energies

Article

Environmental Impact Assessment of Waste Wood-to-Energy Recovery in Australia

Shahjadi Hisan Farjana [1,*], Olubukola Tokede [2] and Mahmud Ashraf [1]

[1] School of Engineering, Deakin University, Geelong 3216, Australia; mahmud.ashraf@deakin.edu.au
[2] School of Architecture and Built Environment, Deakin University, Geelong 3216, Australia; olubukola.tokede@deakin.edu.au
* Correspondence: shahjadi.farjana@deakin.edu.au

Abstract: Wood is a renewable material that can store biogenic carbon, and waste wood can be recycled to recover bioenergy. The amount of energy recovery from the waste wood can vary depending on the type of wood and its chemical and structural properties. This paper will analyse the life cycle environmental impact of energy recovery from waste wood, starting from the wood production stage. These are cradle-to-cradle systems, excluding the use phase and the waste collection phase. The types of waste wood considered in the current study are softwood, hardwood, medium-density fibreboard (MDF), plywood, and particleboard. The results showed that all waste wood has great potential to produce energy while reducing climate change impact. Hardwood and softwood products showed the most beneficial aspects in terms of energy recovery from waste wood and thus could help to reduce harmful environmental emissions. However, MDF and particleboard show the least potential for energy recovery as they contribute to the greatest emissions among all types of wood products. The outcomes of this study could be used as guiding principles for Australia to consider waste-to-energy recovery facility establishment to generate additional energy while reducing waste wood.

Keywords: life cycle assessment; wood-based composites/panels; waste-to-energy recovery; construction industry waste; waste management

Citation: Farjana, S.H.; Tokede, O.; Ashraf, M. Environmental Impact Assessment of Waste Wood-to-Energy Recovery in Australia. *Energies* **2023**, *16*, 4182. https://doi.org/10.3390/en16104182

Academic Editor: Pavel A. Strizhak

Received: 27 April 2023
Revised: 10 May 2023
Accepted: 17 May 2023
Published: 18 May 2023

1. Introduction

Bioenergy is the energy derived from organic resources such as waste wood that can be used as heat or electricity [1]. Waste wood includes unwanted wood chips, forest residues, sawmill residues/off-cuts, pulp mill residues, and waste wood after their first life of use [2]. Waste wood, after its first life of use, includes a large proportion of processed wood that cannot be recycled due to the presence of chemical components that are hard to separate [3]. Bioenergy recovered from waste wood has a great potential to meet huge energy demand due to its 50 times lower environmental burden in comparison with coal-based energy, as reported by National Timber Stewardship Council Australia [4]. According to the National Greenhouse Gas Accounts (2021), wood waste has the potential to generate 2.9 tons of energy and has minimal environmental impact compared to other conventional construction materials such as concrete and steel. It is therefore understood that the bioenergy market also has excellent opportunities in terms of ecological and economic points of view [5].

Waste-to-energy (WTE) facilities are promising initiatives to mitigate environmental emissions as well as support the achievement of a circular economy [6]. WTE projects provide a sustainable alternative to landfill solid waste management. Wastes suitable for WTE plants are residual wastes that cannot be recycled, and hence, the emission savings, social license, and improved energy security are attractive features for many nations. Waste-to-energy (WTE) facilities use thermal technology to convert residual waste that would otherwise go to landfill into steam generation, which drives a turbine to generate electricity [7,8]. Additionally, at present, most WTE facilities consider municipal solid waste to generate energy, where the amount of wood waste is minimal or negligible compared to solid waste/municipal waste [9–11]. In particular, the waste wood from the construction and demolition industries is out of consideration for municipal solid waste [12–14]. Residual waste is typically sent to a landfill, is considered for energy recovery from waste. These are the leftover waste materials after all the recyclable or reusable materials have already been recovered from the waste [15,16]. Although all types of waste wood are sent for energy recovery, irrespective of the type of their properties, it is essential to understand what type of wood has higher energy [17]. The residual waste wood from structural applications differs in their manufacturing properties and specifications, and even in their volume, while the mass can be the same. These can vary in terms of the language of sustainability based on their impact on human health, ecosystems, and resources. There is little or no evidence of reported comparative analysis on the energy recovery potential from different types of wood waste in the literature. Research gaps also exist about the best circular economy option for waste wood.

The United States Department of Agriculture published a cradle-to-grave attributional LCA-based study on the wood energy for residential heating applications generated from wood pellets. This study also identified the opportunities for wood pellet production in southeast Alaska [18]. Andrea et al., (2020) analysed and compared the bioenergy produced from the wood pellet supply chain in the U.S. based on a cradle-to-grave study using the attributional approach. This paper considered sawmill residues, roundwood logs, whole trees, and logging residues [1]. Blanca et al., (2020) conducted a consequential LCA study for the assessment of energy generation of waste and forest residues, analysing the effects of resource-efficient additives [19]. Esmeralda et al., (2016) analysed the life cycle impact assessment of biomass residues while converting to renewable energy considering the European geographic coverage [20]. Jeffrey (2017) discussed the alternative options for wood waste, such as recycling, energy recovery, or landfills [21]. Joo et al., (2019) conducted an LCA study for energy recovery (electricity) from wood waste in Malaysia [8]. Manyele (2007) conducted an LCA study of biofuel production from wood pyrolysis technologies based on feedstock obtained from different geographic locations and timeframes [22]. Maureen et al., (2013) analysed the LCA to demonstrate and identify the impact of utilising wood waste for heat generation (district heating) in urban environments where waste woods are obtained from forest residues [23]. Milica et al., (2016) conducted an LCA-based study focused on the wood residues from the Servian forest [24]. Uzzal et al., (2018) conducted a comparative LCA of wood waste management pathways while they considered the scenario of energy produced from biofuel, which is produced with recycled waste wood instead of coal [25]. Mirjam et al., (2018) analysed the climate change and relevant environmental uncertainties from energy generation systems from wood waste in the United Kingdom (UK) [26]. Tabata et al., (2012) conducted the life cycle assessment of the woody biomass energy utilisation based on a case study of Japan. They showed that burning of wood pallets causes a significant amount of greenhouse gas emissions; however, in comparison with the petroleum-based energy resources, woody biomass is definitely environmentally friendly [27]. Heller et al., (2012) conducted the life cycle energy and environmental benefit analysis of generating electricity from willow biomass. They identified that, at a cofiring rate of 10% biomass, the system net-zero ration (electricity delivered divided by total fossil fuel consumed) increases by 8.9% and the net global warming potential decreases by 7–10% [28]. Astrup et al., (2015) evaluated the life cycle environmental impact of the waste-to-energy technologies based on a detailed review where they showed that LCA-based waste-to-energy studies vary significantly between their system boundaries, functional unit, temporal and geographic conditions, technological parameters (waste composition, technology, gas cleaning, energy recovery, residue management, and inventory data), and modelling principles (energy/mass calculations, energy substitutions, inclusion of capital goods, and uncertainty evaluation) [29]. Weihs et al., (2022) analysed the life cycle environmental impact of co-firing coal and wood waste for bioenergy. Their results showed that, with 10% co-firing, emission intensity reduces from 938 to 181 $kgCO_2/MWh$. Policy makers should consider incentivising waste co-firing as part of future energy policies towards achieving net-zero targets [30]. Australia produced 84,056 gigawatt hours of renewable energy in 2022, representing 35.9% of electricity generation [31].

Based on the discussion, it is evident that wood waste generated from structural, residential, and industrial applications has not yet been analysed based on its potential for energy recovery as one of the critical circular economy pathways. This paper presents a step-by-step analysis to fill this gap, starting by discussing the manufacturing and waste management steps involved in their life cycle. This study aims to analyse and identify the most sustainable types of wood for energy recovery from an environmental perspective. This paper conducted an environmental sustainability assessment based on the life cycle assessment methodologies considering softwood, hardwood, plywood, MDF, and particleboard. The life cycle assessment is a powerful environmental impact assessment methodology based on ISO standards 14040-14044 [32,33], which involves the standardised procedures to identify the sustainability pathways and communicate impact hotspots in the supply chain. This study could be utilised for the identification of sustainable waste wood types for energy recovery. However, it does not aim to produce comparative assertions among the type of waste wood or circular economy pathways. Only a few studies have considered analysing the environmental emissions generated from energy recovery from wood waste, highlighting a clear gap in the literature for this type of study, especially for waste wood.

2. Wood Production and Waste Management Supply Chain

The type of wood used for structural and other different types of applications is discussed herein alongside the plausible energy recovery process. Softwood and hardwood are used for structural applications, with softwood predominantly used for framing, and hardwood for flooring, decking, etc. [17]. Plywood is used for bracing, joinery, and flooring, whilst MDF and particleboard are used for joinery and flooring. The wood production and manufacturing processes differ from each other, but the energy recovery process is similar for all, irrespective of the type of waste wood. In the energy recovery process, once the wood product finishes its first life of use, instead of wasting it by sending this to landfill, waste wood can be reused, recycled, or burned for energy recovery in terms of bioenergy. To prepare the wood for energy recovery, the waste woods are chipped and dried to reduce the moisture content, which is then sent to the boiler for energy recovery (GBCA Life Cycle Assessment in Green Star Discussion Paper Feedback-FWPA). Figure 1 describes the energy recovery process from the waste wood under consideration for this paper. Once the waste wood is collected, it is then dried to produce thermal energy. During the energy conversion process, renewable secondary fuels are used in conjunction with thermal energy generated using natural gas.

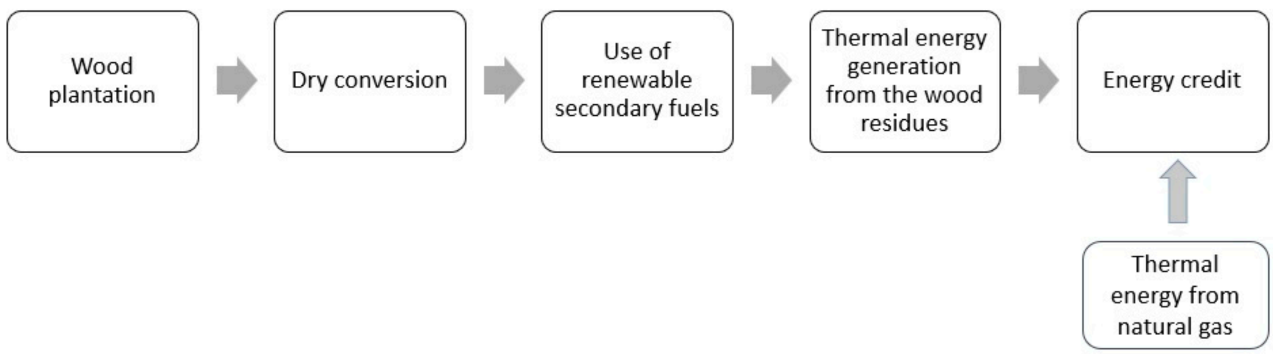

Figure 1. Energy recovery process from the wood waste.

For plywood and MDF, the production phase starts with planting, harvesting the logs, and debarking. The plantation phases are not required for particleboard production as they are made from wood residues. Plywoods are then softened to produce billets, followed by grading and drying. MDFs are chipped, screened, and washed; formed by the MAT; and then dried. Particleboards are chipped and dried, which does not require screening and washing. After drying, plywoods go through clipping and rotary peeling to produce veneer, which is then processed with resins. In the case of MDF, after the drying operation, the blending and refining are conducted, followed by prepressing and hot pressing. Particleboards undergo pre-pressing and hot pressing, mat forming, and coating immediately after the drying operation. The last stages of plywood production are cutting the boards, sanding, and coating/laminating. Similarly, for MDFs and particleboards, the boards are cut/trimmed, sanded, laminated/coated, and packaged into products.

