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Wood Waste Recycling in Sweden—Industrial, Environmental, Social, and Economic Challenges and Benefits

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Abstract: The disposal of wood waste at facilities for incineration in Sweden is the only applied management practice today. Energy production from biomass has gained attention for its potential to recover energy and reduce greenhouse gas emissions. However, besides being a valuable source for energy generation, wood waste can be effectively recycled into new products. Specifically, recycling wood waste into particleboard is the widely practiced method in Europe, while its benefits have not been explored in the country so far. The objective of this study is to assess the environmental, social, and economic sustainability of producing particleboard and generating energy from wood waste in Sweden. This research investigates four alternative systems for wood waste disposal. The first system involves the production of heat, the second system involves heat and power by wood waste, while the third and the fourth systems, in addition to energy recovery, include partial recycling of wood waste in particleboard production. A life cycle sustainability assessment covering all three pillars (environment, social, and economic) of sustainability was conducted to compare these systems. The results show that adding recycling schemes to incineration in wood waste management practices strengthens the sustainability for all three aspects, and hence, these management methods can be considered as complementary methods rather than competing methods. When all sustainability categories are considered, alternative three (heat recovery and recycling) comes forward as the best option in 11 out of 16 impact categories.

Keywords: environmental assessment; social impacts; economic analysis; waste-to-energy; wood waste recycling; particleboard

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1. Introduction

All 28 European Union (EU) countries together generate 50–60 million tons of wood waste annually [1]. Wood waste—often in the form of engineered wood products—is ubiquitous in our society and found in construction and demolition, packaging, and municipal waste streams; often covered with coatings, veneers, and other coverings or embedded in the structural fabric of a building, furniture, or vehicle. Wood is a renewable, reusable, and biodegradable material, and there is thus great potential for the wood value chain to embrace circularity. The EU is committed to increasing the recycling of materials as part of its drive to a fully circular economy. This is demonstrated by a gradual introduction of recycling targets for various waste streams, including a 70% target for the recycling of construction and demolition waste, a 30% target for the recycling of wood contained in packaging, and a 60% target for recycling municipal wastes by 2030 [2,3]. One common management method of dealing with wood waste is to convert it into energy or recycle it. In European countries, for decades, energy utilization of wood waste has exceeded material utilization, accounting for 60–95% of the total utilization [4]. On the other hand, many other European Union countries have insufficient incinerator capacity to accommodate all the polluted waste wood, hence leading to the other disposal route, landfilling. The energy recovered from wood waste can be used for district heating systems. District heating from waste wood has substantially increased in countries with high incineration capacity, such as in Scandinavia and, in particular, Sweden, since the Euro Waste Framework Directive 2008/98/EC [2] does not permit landfilling of waste unless it is the only disposal option. Indeed, of the 1–2 million tons of wood waste generated annually in Sweden, about 90% is combusted for energy recovery in the form of heat or electricity [1,5]. Although energy recovery is an important valorization route for waste materials, it does not fit with the European Union's strategy to maximize recycling.

In Sweden, wood waste is, in principle, not recycled into new materials or products [6]. Wood waste from private households is sorted manually under the guidance of signs and instructed personnel into three wood waste streams: (1) preservative-treated wood ('impregnerat trä', in Swedish), (2) wood ('trä', in Swedish), and (3) pallets. Pallets are reused as pallets. The waste from streams 1 and 2 is collected, chipped and stored at regionally dispersed waste sites—together with wood waste from the business sector—prior to shipment to incineration plants for energy recovery—one plant for stream 1's hazardous waste and one for stream 2's non-hazardous waste. Data from recycling stations in Stockholm and a waste site in Uppsala show that the non-hazardous wood waste stream in Sweden may be estimated at about 90% of the total wood waste stream [7,8]; wood that, when properly sorted, could be used in, for example, the particleboard industry. In other European countries, the particleboard industry is the main user of wood waste wood, and particleboard production is possible with over 95% recovered wood content [9]. Yet, Sweden's only particleboard plant in Hultsfred (annual production capacity 650,000 m^3) has difficulties reaching its target of using 30% recovered wood and has been importing recovered wood from Norway [10]. In fact, only 4–8% of the current total Swedish wood waste stream would enable Hultsfred to reach its recycling targets, and 15–30% enables particleboard production with 100% recovered wood. However, a life cycle sustainability assessment (LCSA) looking into industrial, environmental, social, and economic challenges and benefits of recycling wood waste in Sweden, in addition to using wood waste for energy recovery, is missing, and such a crucial evaluation could provide sensible advice to policymakers, researchers, the waste management sector, and the general public alike.

The aim of this study is to assess the environmental, social, and economic sustainability of producing particleboard and generating energy from wood waste in Sweden. In total, four different scenarios are studied, where two situations are compared (where 100% of the total wood waste stream is used for energy recovery versus 90% of the total wood waste stream for energy recovery with the other 10% being recycled into particleboard), and two types of energy recovery methods are included (only heat versus heat and power). Sweden has excellent incineration infrastructure, and therefore, all alternatives include incineration, while two alternatives include material recovery in addition to the current system. Identifying the challenges and benefits of wood waste recycling would contribute to the discussion regarding goal conflicts in wood waste management and relevant decision-making.

2. Literature Review

The life cycle assessment (LCA) is a valuable tool for evaluating the environmental impacts of different waste-to-energy technologies, including those related to wood waste. Several have explored the LCA of wood waste-to-energy systems, shedding light on the environmental performance and sustainability of these processes. Wolf et al. [11] used the LCA to assess wood energy's environmental impact across 97 systems in North America and Europe. Their findings highlighted a median global warming impact of 0.169 kg carbon dioxide equivalent (CO_2-eq) per kWh for power generation, 0.098 kg CO_2-eq per kWh for biomass fraction, and 0.040 kg CO_2-eq per kWh for heat production. Combined heat and power (CHP) systems show the highest variability in kg CO_2-eq per KWh, with a median impact of 0.066, emphasizing the need for standardized approaches in comparing wood energy services. Choong et al. [12] evaluated a biomass-fired power plant utilizing wood waste, emphasizing climate change impacts through greenhouse gas (GHG) emissions. The results showed the wood waste-to-energy (WtE) plant emits 0.032 kg CO_2-eq per kWh, achieving a remarkable 96.1% reduction compared to the national grid's 0.820 kg CO_2-eq per kWh emissions. Despite the many advantages of CHP generation from wood waste, combusting wood waste can release various air pollutants, resulting in the production of ash, heavy metals, and other pollutants. Hence, it is advisable to substitute wood combustion partially with the recycling of wood waste for reuse in diverse products, such as particleboard. The LCA has also been applied to evaluate the environmental effects of recycling wood waste into new products like particleboard. The LCA with an eco-indicator of 99 on particleboard in short-life-time applications showed that recycling is favorable compared to energy recovery in terms of climate change [13]. In addition, a 9% reduction in total emissions was achieved when producing particleboard with recovered wood and cement as aggregates compared to virgin wood and traditional binders, while GHG emissions were little affected and were mainly dependent on wood waste recycling rates [14].

