estimations will also be refined based on experts‘ feedback.

In general, our goal as partners of the Biofficiency project is to provide substantial information to policymakers and stakeholders regarding the feedstock, pretreatment technology and supply chain options that carry potential environmental or financial risks, signaling the need for a careful approach when planning project implementation. Stakeholders need to make the best use of our limited sustainable biomass resources to promote this versatile and robust renewable energy source.

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