2.1. Softwood

This section details the process description of softwood production considering cradle-to-gate operations. Softwood production includes wood production from forests, sawmilling (log storing, debarking, milling), kiln drying, and product manufacturing. However, preservative treatment is excluded from the softwood production process. The datasets originated from Australian contexts, originally developed by Forest and Wood Products in Australia (FWPA) (GBCA Life Cycle Assessment in Green Star Discussion Paper Feedback-FWPA). The plantation steps include seedlings and cuttings, followed by chemical treatment and fertilisation once the plants are irrigated. The transportation medium can be different types of trucks, graders, rollers, bulldozers, etc. During harvesting, trees are processed by a mechanical harvester. Then extraction is carried out by the forwarders to collect and dump the tree log. The transportation distance varies depending on the location of the wood being harvested and the location of the wood processing facilities, which are typically within 50 km [34]. The wood manufacturing operations produce wood residues, including chips, sawdust, shavings, and bark, which are sold or used as fuel for the drying process. Logs are transported from the forest to the mills, where they are stored and transported to the next facility. The bark is usually left on the log to protect it during handling. Debarkers and sawmills are powered by electricity [35]. Then drying produces dry-sawn wood products, which use green-sawn timber and wood residues. Other than the rough-sawn softwood, other softwoods produce planed dry-sawn timber products from a drying kiln, which also produces wood residues, including sawdust and shavings to be used as fuel for the drying process [36].

2.2. Hardwood

The sawmilling processes include log storing, debarking, and milling (Figure 2). After these processes, green-sawn hardwood is produced, which can be sold as it is. Additionally, it can be dried to produce different types of hardwood. These also produce wood residues in the form of wood chips, sawdust, shavings, and bark, which can be sold or used as fuel for the drying process directly. So, the processes cover log storing, debarking, milling, and transportation to the plant. The bark is usually removed before delivery to the sawmill, but debarking is sometimes done at the sawmill. Like softwood plants, debarkers and sawmills are run by electricity and produce off-site emissions. The green-sawn hardwood can further be dried to produce dry-sawn timber, which uses green-sawn wood from the mill and wood residues to produce the fuel for the boiler. The planing process produces planed dry-sawn timber product, which uses dry-sawn timber from a drying kiln. This planing process also produces sawdust and shavings, which might be used or sold separately. Forest management includes fire protection and control, road construction and maintenance, and forest assessment and supervision. However, forest management activities are hard to quantify in terms of life cycle inventory. Chemical and fertilizer applications are rarely carried out; however, they impact biodiversity and water quality. So, the wood production inventory starts with logging, which can be done by machine or by hand. Depending on the location of the tree, cable logging can be used. After that, the logs are sorted based on the product classes, which would be ready for loading. The loading and haulage would be carried out by the harvesting contractor or a separate subcontractor. The type of transportation depends on the amount of load/haulage. The transportation distance depends on the location of the forest and the processing facility [36,37].

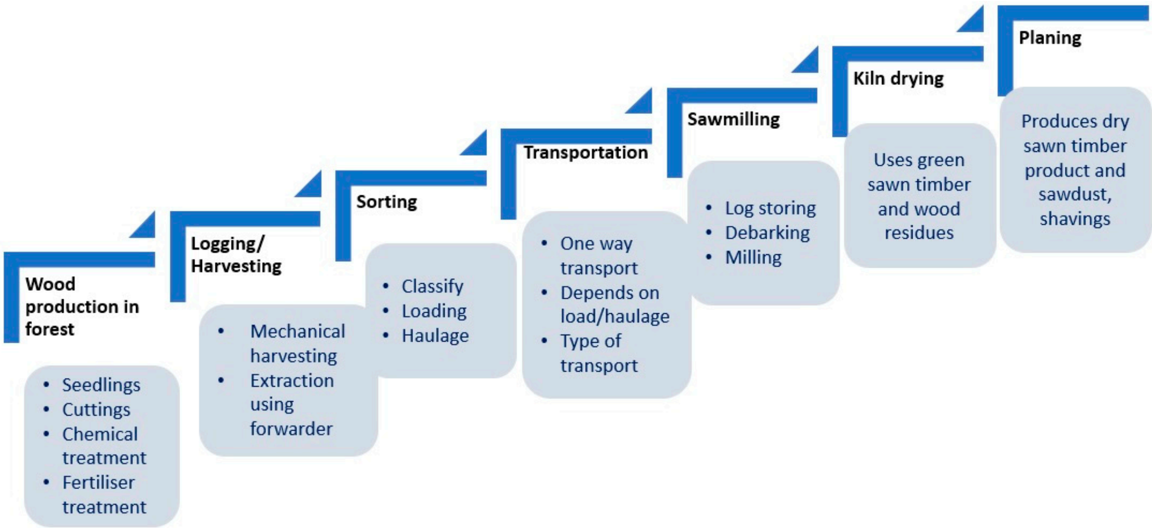

Figure 2. Softwood and hardwood production process.

2.3. *Plywood*

The plywood production process starts with growing the plants and harvesting the plywood logs (Figure 3). The logs are then debarked and softened, which are further processed into billets. Those are then processed to veneer by rotary peeling. The veneers are then clipped, dried, and graded based on their properties and appearance. The veneers are then processed with resins. In this paper, the A-bond resins are only considered, which are phenol formaldehyde and used for exterior applications. Then, it is cut into the size to meet the specifications, sanded, finished, and then coated or labelled with ink/paint. The stacks of plywood might be left loose or held by plastic films or steel straps. However, all of these options are considered and made into a weighted average in the corresponding dataset, excluding the preservative treatment. *Pinus radiata* (Radiata Pine) is the most common type of softwood in Australia that is used for plywood production [36].

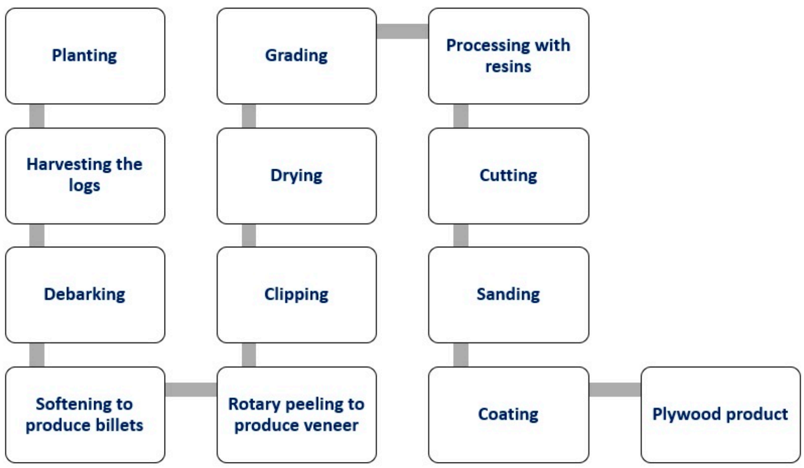

Figure 3. Plywood production process.

2.4. MDF

At first, the wood logs are debarked and chipped from the plantation. Woodchips are also produced as a by-product of the sawmill (Figure 4). Then, the wood logs are screened and washed. The wood chips are then refined, blended, and dried. The blending is done for the fibres and resin/wax. The prepressing and hot pressing take place. After, the edges are cut via trimming. Sanding is done on the surfaces. The MDFs are then laminated and packaged. The packaging plant of MDFs also consists of an energy plant that produces process heat in the form of hot gases, hot oil, and steam [36].

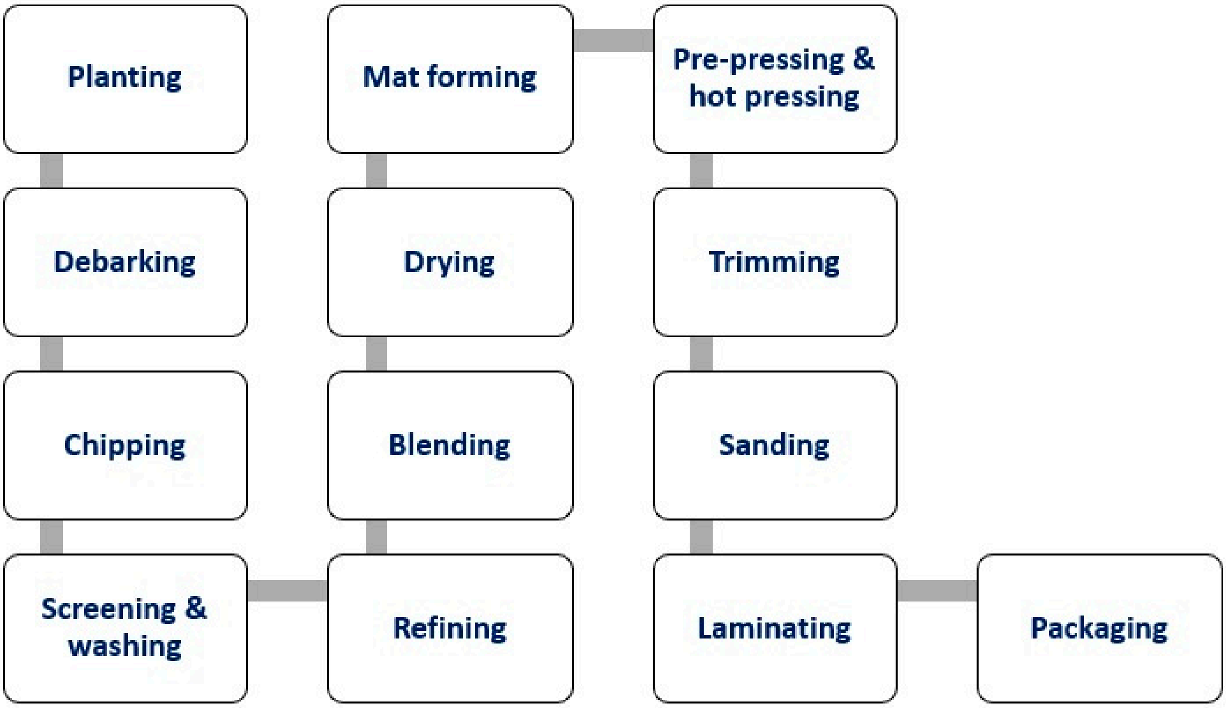

Figure 4. MDF production process.

2.5. Particleboard

Particleboard is mainly produced using wood residues, which include forest thinning, wastes from log harvesting, sawmill residues, and it co-produces post-consumer wood for recycling. The key steps included in particleboard production start with the production of the particles and fibres and chip preparation (Figure 5). The particles, fibres, and chips are then dried to reduce the moisture content to 3–5%. Those are then classified based on their type. The fibres are then blended and coated with wax/resin, similar to MDF. Mat forming and prepressing are conducted, which are then followed by pressing into boards. Wood chip trimming and sanding on both surfaces then take place. Then, the particleboards are laminated and packaged. The energy plant produces heat in the form of process heat for running the manufacturing process operations. In some plants, this energy generation is run through wood wastes from the production processes [36].