Life cycle costing (LCC) is a method to evaluate the economic impact of technologies, including wood waste management methods. According to Nandimandalam et al. [15], states in the USA that can produce more electricity than their needs, particularly through utilizing wood, offer to assist their nearby states by providing them with electricity. With a capacity of 630 MW and an estimated cost ranging from 10 to 13 cents/kWh, the use of alternative sources becomes economically feasible. They claim that generating electricity from wood waste produces less greenhouse gases than using fossil fuels, thus lessening dependence on finite resources. Furthermore, the avoided CO_2-eq emissions resulted in significant carbon tax savings. A CO_2-eq carbon tax of USD 20 per ton raises grid electricity expenses. Hence, due to lower expenses, it has the potential to accelerate the transition toward renewable energy sources like wood, solar, wind, and hydro. The LCC assessment in [16] has shown that utilizing renewable energy along with carbon footprint pricing could eventually make renewable-based energy production cheaper than fossil fuels. Overall, this approach holds promise for fostering cleaner and more sustainable energy practices.

Marchenko et al. [17] found that utilizing wood waste is economically advantageous for operating power plants. Similarly, Tschulkow et al. [18] investigated various plant scales and determined that employing wood waste enhances profitability for smaller plants. However, Golonis et al. [19] argued for the prioritization of biomass reuse and recycling over conversion to bioenergy or disposal, aligning with the principle of sequence. Despite these insights, a comprehensive economic evaluation considering the use of wood waste for energy generation and material recycling remains missing in the literature.

The social life cycle assessment (S-LCA) method has been used to evaluate the social impacts of waste management alternatives. The S-LCA is a method for assessing the positive and negative social impacts of a product or service over the course of its life cycle, focusing on the people [20–22]. The S-LCA gathers information on the organizational aspects of the enterprise along product life cycles concerning the social and socio-economic impacts [23]. The 2020 UNEP-SETAC guidelines provide more details and consensus-based guidance for each step of the S-LCA process. Hunkeler [24] compared the societal impacts of two different types of detergents using a life cycle inventory database of the S-LCA. Menikpura et al. [25] assessed the social aspects associated with municipal solid waste management systems in Thailand. It proved that solid waste recycling contributes to the prevention of human health damage and generates a sizable earning by selling point-source separated recyclables [25]. Indeed, the disposal of wood waste at Swedish recycling stations implies a cost, while it could potentially become revenue [8]. It has been shown in other waste management sectors that the recycling process chain generates many employment opportunities in a variety of hierarchical roles [25]. For packaging waste, formal waste collection systems, such as door-to-door separated waste collection by municipality, demonstrated more negative social impacts than an integrated formal–informal system in which waste pickers separate waste from containers [26]. The use of renewable energy from lignocellulosic biomasses greatly enhances human health and lowers pollution [27,28]. The recycling of materials and products generally opens new potential for creative businesses while also benefiting society and the environment by fostering the development of a circular economy [29]. Potential negative social impacts have also been identified in the literature. Direct combustion of woody biomass for energy has less CO_2 emissions than wood pellets, but it has less of an effect on increasing output and job creation [30]. However, the bioenergy sector has created several jobs [31]. In addition, it was shown in a sustainability impact analysis of forest wood chains that the average rate of accidents is higher in the sector providing virgin wood but, at the same time, generates greater employment and higher labor expenses [32].

In the literature, a comprehensive sustainability assessment (including all three pillars of sustainability) of wood waste management systems covering both energy and material recovery does not exist up to the authors' knowledge. This gap needs to be filled since a system with good environmental performance is not always the most sustainable option if all aspects are considered.

3. Methods

3.1. Description of Systems and Boundaries

The schematic and boundaries of the four selected systems are shown in Figure 1. The present study investigates different systems for the production of energy (heat and electricity) based on wood waste combustion as well as the production of particleboard by material recovery from wood waste. In the first system, the waste heat of flue gasses is captured for thermal energy production via the incorporation of an incineration part into the heat production unit. In the second alternative, the recovered heat of output flue gasses is utilized for both heat and power production by linking the combustion system to the CHP unit. The third and fourth systems are similar to the first and second options, respectively, with the difference that 10% of wood waste is recycled into particleboard.

Wood waste combustion by incineration, including both municipal and hazardous incineration, is a common part of all systems. Municipal incineration refers to the process of burning municipal solid waste (MSW), which includes household trash, commercial waste, and non-hazardous industrial waste, in specialized facilities called incinerators. These incinerators are designed to efficiently burn waste and produce electricity and heat as by-products. Hazardous incineration, on the other hand, involves the burning of hazardous waste materials, including but not limited to certain types of wood waste contaminated with toxic chemicals or treated with hazardous substances such as preservatives, paints, or varnishes. When discussing carbon emissions, it is important to note that both municipal incineration and hazardous incineration contribute to carbon emissions in different ways. Municipal incineration releases CO_2 into the atmosphere, which is a greenhouse gas contributing to global climate change, but the hazardous incineration of wood waste can release higher levels of carbon emissions compared to municipal incineration. This is because the presence of hazardous substances in wood waste can result in the emission of additional pollutants during combustion, including volatile organic compounds (VOCs), heavy metals, and other harmful air pollutants. By burning MSW, municipal incineration reduces the volume of waste going to landfills, which helps minimize methane emissions produced by decomposing waste in a landfill. However, hazardous incineration of wood waste may require more rigorous pollution control measures to ensure that emissions are within acceptable limits. Technologies such as scrubbers, filters, and monitoring systems are employed to reduce the release of pollutants into the environment [33,34].

The amount of raw wood material required for particleboard production varies depending on the manufacturer and the desired thickness and density of the board. Generally, to produce 1 m^3 of particleboard, approximately 600–700 kg of wood particles are required. These wood particles can be obtained from various sources: virgin round wood, processing residues (e.g., sawdust, off-cuts, and planer shavings), and wood waste [35]. When particleboard is produced from wood waste, there can be a significant impact on carbon reduction. By using recycled wood, the demand for raw virgin wood is reduced, which in turn helps to preserve forests and reduces deforestation [36].