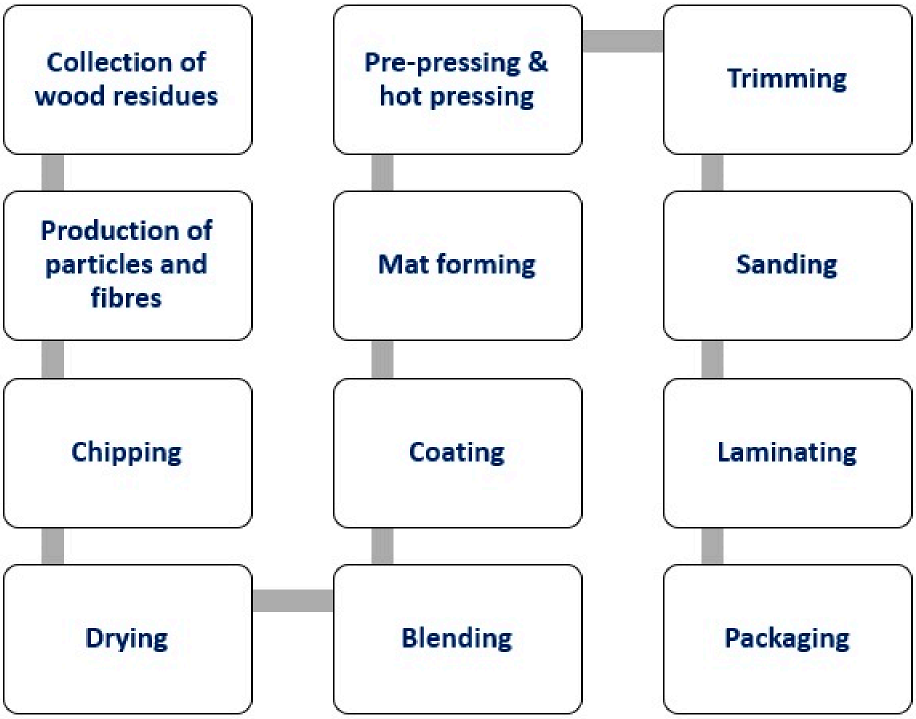

Figure 5. Particleboard production process.

3. Methodology

In this paper, the life cycle assessment will be conducted to analyse sustainability from the environmental perspective. Life cycle assessment is a powerful environmental impact assessment methodology that can analyse the input materials and resources along with the output products, wastes, and emissions to quantify the environmental burdens associated with those sets or subsets of production activities. Life cycle assessment or LCA contributes to sustainability assessment via quantified impacts of several impact categories of human health, ecosystem, and resources. The outcome of the LCA study can be interpreted as the environmental impact hotspot identification, potentiality implications, and policy recommendations. The customisation of the analysis methodology, results, and consequences of the results are solely dependent on the intended applicability of the study conducted, the intended audience, and the manufacturing processes under consideration. LCA is an ISO-standardised methodology that follows four key stages for conducting an LCA-based study: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and results interpretation [38–40].

3.1. Goal and Scope Definition

The goal of this study is to analyse the life cycle environmental impact of wood production and energy recovery from waste wood to assess the future potential for energy recovery from wood waste. Evaluating the end-of-life scenario is the focal point of the study, which will be conducted only for the energy recovery scenario. The key assumption is that all wood products will be completely utilised for energy recovery; other end-of-life alternatives, such as reuse, recycling, or landfills, will not be considered in the current study. The LCA results could be further analysed to complement future policy recommendations toward energy and resources management. It is envisaged that the current study will pave the way for unlocking the potential of bioenergy recovery from wood waste in Australia.

As documented by Forest and Wood Products Association (FWPA), the scope of this study is focused on the Australian geographic context, where all the wood production and energy production datasets originated from Australian wood producers. The technological average of the Australian production datasets, which were originally collected in 2015–2016, was used in the current study. Considering that the datasets are less than six years old, the quality of life cycle inventory data can be considered appropriate/accurate in terms of data quality assessment. The functional unit would be 1 m^3 of wood produced from the forest resources, and we also will consider this functional unit for calculating the energy recovery to analyse and compare the impacts generated from the energy recovery of 1 m^3 of wood waste. This is an LCA study based on the attributional LCA approach, so the study method would not change the currently available system for energy generation from waste or wood production from forestry. The system boundary includes the wood chip and log generation from the forests, wood processing to produce the wooden product ready to sell in the market, and energy recovery from the waste. The transportation phase from wooden products to the end-user to utilise those in structural or other applications is excluded in this study. Similarly, the transportation required to return end-of-life products back to the energy recovery plant was also excluded considering all types of wood wastes shall be transported using the same type of transport vehicle and will travel the same travel distance in one-way transportation irrespective of the product type. The use phase was also excluded since wood products are reported to store biogenic carbons rather than creating harmful emissions for the environment during their use phase. Types of wood and wood products considered in this study are Australian softwood, hardwood, MDF, particleboard, and plywood. For all categories, the functional unit is 1 m^3 of wood, which would be produced and then wasted to generate energy in the form of process heat. The system expansion-based approach was adopted to avoid allocation.

The system boundary will marginally differ between considered products considering their production phase, but the waste-to-energy phase will be the same for all types. The system boundary encompasses all the input process components among these processes involved in system 1 (S1) and system 2 (S2) from Figure 6. These include input materials, resources in the form of water and energy, organic and inorganic chemicals, and one-way transportation from the forest to the sawmill. These also include similar input components for the energy recovery process, where the key input is the waste wood recovered from the users and the process components to convert the waste to energy. The outputs are generally the output product, wastes, and emissions to air, water, and soil. It can also include any co-products or by-products, which is not the case in this analysis due to the system expansion approach. For each type of wood, multiple types of structural products are used for the analysis. The dimension varies even within the same type of wood, which is detailed in Table 1. The key focus of this paper is to identify the potentiality of wood products for energy recovery from waste. The wood production processes are also analysed to correlate the environmental impacts and benefits due to their specifications, production, and applications. The waste collection phases are excluded from this paper, assuming that all five types of wooden product wastes travel through the same vehicles and distances, which can be omitted from the consideration.

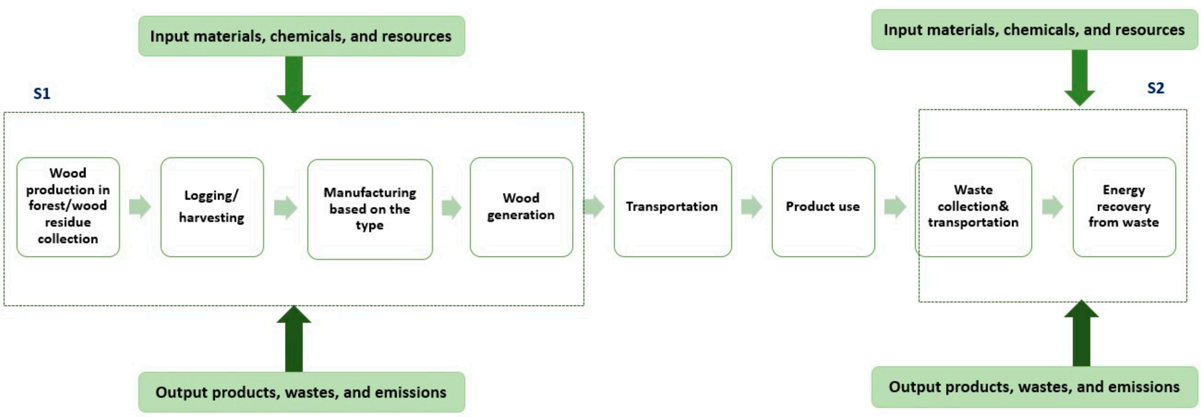

Figure 6. System boundary for this study.

Table 1. Description of the type of wood considered in this paper for LCA analysis.

Type of Wood Product	Variants of the Wood Product	Description of Process/Applications	Density at the Preferred Moisture Content
Softwood (Australian native grown)	Kiln-dried, dressed (machine finished)	Planing process is included	551 kg/m^3 at 12% moisture content
	Rough-sawn	Planing process is excluded	551 kg/m^3 at 12% moisture content
Hardwood (Australian native grown)	Kiln-dried, dressed (machine finished)	Planing process is included	735 kg/m^3 at 10% moisture content
	Kiln-dried, rough-sawn	Planing process is excluded	735 kg/m^3 at 10% moisture content
	Green, rough-sawn	Drying and planing process is excluded	768 kg/m^3 at 26% moisture content
Plywood	Exterior, A-bond, 7 mm	Structural applications	3.45 kg/m^2 at 8% moisture content
	Exterior, A-bond, 9 mm	Structural applications	4.44 kg/m^2 at 8% moisture content
	Flooring, A-bond, 15 mm	Flooring applications	8.75 kg/m^2 at 8% moisture content
	Flooring, A-bond, 25 mm	Flooring applications	12.3 kg/m^2 at 8% moisture content
MDF	Moisture-resistant, 16 mm	Moisture resistant	11.7 kg/m^2 at 7% moisture content
	Moisture-resistant, 18 mm	Moisture resistant	13 kg/m^2 at 7% moisture content
	Moisture-resistant, 25 mm	Moisture resistant	17.6 kg/m^2 at 7% moisture content
Particleboard	Standard, melamine-coated 16 mm	Standard product	10.6 kg/m^2 at 8% moisture content
	Standard, melamine-coated 18 mm	Standard product	11.8 kg/m^2 at 7% moisture content
	Moisture-resistant, melamine-coated 16 mm	Dried to reduce the moisture content	10.6 kg/m^2 at 8% moisture content
	Moisture-resistant, melamine-coated 18 mm	Dried to reduce the moisture content	11.8 kg/m^2 at 7% moisture content
	Flooring, 19 mm	Flooring applications	13.6 kg/m^2 at 10% moisture content
	Flooring, 22 mm	Flooring applications	15.9 kg/m^2 at 9% moisture content
	Flooring, 25 mm	Flooring applications	18.3 kg/m^2 at 9% moisture content

3.2. Life Cycle Inventory Analysis

In the life cycle inventory analysis, the subprocesses involved in each system are described, and the relevant data were collected, documented, and analysed as part of the current study. Five types of wood and a total of 19 types of wood and wooden products are analysed in this paper. Softwood has two types: kiln-dried and dressed-type softwood and rough-sawn softwood. The general production processes are the same for both except for the planing process. Planing is not done in rough-sawn softwood. Similar approaches are adopted for hardwood. Three types of hardwood are analysed in this paper: kiln-dried and dressed, kiln-dried and rough-sawn, and green and rough-sawn hardwood. The first two types are similar to softwood, which only differs in the planing process. However, the green, rough-sawn softwood excludes the planing process and the drying process as well. Hence, the moisture content is higher in the green rough-sawn hardwood. Softwood and hardwood have similar production processes starting from wood production in the forest, involving seedlings, cuttings, chemical treatment, and fertilizer treatment. Then logging covers the mechanical harvesting and extraction using forwarders. Sorting is carried out following the logging through classification, loading, and haulage. Then the logs are transported to the sawmill for milling, and they are kiln-dried. The last step is the planing process, if required. Four types of plywood are analysed in this paper, which vary in their structural applications and properties. Plywood utilised for exterior applications has a lower moisture content, while plywood for flooring applications contain a higher amount of moisture. Additionally, the thickness of the wooden product is proportional to the moisture content, as it can contain a higher amount of moisture per unit volume. Like plywood, medium-density fibreboards also vary based on the thickness of the wooden product and moisture content. However, the MDFs are processed and coated to make them moisture resistant. The particleboards are of seven types among the standard, moisture-resistant, and flooring applications classes. They vary in both subprocess inclusions and applications. For all 19 types, wooden products of the five wood categories are described in Table 1. The details of the inventory analysis, life cycle impact assessment can be found in the Supplementary File S1 of this manuscript.

The background datasets are modelled using country-specific scenarios. The electricity and the thermal energy consumption are modelled based on the country-specific electricity grid mix, which is based in Australia. The technological representation is based on secondary datasets, which are primarily collected from the producers, and then industry average datasets are calculated and documented. The temporal focus is based on the year 2015–2016, which is less than six years old.