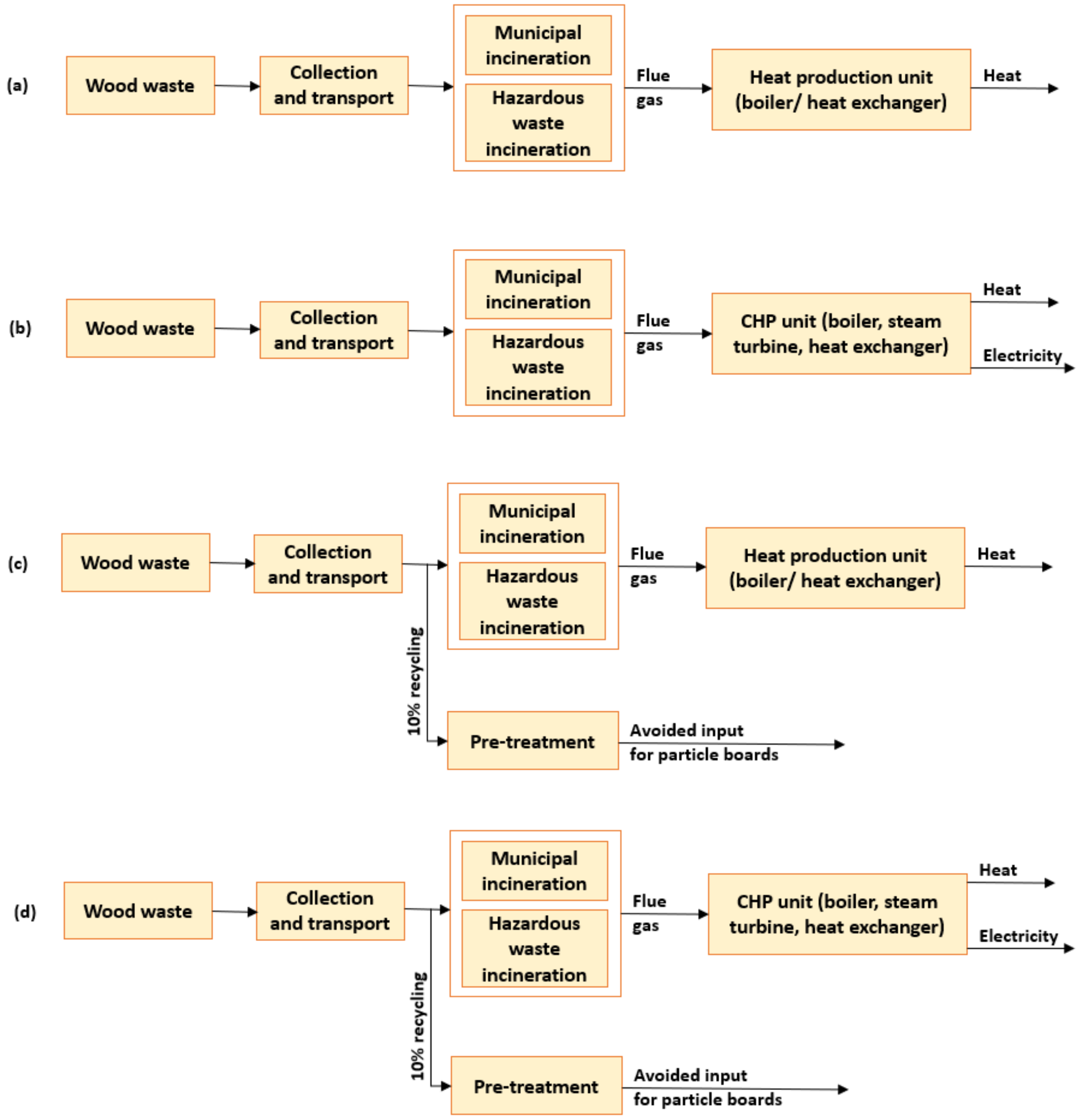


Figure 1. Process map and systems boundaries: (**a**) alternative 1, wood waste to heat; (**b**) alternative 2, wood waste to heat and power; (**c**) alternative 3, wood waste for heat and partly for particleboard production; and (**d**) alternative 4, wood waste for heat, power, and partly for particleboard production.

3.2. Environmental Sustainability Assessment

By utilizing the LCA, it is possible to measure the environmental effects of a product, service, or activity throughout its entire life cycle, including the indirect impacts [37,38]. In this work, the LCA was applied to assess and compare the potential environmental impacts of wood waste conversion to energy and particleboard in Sweden. The LCA in this paper relies on the procedures recommended by ISO 14040 [39] and ISO 14044 [40]. According to these standards, the LCA process involves three main stages: defining the goals and scope, gathering life cycle inventory data, and conducting a life cycle impact assessment to interpret the results. The aim of this part of the study was to investigate and compare the environmental impacts associated with wood waste collection, transportation, and processing to produce energy (heat and electricity) and products (particleboard). To compare various alternatives, a similar wood waste input of 1 ton for all options has been considered as the functional unit of the system. The considered scope in this study was a gate-to-gate method starting from wood waste collection and ending at energy production as well as providing input material for particleboard production instead of virgin wood. In this study, the CML 2001 method was employed to assess the environmental impacts, including climate change, acidification, eutrophication, human toxicity, ozone depletion, and abiotic depletion. Ecoinvent v3.9 was utilized as the background source of the life cycle inventory (LCI) data, and the LCA was conducted by using GaBi 10.7 software, which calculates the environmental indexes and lists the most contribution parts of the systems' life cycle. Other primary assumptions relevant to the systems and efficiencies are also depicted in Table 1.

Table 1. Primary assumptions of the systems.

Parameters	Unit	Value
Input wood waste	kg	1000
Waste collection and transport	tkm	50
Wood waste energy content	MJ/kg	14
Boiler efficiency	%	75
CHP efficiency	%	45
Power-to-heat ratio	-	0.45
Recycling share of wood waste	%	10
Particleboard density	kg/m^3	650

3.3. Economical Sustainability Assessment

In this section, we explain the utilized methods to evaluate the economic impact of the wood waste management methods. To assess the economic sustainability, the LCC method was utilized. In this analysis, various cost elements were considered, such as capital expenditure (CAPEX) and operational expenses (OPEX), such as energy and material consumption, maintenance, revenues, and recycling. Similar to the LCA (Section 3.2), a wood waste input of 1 ton for all options has been considered as the functional unit of the systems. A duration of a 25-year lifespan with no discount rate has been considered. Additionally, revenues generated from recovered by-products were accounted for as negative costs. Since the taxation regulations towards waste management for biomass and the energy price were changed in 2023, the analysis was provided with these regulations and the most recent costs. The text below summarizes the included main components of the wood waste management scenarios and illustrates the existence of each component for each alternative:

a. The first alternative includes boiler costs and the production of heat at the end system.
b. The second alternative includes the CHP unit costs and the heat and power production at the end system.
c. The third alternative includes boiler costs with the heat production at the end system and the recycling cost of the wood in the system.
d. The fourth alternative includes the CHP costs with the heat and power production at the end system and the recycling cost of the wood in the system.

3.4. Social Sustainability Assessment

In this study, the S-LCA method was used to evaluate and compare the social performance of the four alternatives. There are primarily two types of S-LCA methods in use, i.e., a reference scale and impact pathway methods [41]. In this study, a reference scale approach was used to assess the social impacts in relation to wood waste recycling. The social hotspots database and the social hotspot index calculation method correspond to the S-LCA [41]. The social hot spot database (SHDB) 2023 edition was used to calculate the social impacts of the alternatives in medium-risk hour equivalents (mrh-eq). The database provides the potential social impacts of different sectors based on country-specific data. The database is used amongst the LCI and cost for each input covered in wood waste management alternatives. The UNEP-SETAC guidelines for the S-LCA (2020) state that the impact categories used should correspond to the goal and scope of the study and represent social issues that impact stakeholders. In this study, five impact categories integrated into the SHDB were calculated using the social hotspot 2022 category endpoint method as follows: (i) labor rights and decent work; (ii) health and safety; (iii) human rights; (iv) governance; and (v) community.