The input materials and resources, along with the output products, wastes, and emissions, are analysed. The subcategories in the input inventories are as follows: flows (elementary and non-elementary), resources in total, energy resources (they constitute a part of the total resource count), land use, material resource, valuable substances, and other types of inputs. The analysis of the input inventory shows that hardwood production consumes the highest amount of energy and resources, while hardwood consumes the lowest number of resources for the energy recovery process. The analysis of energy recovery processes shows that energy recovery from the MDF is the most resource-intensive process. The output emissions show that MDF has the highest number of emissions in freshwater and also, to some extent, in seawater. They also generate some production residues as part of the energy recovery processes due to the coatings and laminates. For particleboard production, the emission accounting is similar to MDF, with the highest emissions to freshwater and then seawater. For plywood, the emissions are mostly airborne emissions, followed by the emissions to freshwater. In terms of emissions, softwoods and hardwoods are environmentally friendly, which helps to reduce emissions from the environment. The details of outputs and emissions from the energy recovery processes are shown in Figure 7.

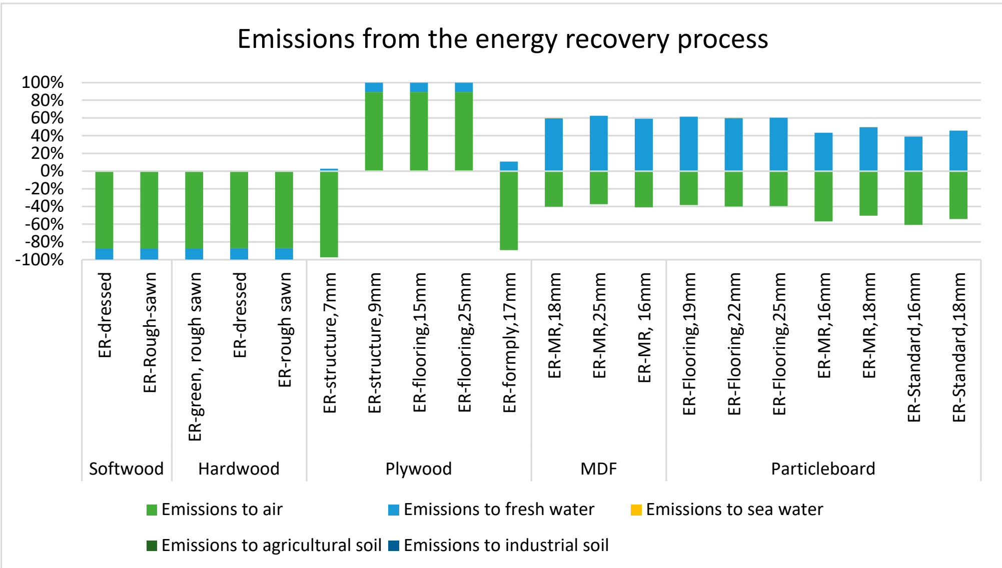

Figure 7. The output emissions from the energy recovery processes.

Based on the output emission from the energy recovery process, a regression model was developed in Microsoft Excel for calculating and predicting the output emissions from energy process. The correlation coefficient was 0.99839, and the percentage of variation in R accounting for the model was identified (i.e., R Square = 0.9968). The predictive equation and the line of best fit are provided on Figure 8.

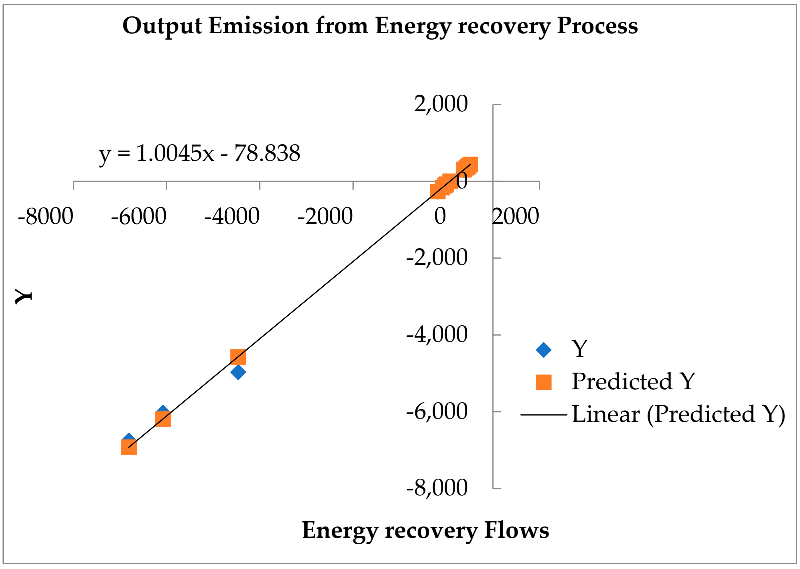

Figure 8. Linear regression model for the energy recovery processes.

Figure 9 describes the emissions from the wooden product manufacturing processes. The wood manufacturing processes are also analysed to compare their resource consumption and generation of emissions toward the environment. With the energy recovery processes, hardwood and softwood are material and energy-intensive products. The material consumption is lowest in MDF, followed by particleboard and plywood. The output emissions are dominant in the air emissions category for all types of wood, where the highest air emissions are caused by hardwood and softwood. MDF, particleboard, and plywood have impacts on freshwater and seawater. Comparing the energy recovery processes and the wooden product manufacturing processes, the manufacturing processes have a higher number of emissions toward the environment.

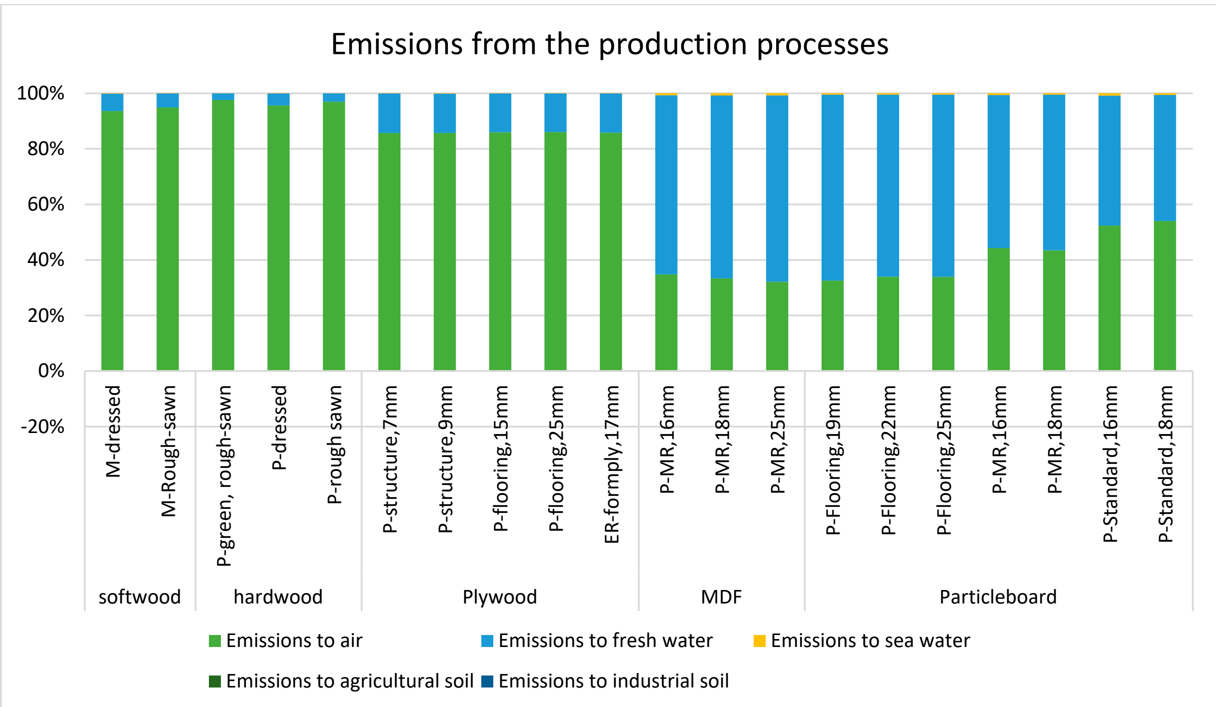

Figure 9. The outputs and emissions from the wooden product manufacturing processes.

4. Life Cycle Impact Assessment and Results Interpretation

The life cycle impact assessment was carried out based on the environmental footprint method (EF) in 16 impact categories. The European Commission's product environmental footprint method (PEF) is one of the most comprehensive methods for conducting a life cycle assessment, which covers all the impacts on air, water, soil, human health, land use (biodiversity), and resources. The impact categories considered are acidification (mol of H+ eq.), climate change (kg CO_2 eq.), marine eutrophication (kg P-eq.), freshwater eco-toxicity (CTUh), freshwater eutrophication (kg P-eq.), terrestrial eutrophication (kg P-eq.), human toxicity cancer (CTUh), human toxicity non-cancer (CTUh), ionising radiation (kBq U235 eq.), land use (Pt), ozone depletion (kg CFC-11 eq.), particulate matter (disease incidence), photochemical ozone formation (kg NMVOC eq.), resource depletion of fossils (MJ), resource depletion of minerals(kg Sb-eq), and water use (M3 world eq.). The normalisation was also conducted based on the environmental footprint method using 1Pt.

Acidification potential quantifies the decrease in the pH value of the rainwater and fog due to the acidifying effects of anthropogenic emissions. This is a measure of acidity increase in soil and water systems. Acidification impact is highest from the hardwood. Among the three types of hardwood production systems, the effect is higher from the kiln-dried, dressed-type of hardwood, whereas the green rough-sawn hardwood produces less impact via acidification. For energy recovery processes, rough-sawn softwood is more environmentally friendly. However, particleboard has a higher impact on the energy recovery processes.

Climate change defines the change in global temperature caused by the impacts of greenhouse gases caused by human activities. These quantify the greenhouse gases and their global warming potential. The production processes of hardwood and softwood show that the kiln-dried, dressed, and rough-sawn wood has a higher climate change impact, while the green rough-sawn wood has the lowest impact. However, softwood and hardwood production processes have a greater climate change impact than plywood, MDF, and particleboard. Among the energy recovery processes, hardwood and softwood are more environmentally friendly in terms of climate change due to biogenic carbon storage potential.

Eutrophication quantifies the impacts through an increase if the concentration of chemical nutrients in the marine ecosystem, which leads to abnormal productivity in plants like algae. These are due to the emissions of ammonia, nitrates, nitrogen oxides, and phosphorus. In this paper, we analysed three types of eutrophication: marine, freshwater, and terrestrial (dry land). As in the climate change impact category, all these three types of eutrophication impacts are highest from the dressed type of softwood and hardwood; however, rough-sawn wood has a comparatively lower impact. For the energy recovery processes, significant emissions occur from the MDF (impact increases as the structural area increases) and particleboard (higher in the case of particleboard for flooring applications). Like climate change, hardwood and softwood are beneficial for the environment in terms of eutrophication.

Ecotoxicity is measured via freshwater-, marine-, and terrestrial (land)-based toxicity impacts caused by some substances such as heavy metals, which can heavily impact the environment. From the production processes, hardwood production has the highest eco-toxicity impacts, while the MDF and particleboard sit next to the hardwood. Plywood and softwood production processes have a comparatively lower environmental burden. Among the energy recovery processes, all these types of wood are environmentally beneficial. However, hardwood and softwood show greater benefits.

Human toxicity potential (cancer and non-cancer) is the calculated index that reflects the impact of chemical release in the environment on human health. The toxicity impact can be cancerous or non-cancerous. As with the ecotoxicity impact, energy recovery processes from waste wood help to reduce human toxicity non-cancer emissions, while the most beneficial ones are energy recovery from hardwood and softwood. The human toxicity cancer impact is largest from the MDF production processes, followed by the standard type of particleboard. Human toxicity and non-cancer impacts are largely caused by the hardwood and softwood production and energy recovery processes.

Ionising radiation is caused by the damage to human health and ecosystems caused by the radionuclide emissions throughout the product life cycle, which can also be linked to nuclear power consumption, which quantifies the radiation types and neutrons. The ionising radiation impacts are heavily dominated by the MDF and particleboard production processes, as well as the energy recovery processes. Among the seven types of particleboards, the impact is largest from the particleboards produced for flooring applications. Softwood- and hardwood-based energy recovery processes are still environmentally beneficial in terms of ionising radiation (Figure 10).

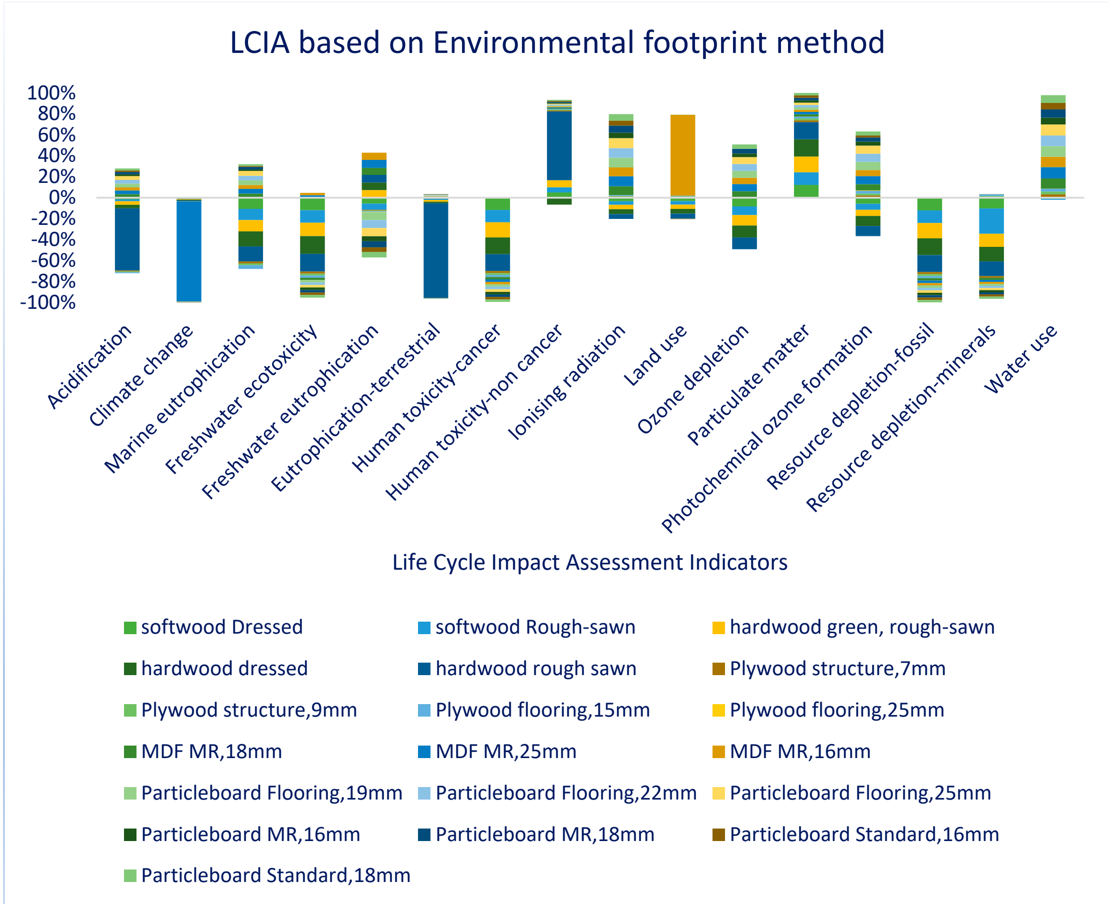

Figure 10. LCIA impacts from the energy recovery processes based on the PEF method for 16 impact categories.

Land use impact is quantified based on land occupation/utilisation, which impacts agriculture, anthropogenic settlement, and resource extractions. The land use impact is significantly caused by the particleboard production processes, followed by the hardwood and MDF production processes. However, the energy recovery processes from the hardwood and softwood help greatly reduce negative emissions from the environment.

Ozone layer depletion is caused by the gases like chlorinated and brominated compounds that can reach the stratosphere. The responsible gases are CFCs, halons, and HCFCs. Plywood energy recovery processes both cause significant impacts on ozone depletion, and MDF and particleboard production processes cause the same as well. As in the land use impact category, energy recovery processes from the hardwood and softwood help greatly to reduce negative ozone-depleting emissions from the environment.

Particulate matter impacts are caused by extremely small particles, including acids (nitrates and sulphates), organic chemicals, metals, soil, or dust particles. Hardwood and softwood production processes, as well as the energy recovery processes, cause significant impact via particulate matter. Other types of wood-based processes have a negligible impact.

Photochemical oxidation is related to the ozone level, the same as the ozone depletion potential. However, this impact category quantifies the ground-level ozone, which forms by the reaction of volatile organic compounds and nitrogen oxides with the involvement of heat and sunlight. MDF and particleboard production processes cause a significant impact in terms of photochemical oxidation. While hardwood and softwood production processes seem beneficial, energy recovery processes from the hardwood and softwood cause a significant impact on photochemical oxidation.

Resource depletion quantifies the damage to natural resources in terms of energy resources (fossil fuel) or mineral resources. Energy recovery processes have great potential to reduce the resource depletion (fossil fuel and mineral resources) impact due to the generation of bioenergy. However, the wood production processes also have a negative impact, especially the hardwood production processes. The softwood production process heavily affects the resource depletion (mineral resources), followed by plywood and particleboard production.

Water use impacts quantify the reduction and use of water utilisation for a product life cycle (Figure 11). The MDF and particleboard production processes heavily impact water use. Hardwood, softwood, and particleboard production processes cause significant water use impact. Among the energy recovery processes, MDF- and particleboard-based processes cause a dominant impact.

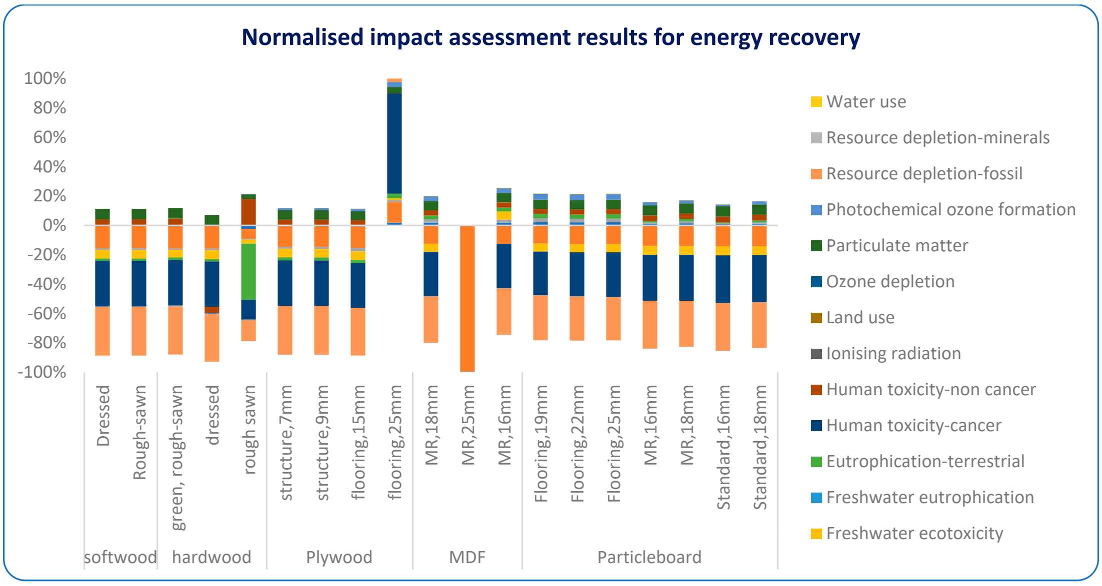

Figure 11. Impacts caused by different waste wood-based energy recovery processes.

5. Discussion

Figures 12–16 present the normalised impact assessment results to understand the comparative results of the impact categories for each individual type of wood waste. The X-axis shows the impact assessment results, which are normalised to compare among the impact categories for understanding their relevant significance; hence, they are unitless quantities. The Y-axis denotes the impact categories. Figures 13 and 14 show that for the energy recovery from the wood waste, particulate matter, and human toxicity non-cancer categories have significant impacts. However, both help to reduce the negative environmental emissions in resource depletion (fossil), human toxicity cancer, climate change, and freshwater ecotoxicity categories. For the energy recovery from plywood, photochemical ozone formation, ozone depletion, and human toxicity non-cancer have a significant environmental impact, while other impact categories show the potential to reduce the environmental burden. Energy recovery from MDF is harder than other sources in terms of the environmental perspective. The emissions are evident in acidification, freshwater ecotoxicity, marine eutrophication, terrestrial eutrophication, human toxicity non-cancer, particulate matter, and photochemical ozone formation. Only 4 impact categories out of the 16 show environmental potential to reduce the burden from the energy recovery from MDF: climate change, resource depletion (fossil and minerals), and human toxicity cancer. Energy recovery from the particleboard shows that the high impact is evident in photochemical ozone formation, particulate matter, human toxicity non-cancer, terrestrial eutrophication, marine eutrophication, and acidification. Like MDF, environmental benefits are observed in resource depletion, human toxicity cancer, and climate change. The overall results show that bioenergy recovery from wood waste has great potential to reduce the environmental burdens on human health, ecosystem, and resources. The greatest potential for energy recovery is observed in the softwood- and hardwood-based waste-to-energy recovery processes.

Among all five types, hardwood is the most environmentally sustainable bioenergy resource. On the other hand, MDF and particleboard showed the least potential for energy recovery among the five types. In hardwood and softwood, kiln-dried dressed-type wood has more impact than rough-sawn wood because of the inclusion of the planing process. However, green-sawn wood has the greatest potential, which excludes the planing process and drying process. Among the plywood, MDF, and particleboards, the greater the dimension is, the higher potential of energy recovery is shown, even though the mass is the same for all the products under consideration. Particleboards have seven varieties under consideration that vary in their type (standard or moisture-resistant design) and applications (flooring applications)—which shows that a lower number of chemical applications tends to lower environmental burdens. The results also indicate that moisture-resistant wooden products lead to a greater environmental burden than less-processed/less-dried wood. Among the 16 impact categories, the overall impacts are higher in terms of human toxicity non-cancer, ionising radiation, land use, ozone depletion, particulate matter, photochemical ozone formation, and water use. Analysing these impact categories and the respective impact assessment results shows that toxicity emissions are contributing factors via emissions to air and water.