3.5. Limitations and Delimitations

Recycling wood waste is a complicated process since wood waste covers a wide range of products like medium-density fiberboards, particleboards, and solid wood, and it includes paint, other materials, and chemicals. In this study, the recycling process was estimated to be the same as the manufacturing process of particleboard from primary resources due to the unavailability of wood waste recycling process inventory data. It is expected that board production from recycled wood process is different from board production from primary wood; for example, using more resin in the production.

4. Results

4.1. Environmental Sustainability Assessment

Figure 2 provides a comprehensive comparison of the environmental impacts of four alternatives. These alternatives include (1) wood waste to heat, (2) wood waste to heat and power, (3) wood waste to heat and avoid particleboard, and (4) wood waste to heat, power, and avoid particleboard. The comparison made in the figure is based on the total emissions that result from each system's life cycle from waste collection to heat and electricity generation and particleboard-product manufacturing. Overall, the results indicate that the fourth alternative is relevant to both heat and power generation as well as considering 10% recycling for particleboard production, and has fewer emissions of CO_2, SO_2, and PO_4 (Figure 2a–c) in comparison with the other alternatives, but is comparable to alternatives 1–3 regarding the other emissions (Figure 2d–f).

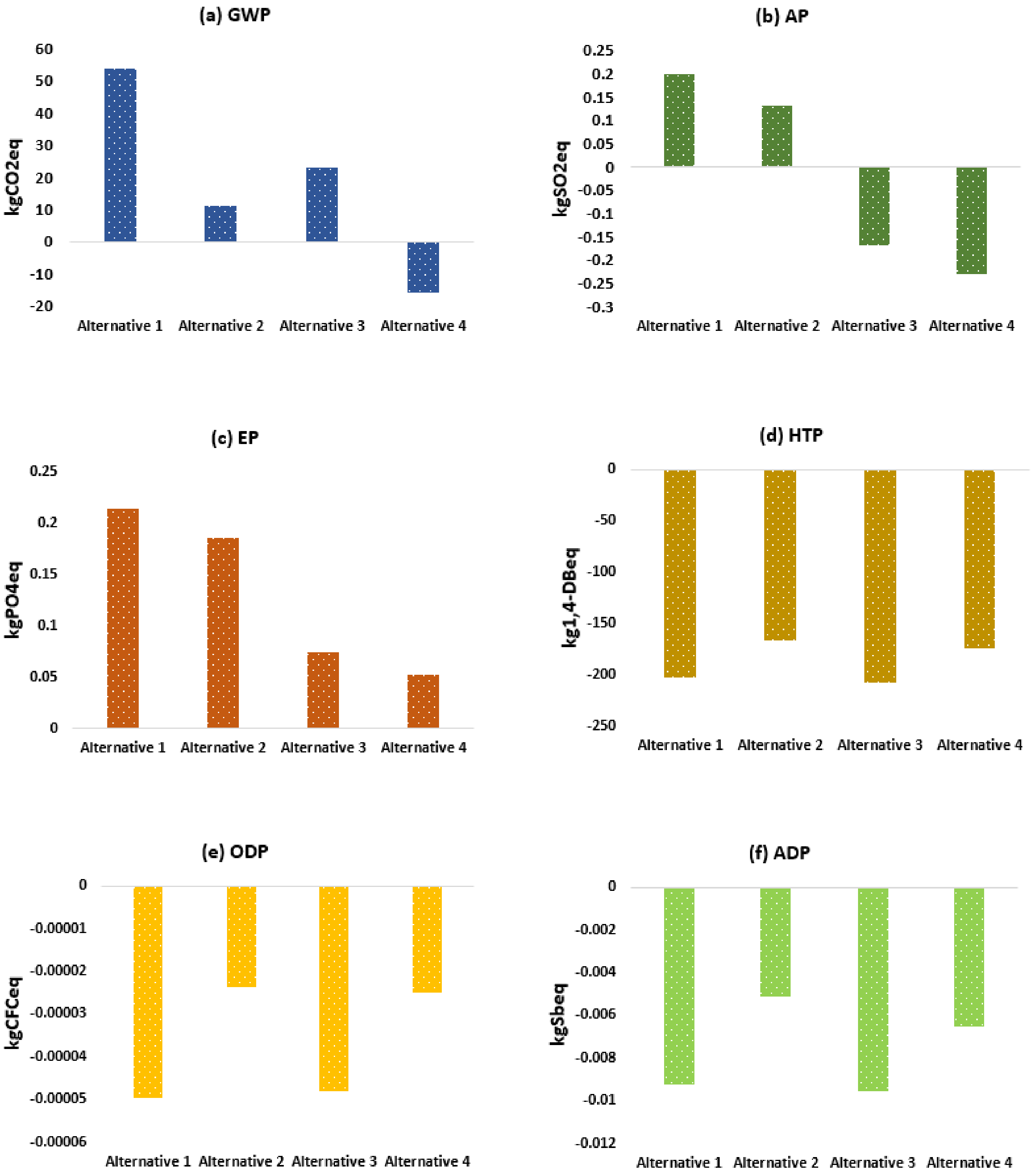


Figure 2. Environmental impacts of the four alternatives per functional unit: (**a**) global warming potential (GWP), (**b**) acidification potential (AP), (**c**) eutrophication potential (EP), (**d**) human toxicity potential (HTP), (**e**) ozone depleting potential (ODP), and (**f**) abiotic depletion potential (ADP).

For clarification, the proportion of the environmental impacts of wood waste-based systems are shown in Figure 3 per category: collection and transport, incineration type (municipal and hazardous), and avoided production (heat, electricity, and virgin wood for particleboard). The negative values represent an environmentally benign unit, whereas the positive values indicate an environmentally harmful unit.