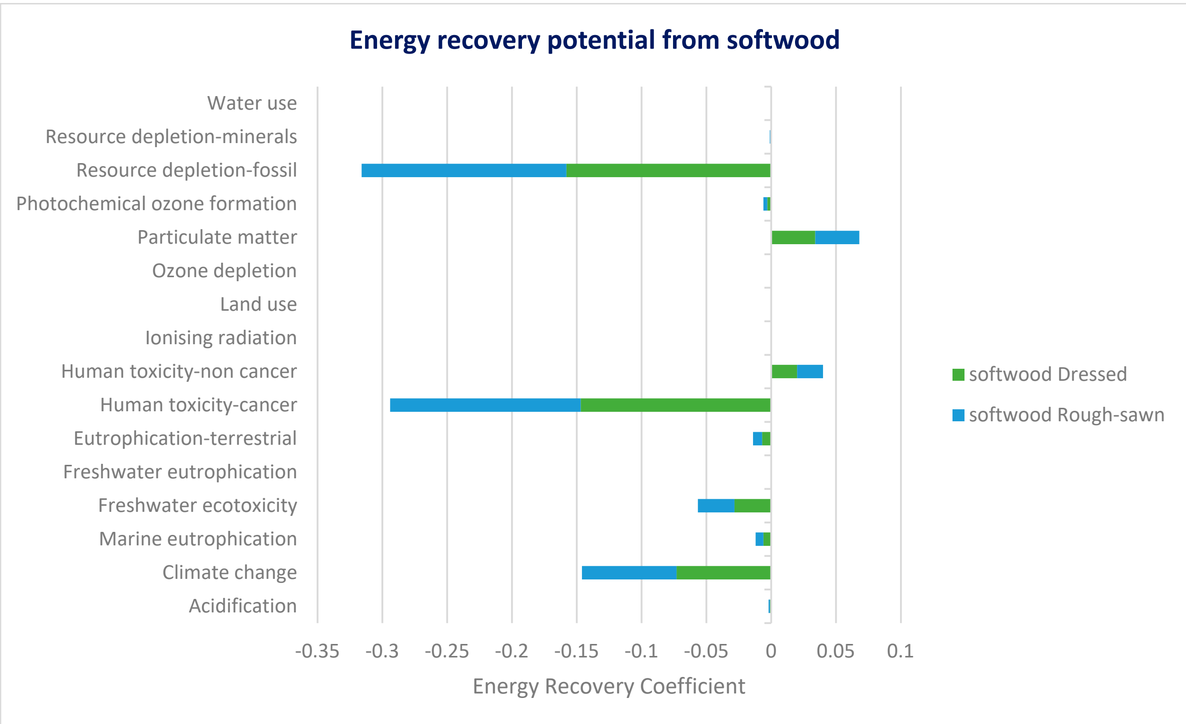

Figure 12. Normalised impact assessment results for energy recovery processes of softwood.

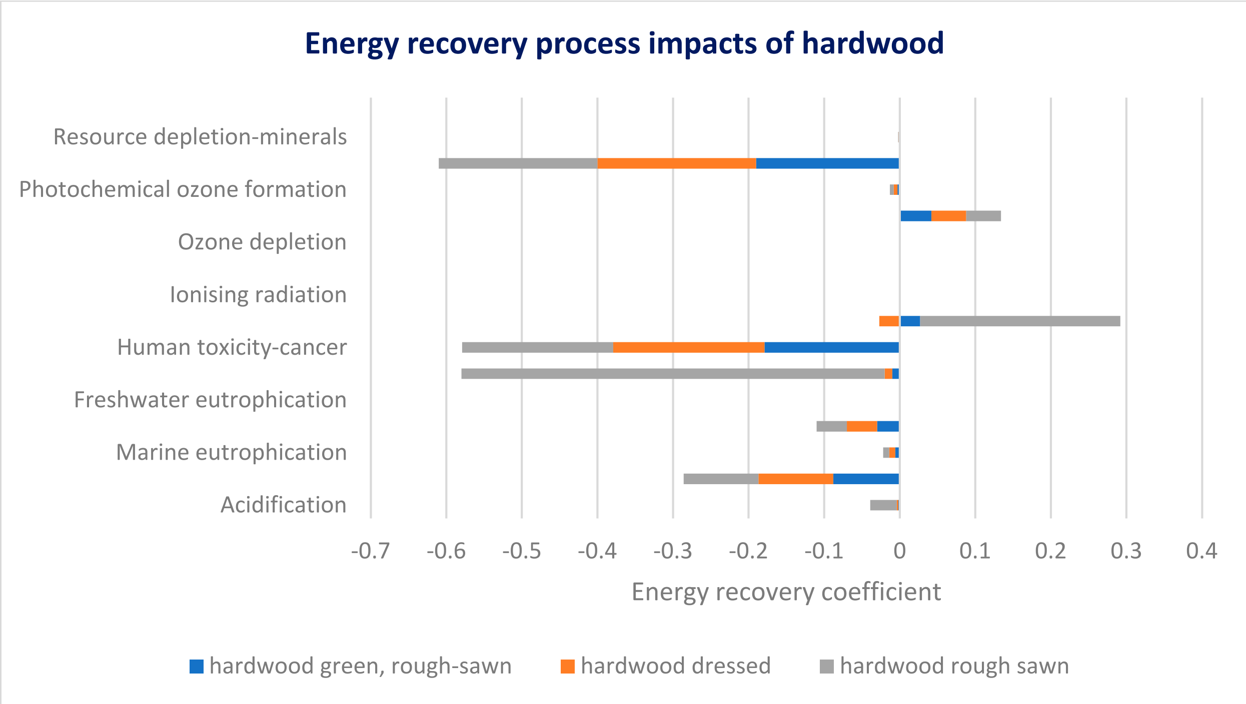

Figure 13. Normalised impact assessment results for energy recovery processes of hardwood.

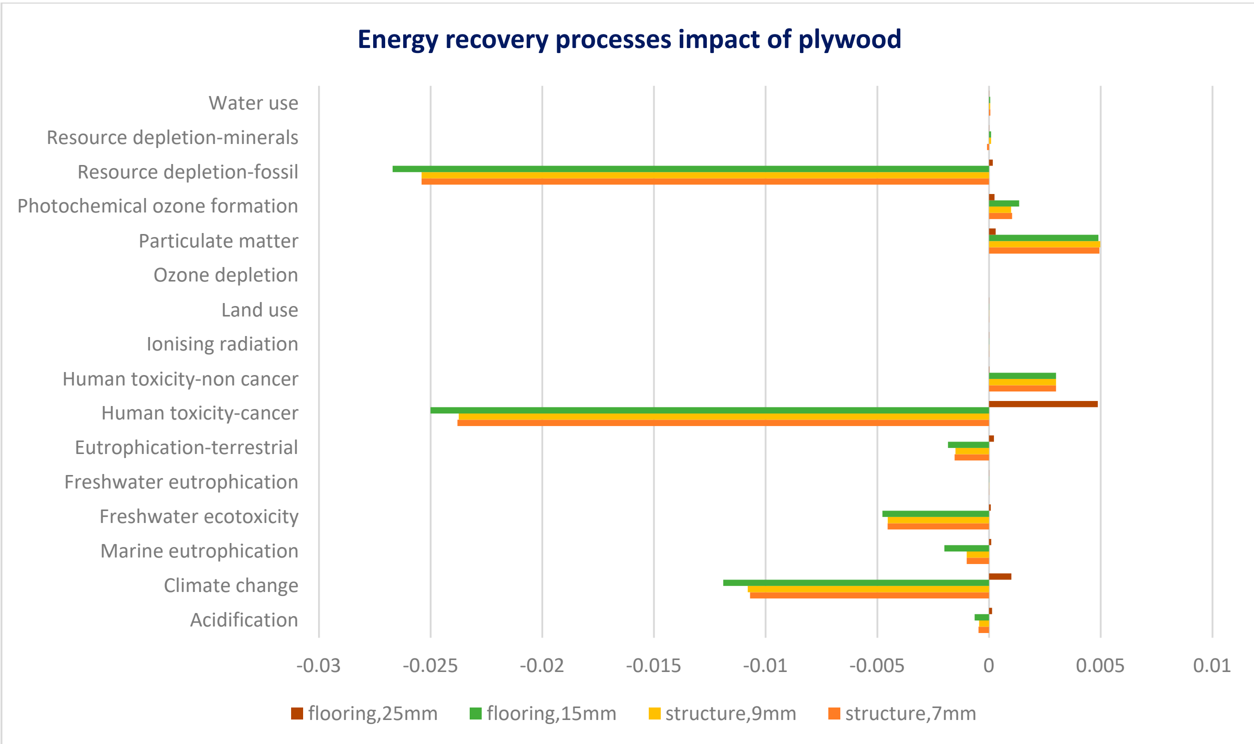

Figure 14. Normalised impact assessment results for energy recovery processes of plywood.

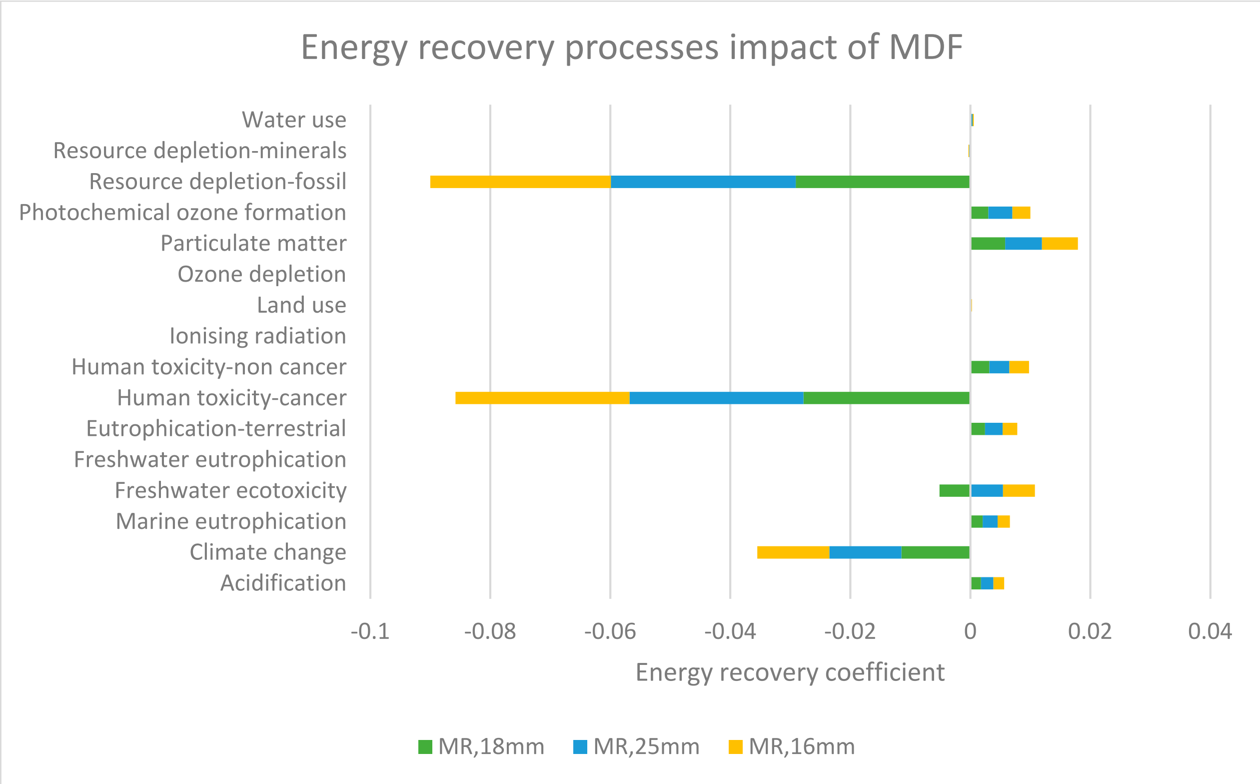

Figure 15. Normalised impact assessment results for energy recovery processes of MDF.

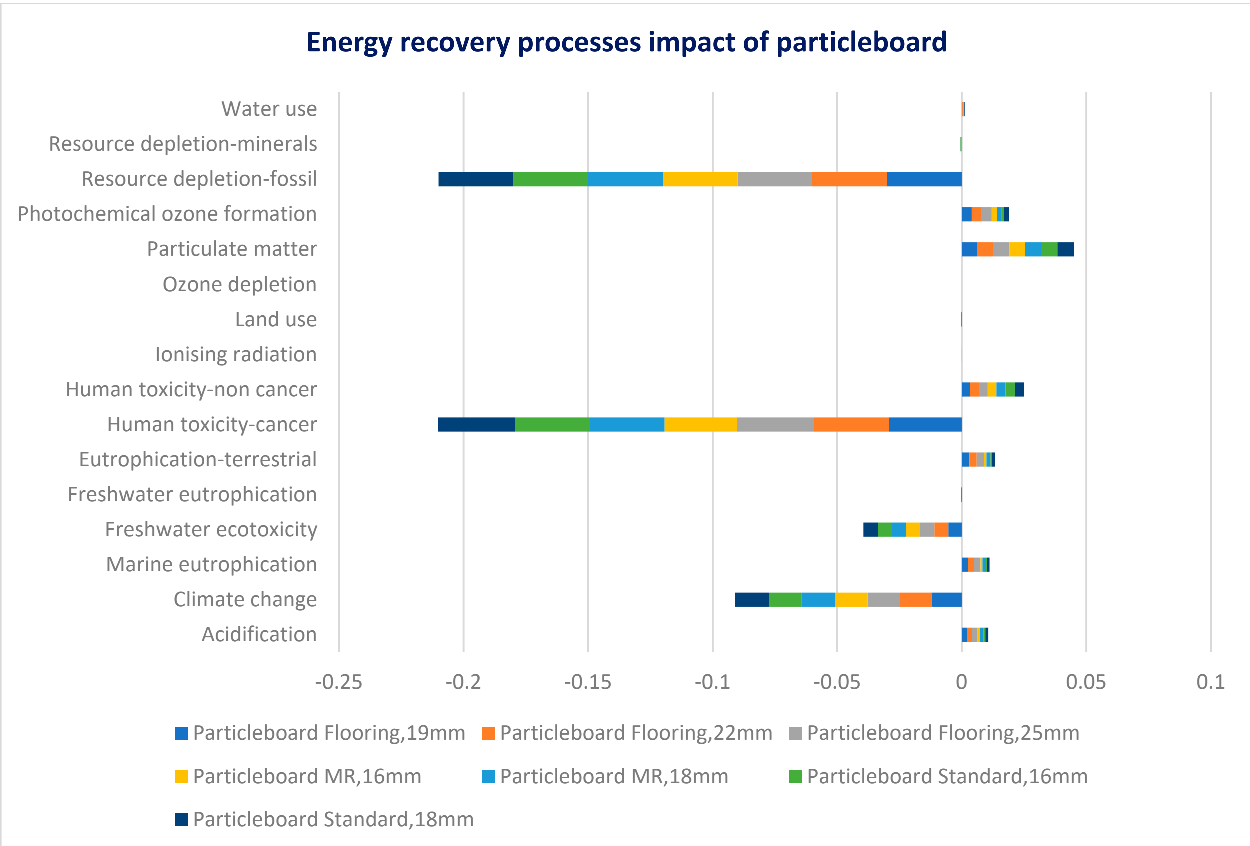

Figure 16. Normalised impact assessment results for energy recovery processes of particleboard.

There are several limitations of the analysis model and the datasets.

(a) The dataset is based on the industry average dataset and the aggregation of the processes involved in the system. The major limitation of using aggregated datasets in life cycle assessments is that it is hard to identify the impact hotspots in the subprocesses in the production chain. It is also hard to identify whether each of the subprocesses is based on accurate technological representations in the aggregated process datasets.

(b) The use phase of the wooden products is excluded here from the analysis if the use phase does not contribute to the environmental emissions. The waste collection phases are also excluded here if all the different types of wooden products undergo the same collection process and travel the same distance using the same vehicle. However, it might lead to a difference in the impact calculation because the dimensions of these wooden products vary from one another, so even to carry the same mass, the haulage capacity could be different. These are the types of uncertainty associated with this model.

(c) The study is solely focused on the identification of the future potential and the policy recommendations. However, it is not intended to be used for hotspot analysis and comparative assertions. In future, it would be great to conduct a sensitivity analysis to identify the hotspots. Hotspot analysis would be better if the unit process datasets could be collected and documented.

(d) The analysis is solely based on the industry average datasets from Australian manufacturers. So, it would be great to extend the analysis based on the global average dataset or analyse it for another regional context. For that purpose, in-depth work is required to build the life cycle inventory for global average datasets for energy recovery from wood waste.

(e) The policy recommendation would be solely based on environmental context. However, the social impact assessment or the economic analysis would be beneficial to consider in future to add the triple-bottom-line perspective from sustainability.

In Australia, WTE projects are being contemplated due to the closure of many coal-fired power generation and fossil-related power stations. Recently, many policies have been formulated at a state level to support the development of WTE facilities A case in point is the New South Wales Government's recommendation that energy-from-waste (EfW) facilities only be constructed in infrastructure priority areas (that is, in rural areas) [41] and the Victoria State Government's cap on the material capacity to 1 million tons per facility [42]. In other states and territories, similar laws are being considered to regulate the WTE facilities further. These arbitrary policy directives with limited scientific backing are of concern to practitioners and researchers involved in the WTE sector [7], as they increase risks in successful implementation, leading to problem shifting, and resulting in poor financial viability and accentuating the potential for unplanned obsolescence. The policy recommendations from this research are as follows.

5.1. Future Electricity Grid Scenario

Electricity scenarios are vital to provide future projects on the emissions intensity of WTE plants. The default analyses use a grid emissions intensity of 0.77 tCO_2e/MWh as representative for two emissions in the National Electricity Market (NGA, 2021). If the emission factor is used to estimate the benefits, there is a chance that the net benefit from a wood WTE may amount to approximately 15ktCO_2e for a 110,231.13-ton capacity plant.

Furthermore, the design life of the WTE facility is estimated at 25 years [43]. There is a possibility that, over the lifetime of the facility, various changes could impact on the LCA results. Increased uptake of renewable energy and more use of natural gas over coal power generation. It is generally acceptable that the trend of decarbonisation of the grid will continue, as most Australian states have introduced renewable energy targets amounting to net-zero emissions by 2050.

With the decarbonisation of the electricity grid over the design life of the facility, the direct emissions benefits are expected to diminish given the energy recovery potentials from softwood and hardwood production processes. It is also recognised that the wood waste to energy will provide reduction of landfill spaces, which will positively impact the wood WTE facilities. Even though the direct emissions of the wood waste are set to more than double by 2045, in the most aggressive grid emissions intensity reduction scenario, the overall net benefits for all the wood wastes remain very strong at 100 kt CO_2e/yr.

5.2. Establishment of WTE Facility in Australia

Depending on the location of transport waste to the waste-to-energy plants, there might be increase in the emission impacts of transporting wood from construction and demolition projects to waste-to-energy plants [44]. In the safe assumption that there will be twice the impact of business-as-usual transport to landfill sites across state, there is potential for an increase of 2–3%, which could further diminish the business case for wood-to-waste WTE facilities. There is therefore a need to optimise decisions made on commissioning WTE facilities, thereby initiating transformative change in Australia's WTE sector. Establishing robust methodologies that support the feasibility of prospective facilities and establishing suitable plant capacity will be helpful in sanctioning and positioning WTE facilities across Australia. Australia's ability to embrace the necessary context and recognise the dynamic process of managing the evolving society's wood waste, as well as making provisions for balances that shifts and change over time, will be vital in optimising Australia's waste-to-energy landscape.

5.3. Transition to Engineered Wood Products

The distinction between biogenic and fossil emissions is relevant for all types of processes (including combustion, landfill, composting, etc.), and thus applies to WTE facilities. The uptake of engineered wood products, such as cross-laminated timber, laminated veneer lumber, and other emerging products, will impact the quantities of wood waste as well as the quantity available for waste recovery. While the proportions of hardwood and softwood appear to be significant in the current analysis, there is likelihood for more chemical additives applied to EWP to create substantial impacts especially for human toxicity and abiotic depletion. There is, however, little information on the amount of wood waste that could emerge from EWP, as this is relatively recent and there are little or no case studies where demolition might have occurred. It is, however, anticipated that wood waste quantities from engineered products will increase and conducting the LCA on such wood variants will provide further directions on the potential for energy recovery. The findings from this study, however, suggest that developing technologies that can remove hazardous resins and chemical additives from wood products could help in improving the circular economy potentials of wood in the foreseeable future.

6. Conclusions

Bioenergy production from wood waste in Australia has the greatest potential for the future. Energy production from fossil fuels significantly impacts climate change, whereas bioenergy extraction from wood waste helps to reduce the climate change impact. Bioenergy production from waste is a growing industry not only in Australia, but also in the European Union. This study has conducted an attributional LCA-based life cycle assessment, where the system boundary is cradle-to-cradle, excluding the use phase and waste collection phase. The goal of the study was to identify the future potential of energy recovery from wood waste while making policy recommendations.

The study analysed two subsystems as part of the total system for each type of wooden product—the production system and the energy recovery system. The production subsystem varies from one type of wood to another in their subprocesses. On the other hand, the energy recovery system is the same for all types of wooden products. The production processes are considered to correlate the environmental impacts from the energy recovery process to their production routes. The type of wood considered included five types and 19 subtypes. The five types include softwood, hardwood, MDF, particleboard, and plywood. The analysis was conducted using product environmental footprint methodology for 16 impact assessment categories. The analysis was conducted in the Australian geographic context.

The analysis results show that Australian-grown and -produced softwood and hardwood have the greatest potential for energy recovery from wood waste while minimising the negative environmental emissions. Energy recovery from the wood waste will significantly reduce the environmental emissions in the categories of resource depletion (fossil), human toxicity (cancer), climate change, and freshwater ecotoxicity. However, due to toxic chemical substances in the engineered wood, energy recovery from the wood waste will cause impact on particulate matter and human toxicity. The overall results showed that the energy recovery from the MDF is harder than other types of wood. Australian-grown hardwood is the most sustainable among these five different types of wood.

For the development of a waste collection system for the wood waste-to-bioenergy production process, it would be great to emphasise softwood and hardwood waste collection for energy recovery. Recycling might be the better alternative in terms of circular economy, where possible. However, recycling/reusing the waste wood is dependent on the reusability of the structural components, which requires analysis, standardisation, or stewardship procedure. This paper could serve as the policy guidelines for the establishment of a new wood waste-to-energy recovery plant, what should be collected, and which emissions should be managed to reduce the environmental burdens. Even the most sustainable systems might have a great impact in some categories. It can also serve as the guidelines for setting environmental emission goals. In future, in-depth analysis is required in terms of triple-bottom-line sustainability assessment, either in a regional or global geographic context. Research is also required to reduce the toxic chemical compound utilisation in the engineered wood products so the end-of-life processing of the engineered wood becomes easier and less emission-intensive.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en16104182/s1, File S1: Detailed life cycle inventory analysis and life cycle impact assessment.

Author Contributions: Conceptualisation, M.A.; methodology, S.H.F. and O.T.; software, S.H.F.; validation, O.T.; formal analysis, S.H.F.; writing—original draft, S.H.F.; writing—review and editing, O.T.; supervision, M.A. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the MAAP Discovery 2023 grant and Alfred Deakin Postdoctoral Research Fellowship funding supported by Deakin University Australia.