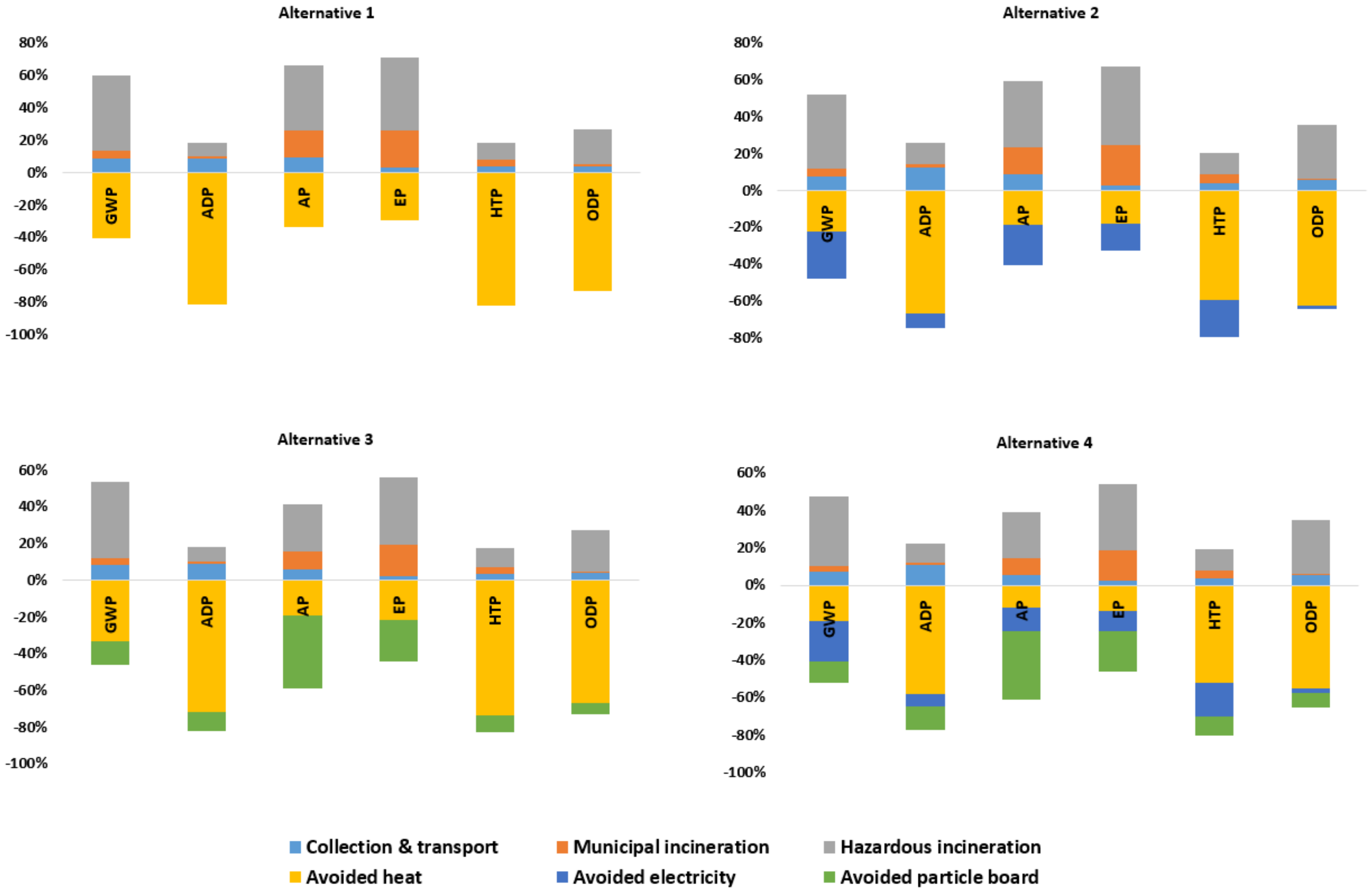


Figure 3. Contribution of the process to the various environmental impacts for different alternatives.

The life cycle CO_2 emissions of alternatives are predicted in Figure 2a. It is conspicuous that the first alternative that produces heat with 53.92 kg CO_2 emissions per 1 ton applied wood waste has by far the largest GWP emissions. This is followed by the third alternative, based on heat production and avoided particleboard production, with a 57% reduction in CO_2 emissions compared to alternative 1. Apparently, recycling some parts of wood waste as avoided particleboard could effectively affect carbon reduction compared to the option based on only heat production. The second alternative, with 79% in carbon reduction compared to alternative 1, shows much more impact in view of the GWP. Electricity generation has a significantly greater impact in reducing carbon dioxide (CO_2) emissions compared to heat production, mostly due to efficiency gains. Electricity generation systems have seen significant improvements in efficiency over the years. Combined-cycle power plants can convert a higher proportion of the fuel's energy content into electricity, resulting in lower fuel consumption and reduced CO_2 emissions per unit of electricity produced. This level of efficiency is difficult to achieve in heat production systems.

A wood waste system that produces heat and power while also recycling some parts of the wood for particleboard production is the most beneficial compared to other systems in view of climate change. Indeed, using wood waste as a fuel source ensures that the maximum energy potential of the wood is harnessed. This not only minimizes waste but also reduces the need for other energy sources that might have higher CO_2 emissions. By reusing and repurposing the wood waste, it reduces the overall demand for virgin wood, thereby lowering the CO_2 emissions associated with logging and transportation.

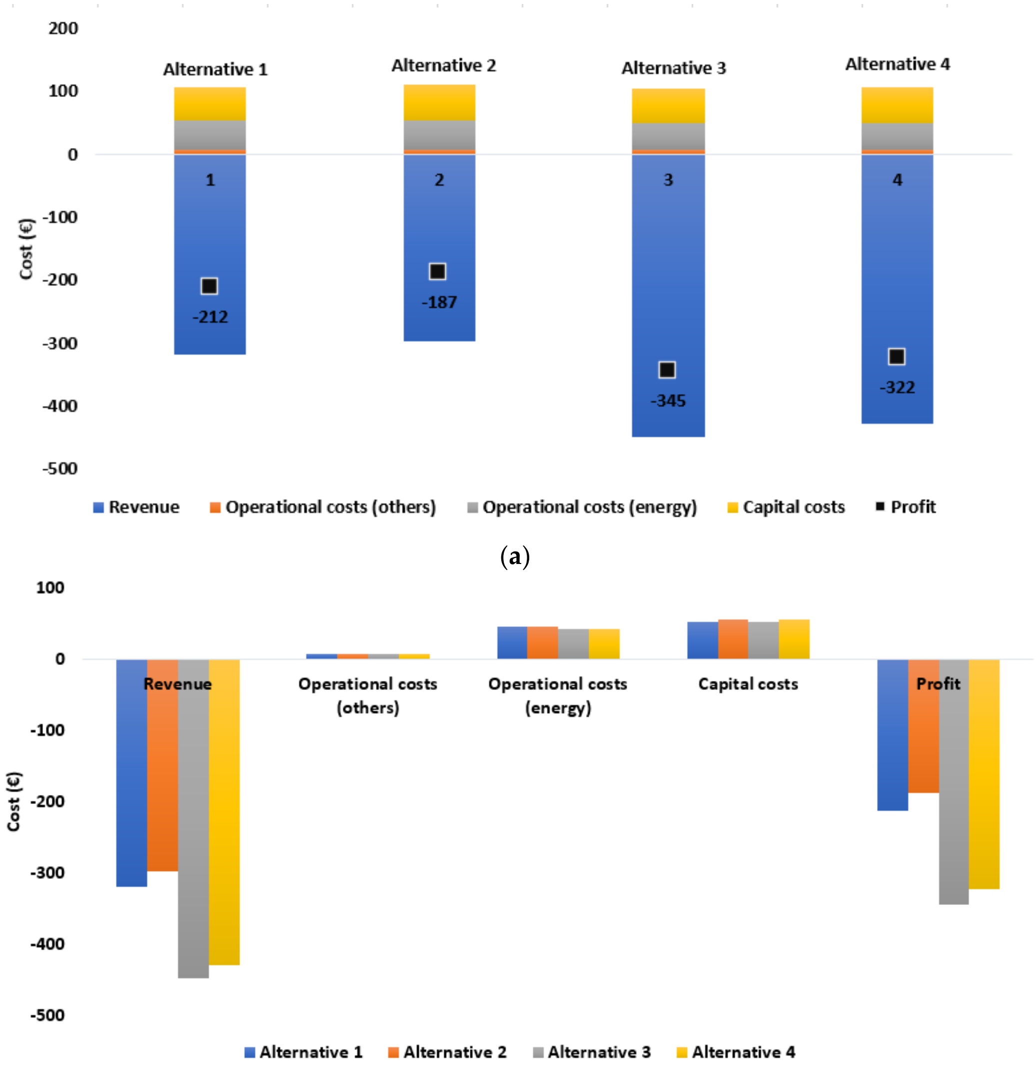
As can be seen in Figure 2b,c, the recycling of wood waste for particleboard production can significantly reduce the acidification potential and eutrophication potential. This is confirmed by the data shown in Figure 3, i.e., alternatives 3 and 4. It could be because of a reduction in logging and deforestation, a decrease in waste disposal, and closed-loop production systems. By recycling wood waste, there is a reduced demand for virgin wood, leading to a reduction in logging activities. This helps to preserve forests, which act as carbon sinks and help regulate nutrient cycles. Reduced deforestation also minimizes soil erosion and the release of organic matter, which can contribute to acidification and eutrophication. Moreover, by recycling wood waste, the need for disposal in landfills or incineration facilities is reduced. Landfills can produce methane—a potent greenhouse gas—and incineration releases pollutants into the atmosphere. By diverting wood wastes from these disposal methods, the release of harmful substances that contribute to acidification and eutrophication is minimized. Most important, in the production of particleboards, wood waste can be reused as raw material, creating a closed-loop system. This reduces the need for extracting and processing new resources, thereby reducing the environmental impact associated with resource extraction, transportation, and manufacturing. Closed-loop systems help conserve energy and resources, thus minimizing the acidification and eutrophication potential associated with traditional production processes.