Data Availability Statement: No data was used for the research described in the article or Supplementary Materials.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Sgarbossa, A.; Boschiero, M.; Pierobon, F.; Cavalli, R.; Zanetti, M. Comparative Life Cycle Assessment of Bioenergy Production from Differentwood Pellet Supply Chains. *Forests* **2020**, *11*, 1127. [CrossRef]
2. Rivela, B.; Moreira, M.T.; Muñoz, I.; Rieradevall, J.; Feijoo, G. Life Cycle Assessment of Wood Wastes: A Case Study of Ephemeral Architecture. *Sci. Total Environ.* **2006**, *357*, 1–11. [CrossRef] [PubMed]
3. Falk, R.; McKeever, D. Recovering wood for reuse and recycling, a United States perspective. In *Management of Recovered Wood Recycling, Bioenergy and Other Options, Proceedings of the European COST E31 Conference*; Thessaloniki, Greece, 22–24 April 2004, University Studio Press: Thessaloniki, Greece, 2004; pp. 29–40.
4. Maqsood, T.; Shooshtarian, S.; Wong, P.; Khalfan, M.Y.R. *Resource Circular Economy: Opportunities to Reduce Waste Disposal across the Supply Chain, Timber*; Sustainable Built Environment National Research Center Australia: Perth, Australia, 2019; pp. 1–48.
5. Department of the Environment. *National Greenhouse Accounts Factors*; Department of the Environment: Canberra, Australia, 2014.
6. Dastjerdi, B.; Strezov, V.; Kumar, R.; Behnia, M. An Evaluation of the Potential of Waste to Energy Technologies for Residual Solid Waste in New South Wales, Australia. *Renew. Sustain. Energy Rev.* **2019**, *115*, 109398. [CrossRef]

7. Tan, S.T.; Ho, W.S.; Hashim, H.; Lee, C.T.; Taib, M.R.; Ho, C.S. Energy, Economic and Environmental (3E) Analysis of Waste-to-Energy (WTE) Strategies for Municipal Solid Waste (MSW) Management in Malaysia. *Energy Convers. Manag.* **2015**, *102*, 111–120. [CrossRef]
8. Choong, J.E.; Onn, C.C.; Yusoff, S.; Mohd, N.S. Life Cycle Assessment of Waste-to-Energy: Energy Recovery from Wood Waste in Malaysia. *Pol. J. Environ. Stud.* **2019**, *28*, 2593–2602. [CrossRef]
9. Zaman, A.U. Life Cycle Environmental Assessment of Municipal Solid Waste to Energy Technologies. *Glob. J. Environ. Res.* **2009**, *3*, 155–163.
10. Zacho, K.O.; Mosgaard, M.; Riisgaard, H. Capturing Uncaptured Values—A Danish Case Study on Municipal Preparation for Reuse and Recycling of Waste. *Resour. Conserv. Recycl.* **2018**, *136*, 297–305. [CrossRef]
11. Ayodele, T.R.; Ogunjuyigbe, A.S.O.; Alao, M.A. Life Cycle Assessment of Waste-to-Energy (WtE) Technologies for Electricity Generation Using Municipal Solid Waste in Nigeria. *Appl. Energy* **2017**, *201*, 200–218. [CrossRef]
12. Forsythe, P. Drivers of Housing Demolition Decision Making and the Impact on Timber Waste Management. *Australas. J. Constr. Econ. Build.* **2011**, *11*, 1–14. [CrossRef]
13. Papastamoulis, V.; London, K.; Feng, Y.; Zhang, P.; Crocker, R.; Patias, P. Conceptualising the Circular Economy Potential of Construction and Demolition Waste: An Integrative Literature Review. *Recycling* **2021**, *6*, 61. [CrossRef]
14. Lu, W.; Yuan, H.; Li, J.; Hao, J.J.L.; Mi, X.; Ding, Z. An Empirical Investigation of Construction and Demolition Waste Generation Rates in Shenzhen City, South China. *Waste Manag.* **2011**, *31*, 680–687. [CrossRef] [PubMed]
15. Margallo, M.; Aldaco, R.; Irabien, A.; Carrillo, V.; Fischer, M.; Bala, A.; Fullana, P. Life Cycle Assessment Modelling of Waste-to-Energy Incineration in Spain and Portugal. *Waste Manag. Res.* **2014**, *32*, 492–499. [CrossRef] [PubMed]
16. Pettersson, M.; Björnsson, L.; Börjesson, P. Recycling of Ash from Co-Incineration of Waste Wood and Forest Fuels: An Overlooked Challenge in a Circular Bioenergy System. *Biomass Bioenergy* **2020**, *142*, 105713. [CrossRef]
17. Ng, R.; Shi, C.W.P.; Tan, H.X.; Song, B. Avoided Impact Quantification from Recycling of Wood Waste in Singapore: An Assessment of Pallet Made from Technical Wood versus Virgin Softwood. *J. Clean. Prod.* **2014**, *65*, 447–457. [CrossRef]
18. Brackley, A.M.; Nicholls, D.L.; Puettmann, M.; Oneil, E. *United States Department of Agriculture Forest Service Pacific Northwest Research Station General Technical Report Life Cycle Assessment of Wood Energy for Residential Heating-Opportunities for Wood Pellet Production in Southeast Alaska*; US Department of Agriculture, Pacific Northwest Research Station: Corvallis, OR, USA, 2017.
19. Corona, B.; Shen, L.; Sommersacher, P.; Junginger, M. Consequential Life Cycle Assessment of Energy Generation from Waste Wood and Forest Residues: The Effect of Resource-Efficient Additives. *J. Clean. Prod.* **2020**, *259*, 120948. [CrossRef]
20. Neri, E.; Cespi, D.; Setti, L.; Gombi, E.; Bernardi, E.; Vassura, I.; Passarini, F. Biomass Residues to Renewable Energy: A Life Cycle Perspective Applied at a Local Scale. *Energies* **2016**, *9*, 922. [CrossRef]
21. Morris, J. Recycle, Bury, or Burn Wood Waste Biomass? LCA Answer Depends on Carbon Accounting, Emissions Controls, Displaced Fuels, and Impact Costs. *J. Ind. Ecol.* **2017**, *21*, 844–856. [CrossRef]
22. Manyele, S. Lifecycle Assessment of Biofuel Production from Wood Pyrolysis Technology. *Educ. Res. Rev.* **2007**, *2*, 141–150.
23. Puettmann, M.E.; Lippke, B. Using Life-Cycle Assessments to Demonstrate the Impact of Using Wood Waste as a Renewable Fuel in Urban Settings for District Heating. *For. Prod. J.* **2013**, *63*, 24–27. [CrossRef]
24. Perić, M.; Komatina, M.; Bugarski, B.; Antonijević, D. Best Practices of Biomass Energy Life Cycle Assessment and Possible Applications in Serbia. *Croat. J. For. Eng. J. Theory Appl. For. Eng.* **2016**, *37*, 375–390.
25. Hossain, M.U.; Poon, C.S. Comparative LCA of Wood Waste Management Strategies Generated from Building Construction Activities. *J. Clean. Prod.* **2018**, *177*, 387–397. [CrossRef]
26. Röder, M.; Thornley, P. Waste Wood as Bioenergy Feedstock. Climate Change Impacts and Related Emission Uncertainties from Waste Wood Based Energy Systems in the UK. *Waste Manag.* **2018**, *74*, 241–252. [CrossRef]
27. Tabata, T.; Okuda, T. Life Cycle Assessment of Woody Biomass Energy Utilization: Case Study in Gifu Prefecture, Japan. *Energy* **2012**, *45*, 944–951. [CrossRef]
28. Heller, M.C.; Keoleian, G.A.; Mann, M.K.; Volk, T.A. Life Cycle Energy and Environmental Benefits of Generating Electricity from Willow Biomass. *Renew. Energy* **2004**, *29*, 1023–1042. [CrossRef]
29. Astrup, T.F.; Tonini, D.; Turconi, R.; Boldrin, A. Life Cycle Assessment of Thermal Waste-to-Energy Technologies: Review and Recommendations. *Waste Manag.* **2015**, *37*, 104–115. [CrossRef]
30. Fimbres Weihs, G.A.; Jones, J.S.; Ho, M.; Malik, R.H.; Abbas, A.; Meka, W.; Fennell, P.; Wiley, D.E. Life Cycle Assessment of Co-Firing Coal and Wood Waste for Bio-Energy with Carbon Capture and Storage—New South Wales Study. *Energy Convers. Manag.* **2022**, *273*, 116406. [CrossRef]
31. Green, D. *Clean Energy Australia Report 2012*; Green Energy Council: Melbourne, Australia, 2012.
32. Larsen, V.G.; Tollin, N.; Sattrup, P.A.; Birkved, M.; Holmboe, T. What Are the Challenges in Assessing Circular Economy for the Built Environment? A Literature Review on Integrating LCA, LCC and S-LCA in Life Cycle Sustainability Assessment, LCSA. *J. Build. Eng.* **2022**, *50*, 104203. [CrossRef]
33. Eshun, J.F.; Potting, J.; Leemans, R. LCA of the Timber Sector in Ghana: Preliminary Life Cycle Impact Assessment (LCIA). *Int. J. Life Cycle Assess.* **2011**, *16*, 625–638. [CrossRef]
34. Forest & Wood Products Australia Environmental Product Declaration: Softwood Timber. 2017. Available online: https://www.architectureanddesign.com.au/getmedia/3c90b564-6382-4078-9702-fd822086145c/WoodSolutions-Environmental-Product-Declarations-EPDs-1-7.aspx?ext=.pdf (accessed on 26 April 2023).

35. GBCA Life Cycle Assessment in Green Star Discussion Paper Feedback-FWPA. Available online: https://www.gbca.org.au/uploads/3/34051/LCA_Assessment_in_Green_Star_Discussion_paper.pdf (accessed on 26 April 2023).
36. Tucker, S.N.; Tharumarajah, A.; May, B.; England, J.; Paul, K.; Hall, M.; Mitchell, P.; Rouwette, R.; Seo, S.; Syme, M. *Life Cycle Inventory of Australian Forestry and Wood Products Publication: Life Cycle Inventory of Australian Forestry and Wood Products*; Forest & Wood Products Australia: Melbourne, Australia, 2009; ISBN 978-1-920883-90-4.
37. Knauf, M. Waste Hierarchy Revisited—An Evaluation of Waste Wood Recycling in the Context of EU Energy Policy and the European Market. *For. Policy Econ.* **2015**, *54*, 58–60. [CrossRef]
38. Bataineh, K.M. Life-Cycle Assessment of Recycling Postconsumer High-Density Polyethylene and Polyethylene Terephthalate. *Adv. Civ. Eng.* **2020**, *2020*, 8905431. [CrossRef]
39. Mannan, M.; Al-Ghamdi, S.G. Complementing circular economy with life cycle assessment: Deeper understanding of economic, social, and environmental sustainability. In *Circular Economy and Sustainability: Volume 1: Management and Policy*; Elsevier: Amsterdam, The Netherlands, 2021; pp. 145–160, ISBN 9780128198179.
40. Cascione, V.; Roberts, M.; Allen, S.; Dams, B.; Maskell, D.; Shea, A.; Walker, P.; Emmitt, S. Integration of Life Cycle Assessments (LCA) in Circular Bio-Based Wall Panel Design. *J. Clean. Prod.* **2022**, *344*, 130938. [CrossRef]
41. Protection of the Environment Operations (General) Regulation 2009 Protection of the Environment Operations (General) Regulation 2009 Contents. 2016. Available online: https://legislation.nsw.gov.au/view/pdf/asmade/sl-2009-211 (accessed on 26 April 2023).
42. Victorian Waste to Energy Framework. 2021. Available online: https://www.vic.gov.au/waste-energy (accessed on 26 April 2023).
43. Beard, K.; Gough, T.; Mcvey, L.; Mcvey, L.; Mcvey, L. Waste to Energy Facility. *Greater Dandenong*, 24 September 2020.
44. Khan, I.; Chowdhury, S.; Techato, K. Waste to Energy in Developing Countries-A Rapid Review: Opportunities, Challenges, and Policies in Selected Countries of Sub-Saharan Africa and South Asia towards Sustainability. *Sustainability* **2022**, *14*, 3740. [CrossRef]