From Figure 2d–f, it can be found that heat generation running on wood waste could have the highest impact on human toxicity, ozone depletion, and abiotic depletion potentials. This matter can also be observed in Figure 3 for alternatives 1 and 2. Wood waste is considered a carbon-neutral fuel source, and when it is burned for heat generation, it releases the same amount of CO_2 that was absorbed by the tree during its lifetime, making it a closed-loop carbon cycle. Moreover, burning wood waste typically produces lower emissions of other harmful pollutants, such as particulate matter, compared to fossil fuel combustion. These pollutants can have significant negative impacts on air quality and human health.

4.2. Economic Sustainability Assessment

In this section, results of the life cycle costing of wood waste management for alternatives have been given, assuming a plant operational lifespan of 25 years. All computations are ground in the functional unit. The next phase involves comparing the CAPEX, OPEX, revenue, and profit among the alternatives. OPEX encompasses the operational expenses related to materials, personnel, maintenance, and energy. Maintenance costs and personnel expenses (covering wages, taxes, and insurance) are assumed to be 2% and 10% of the CAPEX, respectively. Energy cost calculations for the alternatives are based on the average annual energy and material prices in 2023 [42] and are fixed at 120 EUR/MWh.

The overall breakdown of the cost's components and revenues for the different alternatives is illustrated in Figure 4. Cost components per alternative are depicted in Figure 4a, and the cost breakdown and overall cost/profit for each alternative are depicted in Figure 4b. The positive values on the y-axis show the costs, while the negative values represent the revenues. Overall, energy and material prices are two crucial variables in the economic assessment. However, the former fluctuated dramatically in the last few years while the latter remained constant. The third alternative has the highest revenue, which is comprised of revenue due to electricity and the recycling of wood into particleboards. Alternative 4 has the second highest revenue while it has slightly less recovered energy compared to alternative 3. Interestingly, alternative 1 has the highest energy revenue because all the wood wastes are converted to heat. The revenue is less in alternatives 1 and 2 than in 3 and 4 because recycling wood waste into particleboards has higher revenue margins compared to using wood waste for energy recovery.



(**a**)

(**b**)

Figure 4. Breakdown of distribution costs and revenues for different alternatives.

4.3. Social Sustainability Assessment

The potential social impacts for all four alternatives were calculated using the SHDB, the amount of each input, and their costs. In this assessment, it was assumed that municipal waste incineration and hazardous waste incineration have the same social impacts since there are no specific datasets in the database focusing on different waste disposal options. The comparison of the alternatives for all social impact category results in medium-risk hours are given in Figure 5. In all social impact categories, alternative 3 is the best option, followed by alternative 4, giving 5 to 20% better results. The social gain provided in avoiding energy generation and particleboard production from primary resources in alternatives 3 and 4 is higher than the social impacts caused by incineration in the social impact categories of labor rights and decent work, health and safety, governance, and community, and therefore the bars are on the negative side of the graphs. On the other hand, in alternatives 1 and 2, the social gains due to energy recovery and recycling cannot overcome the social impacts in any of the impact categories, and the bars are on the positive side of the graphs. When looking only at alternatives 1 and 2, alternative 1 has 6% to 22% less social impact compared to alternative 2.

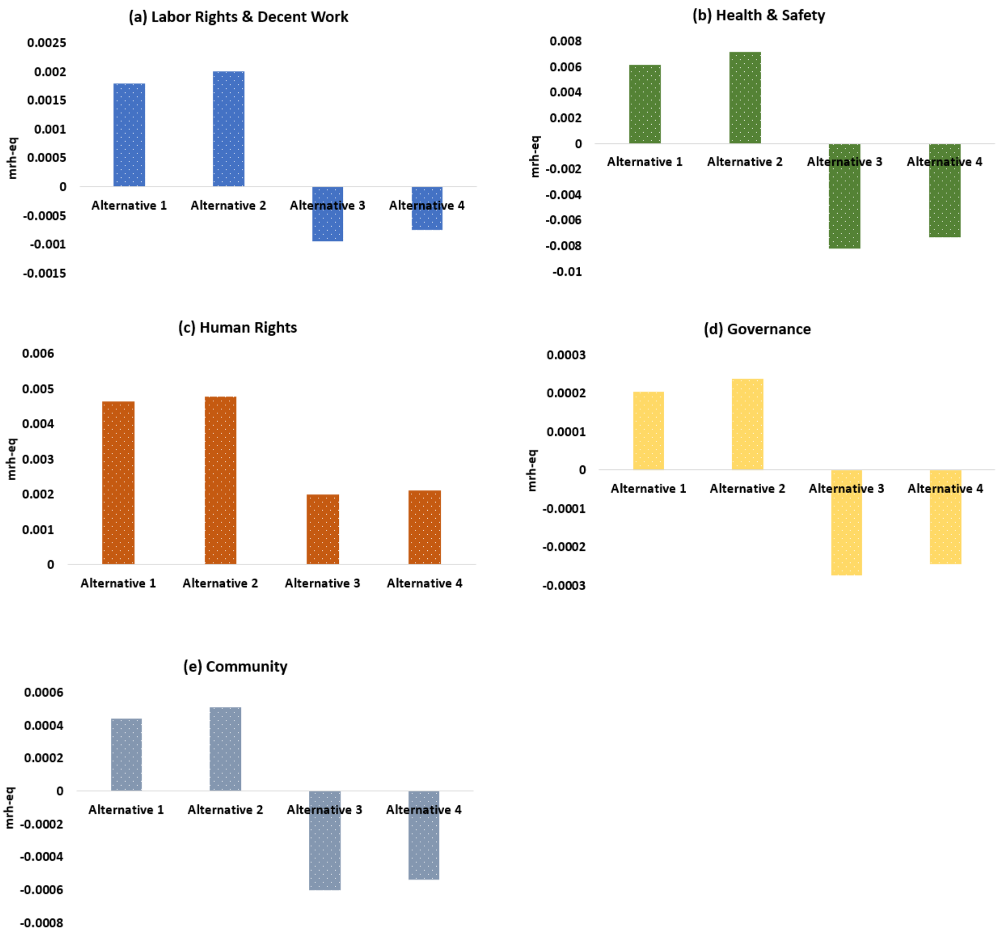


Figure 5. Potential social impacts of the four alternatives: (**a**) labor rights and decent work, (**b**) health and safety, (**c**) human rights, (**d**) governance, and (**e**) community.

To evaluate the contribution of the inputs to the potential social impacts, a contribution analysis has been conducted and the results of the analysis are given in Figure 6. In the figures, the blue color shows the environmental burden caused by the incineration of the wood waste, and the orange, gray, and yellow colors show the environmental gain provided by avoiding heat, electricity, and particleboard from primary resources. Comparing the results of alternatives 1 and 2 shows that, from a social point of view, recovering heat is more beneficial than recovering heat and electricity because heat generation has higher positive social impacts. Therefore, decreasing the gain obtained from heat recovery results in higher impacts. This also explains the superiority of alternative 3 compared to alternative 4. In alternative 3, there is only heat recovery and particleboard production from wood waste, and in alternative 4, this energy recovery part is divided into heat and electricity. An important result is that introducing wood waste recycling brings an important social gain due to avoiding social impacts from particleboard production. Therefore, in alternatives 3 and 4, the social gains overcome the social burdens in four out of five social impact categories.

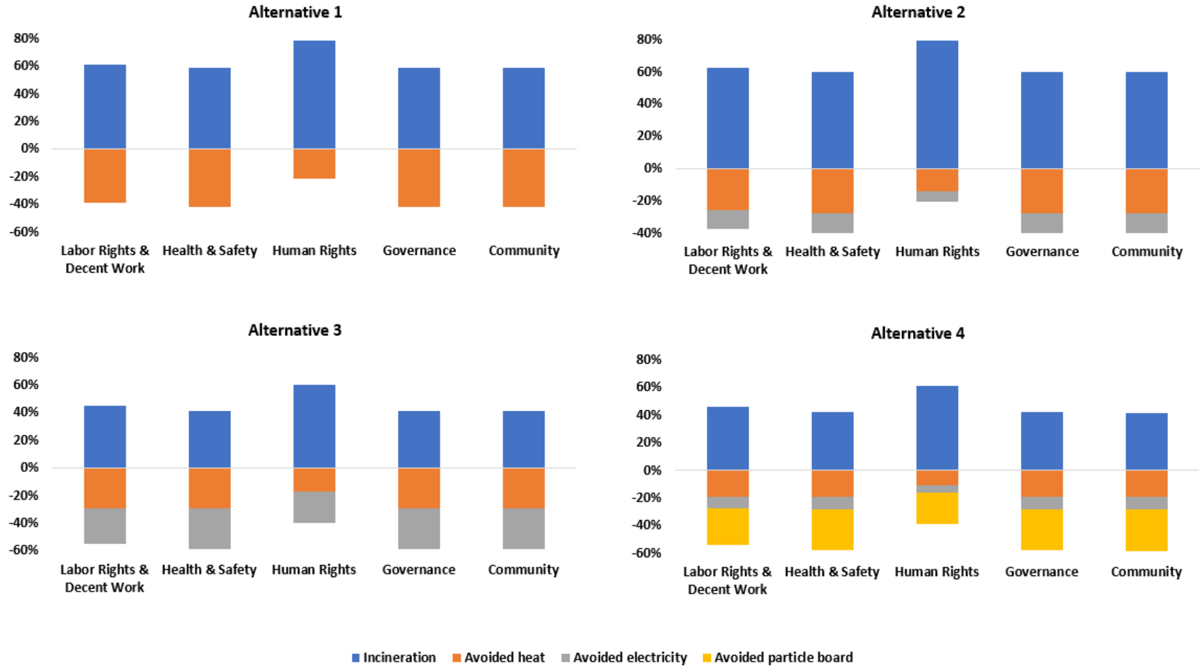


Figure 6. Contribution of the processes to the various social impacts for different alternatives.

5. Discussion

5.1. Environmental Sustainability Assessment

Based on the conducted LCA in this study, alternative 4, which integrates both heat and power generation while incorporating the partial recycling of wood waste into particleboard production, emerges as the most environmentally favorable system, mainly because of the reduced emissions, in particular CO_2. Utilizing wood waste as a fuel source ensures the optimal utilization of the wood's energy potential, resulting in minimal waste generation and a decreased reliance on alternative energy sources with potentially higher CO_2 emissions. Furthermore, recycling wood waste for particleboard production diminishes the demand for virgin wood, and the reutilization and repurposing of wood waste is consequential to the reduction in CO_2 emissions associated with logging and transportation.

Several studies in the literature have explored the environmental analysis of converting wood waste into energy, but there is a scarcity of research specifically addressing wood waste recycling in the context of particleboard production. This is remarkable since, as mentioned earlier, recycling wood waste into new particleboard is the most common recycling route used today in Europe [9]. Importantly, the existing literature lacks comprehensive coverage of both aspects, as accomplished in the present study. Consequently, there is a notable absence of comparable works in the literature that could serve as a basis for result comparisons in this domain. However, it would be possible to assess how much the adaptation of the studied systems from the literature, in lieu of the applied system (alternative 4), could reduce climate change and other environmental impacts. Hossain et al. [14] found that the production of 1 ton of particleboard from virgin wood results in the emission of approximately 890 kg CO_2-eq, with the primary contributor being the glue and curing process (heat)—accounting for about 56% of the total emissions. In the current study, alternative 4 explores using wood waste as a feedstock, aiming to reduce the use of virgin wood. By incorporating this alternative into this work, where 10% of wood waste is recycled into particleboard production, and the remaining wood waste is utilized for heat and electricity generation, the greenhouse gas emissions are reduced to 696 kg CO_2-eq. This integration allows for the substitution of virgin wood with wood waste, enabling the generation of both heat and electricity in a combined heat and power unit. Consequently, the utilization of particleboard based on wood waste can decrease the system's overall CO_2 emissions, offsetting emissions from the production process involved in the particleboard system.

5.2. Economical Sustainability Assessment

The breakdown of costs and revenues across different alternatives, as depicted in Figure 4, underscores the pivotal role of energy and recycled material prices in the economic evaluation. Energy prices have exhibited significant fluctuations in recent years and are strongly dependent on the geographical scope, making it of paramount importance to consider the energy cost in our analysis. In the literature, wood waste is considered an inexpensive, sustainable alternative source of energy. Marchenko et al. [17], compared multiple sources of energy and concluded that it is economically efficient to operate power plants on wood waste. Tschulkow et al. [18], studied the economic feasibility of power plants of different sizes and concluded that using wood waste as a source of energy makes smaller plants more profitable. On the other hand, the principle of the sequence suggests that wood waste, which is a type of biomass, should be reused and recycled before converting to bioenergy or disposal [19]. Despite studies showcasing the potential benefits of utilizing wood waste for electricity generation, the economical assessment of wood waste, considering both biomass and recycling, needs more investigation in the literature.

The recycled material prices have remained relatively stable in the global market. This underscores the sensitivity of cost calculations to market prices of energy and materials. The literature highlighted that the reduction in CO_2 emissions resulted in significant savings in carbon taxes, but these results can vary based on the marketplace since different countries may have various CO_2 taxation policies.

Among the alternatives considered, alternative 3 emerges with the highest revenue, attributed to both heat generation and particleboard recycling. Alternative 4 follows closely, with slightly lower revenue, primarily due to marginally less recovered heat energy. Notably, alternative 1 shows the highest revenue from energy alone; however, its overall revenue falls short of alternatives 3 and 4. This discrepancy can be attributed to the higher revenue margins associated with recycling wood waste wood into particleboard in alternatives 3 and 4, compensating for any shortfall in energy revenue.

In essence, the analysis highlights the intricate interplay between energy and material prices, as well as the revenue streams associated with different alternatives. The analysis illustrates that partial recycling of wood waste is more economically efficient than other alternatives with no recycling. Such insights are vital for making informed decisions regarding sustainable and economically viable waste management practices.

5.3. Social Sustainability Assessment

In the context of Sweden, meeting all EU targets, including a statutory ban on the incineration of recyclable plastic waste, for example, results in the highest generation of net direct jobs (1621 jobs) from increased plastic recycling [43]. In comparison to recycling, which typically comprises more steps in the value chain, the incineration process requires less human power [44]. A study of disposal alternatives for used polyethylene terephthalate (PET) bottles found that 75% flake production (partial recycling) and 25% landfilling have the least social impacts compared to 75% incineration with energy recovery and 25% landfilling and 40% flake production with 60% landfilling [45]. The results of the S-LCA results in this study showed that, when wood waste is used for energy alternatives instead of being recycled into particleboard and heat recovery, the social impacts are adverse. However, recycling into heat and particleboard (alternative 3) has positive effects on health and safety, labor rights, decent employment, governance, and community. The social footprint in mrh-eq for alternative 3 is lower. Alternative 3 reduces the amount of wood waste that goes to incineration and substitutes a fraction of the virgin wood that might be used in the production of particleboard. Thus, from the perspective of social sustainability, integrating the recycling option to heat, alternative 3 is preferred because of its lower social impact assessment results.

5.4. Wood Waste Recycling in Sweden

To have an overview of the sustainability comparison of all four alternatives (Figure 1), the economic, environmental, and social indicators are shown in a radar graph in Figure 7. In this graph, all values were normalized to the results of alternative 1 to avoid the units and, hence, to be able to see all investigated impact categories in one graph. According to the graph, if all three aspects of sustainability are considered, alternative 3 comes forward as the best option in 11 out of 16 impact categories. Alternative 4 follows alternative 3 as being the best option in five impact categories, while alternative 1 is the best option in only two categories (ODP and capital costs). The economic indicator (OPEX-energy) results were identical for alternatives 3 and 4 and are therefore counted as the best option, both for alternative 3 and alternative 4. The results also show that alternative 2 provides no best option considering all categories. Alternative 1 has very close results to the best option for abiotic depletion potential and human toxicity potential (alternative 3). If only the social impacts are considered, a system with only energy recovery producing only heat (alternative 1) is the preferable option.

These results are reached when all impact categories are considered to have the same weight in the assessment. If different weights are considered for different impact categories, it would be possible to reach a different result, or if the global warming category is considered with extra importance for choosing the best option, then alternative 4 can come forward. In this study, weighting amongst impact categories was applied since weighting brings additional uncertainty to the results. Weighting can be applied in future studies.

In Sweden, management systems to support wood waste recycling are not in place. At the same time, good practices in Europe and emerging efficient wood waste sorting technologies show potential [9,46,47]. Yet, the wood waste management conflict in Sweden is obvious: a well-established waste management system through energy recovery is being challenged by public opinion and European policies striving towards material recycling. This study shows (Figure 7) that it is favorable when considering all environmental, economic, and social impact categories to recycle a part of wood waste into particleboard production (alternatives 3 and 4) instead of only using wood waste for energy recovery (alternatives 1 and 2). Even though recycling a part of wood waste decreases the amount of recovered energy, the gain provided by avoiding primary resource usage for particleboard production compensates for this decrease. This information may be of particular interest to waste wood managers and recycling companies interested in new revenue waste streams that, at the same time, provide benefits to the planet and people.

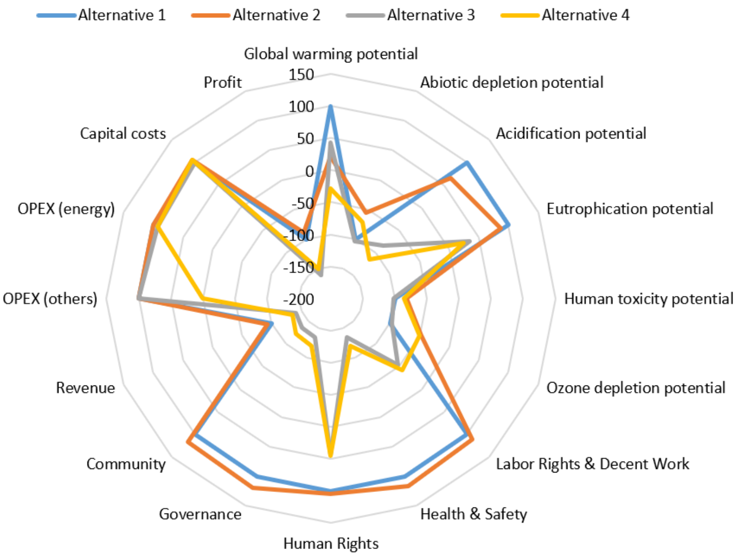


Figure 7. Radar graph showing all impact categories considered in the study normalized to the alternative 1 results.

6. Conclusions

In this study, the environmental, economic, and social impacts of wood waste management in Sweden were investigated. Four different scenarios were compared as follows: the current situation, i.e., 100% wood waste for energy recovery in only heat or heat and power, versus possible future scenarios, i.e., 90% wood waste for energy recovery in heat or heat and power plus 10% wood waste for material recovery. In this section, the main conclusions of the study are listed in bullet points as follows:

- The addition of recycling schemes strengthens the sustainability of wood waste management for all three pillars of sustainability.
- The sustainability performance of wood waste management varies depending on power production amongst heat production.
- A system with the best environmental performance is not necessarily the best option when the economic and social performances of the system are considered.
- Energy recovery and recycling can be considered as competing methods; however, the results of this study showed that they can be used as complementary methods, especially in countries with advanced incineration facilities like Sweden.

Future studies may include the consideration of recycling processes for different types of wood waste and production processes (including raw material streams and adjustments of the manufacturing process). The detailed inputs and outputs of recycling processes can be added to the assessment for more accurate results on the sustainability performance of wood waste management.

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