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Comparative Life Cycle Assessment of Heat-Treated Radiata Pine Lumber: Evaluating Two Heat Supply Scenarios in China

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Abstract: Wood heat treatment is considered by many to be an eco-friendly wood modification method, given that only heat is applied during the treatment. However, it is essential to recognize that energy consumption can give rise to various environmental challenges. Quantitative evaluation of the environmental performance of a wood modification technology is always a challenge faced by the wood processing industry. To perform a comprehensive assessment, it is imperative to adopt a life-cycle-based approach, which is still very limited for heat-treated wood in China. This study investigated the mass and energy consumption of heat-treated radiata pine lumber in life cycle stages from forest management in New Zealand to wood heat treatment in East China and calculated its environmental impacts using the ReCiPe method. Two heat supply scenarios, i.e., on-site wood-fired boilers and off-site coal-fired power plants, were compared to evaluate the influence of national policy on environmental performance. Transoceanic shipping and lumber drying were found to be the life cycle stages dominating the environmental impacts level, and human-health-related impacts, mainly fine particulate matter, photochemical ozone formation, human toxicity, and global warming, were the major environmental impacts of heat-treated radiata pine lumber. With on-site heat supply, more heat and electricity were consumed due to a lower boiler efficiency and more energy demands. However, the impact assessment showed lower environmental impacts in this scenario. The non-fossil and carbon-neutral nature of wood is the key to the environmental advantages of this heat supply scenario.

Keywords: life cycle assessment; wood heat treatment; radiata pine; heat supply; energy mix

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1. Introduction

Wood is a widely used bio-based material which can be treated sustainably when managed and used properly. However, due to its orthotropic structure and biological nature, wood is prone to deformation and biodegradation, especially in outdoor applications. To improve the performance of wood, modification technologies, such as chemical impregnation, acetylation, furfurylation, and heat treatment, have been intensively studied. Among these technologies, heat treatment has been approved as an effective way to improve wood's dimensional stability and biological durability [1], and is suggested by many to be an eco-friendly method because only heat is applied during the treatment, which means that there is no chemical addition during the treatment process and no chemical leakage during the service of heat-treated wood (HTW). However, wood heat treatment involves considerable energy consumption because of the high temperature used [2], and energy consumption has been identified as one of the main environmental drawbacks of HTW [3,4]. It has been suggested that the energy consumption of wood heat treatment is a major contributor to its environmental impacts on climate change, acidification, eutrophication, photochemical oxidant formation, metal depletion, and fossil depletion [5]. In addition, the environmental impacts of HTW are not exclusively determined by the treatment process, but rather by the successive stages from its resource extraction to end-of-life disposal [6]. All these suggest that the environmental performance of HTW is not straightforward, and to reach a comprehensive conclusion, a systematic evaluation should be performed based on the life cycle approach.

Life cycle assessment (LCA) is a scientific and quantitative environmental impact assessment method that takes a life cycle perspective, i.e., from the excavation of natural resources to the final disposal of the products made from them. Such a perspective enables the coverage of a broad range of environmental issues and addresses questions that no other assessment tool can [7]. Nevertheless, the results of LCA are case-specific, meaning that they vary with wood species, region of origin, processing technology, energy supply, transportation, end-of-life disposal, and evaluation method. An analysis of the embodied energy and global warming potential of wood products by comparing published environmental performance declarations (EPDs) has demonstrated considerably scattered data, even for the same product category [8].

LCA results have highlighted the diversity in the environmental performance of HTW products. A study in the US showed that pressurized steam-treated softwood decking was superior to a preservative-treated counterpart in terms of most environmental impacts [9], while studies in Europe suggested that the environmental performance of cladding made of softwood treated either in atmospheric steam [10] or in partial vacuum conditions [11] was comparable to preservative-treated alternatives. Ferreira et al. [5] compared the energy and environmental profiles of wood heat treatment between Spanish and Portuguese companies and concluded that the cumulative energy to produce 1 m^3 of heat-treated maritime pine timber was 14.38 GJ for the Portuguese company and 17.55 GJ for the Spanish company. Another study by Ferreira et al. [12] suggested that the environmental profiles of Portuguese maritime pine wood were altered considerably if the economic allocation was substituted by volume allocation between the co-products. A US study of the carbon footprint of heat-treated pine wood showed significant greenhouse gas (GHG) emission reduction when the electricity scenario was changed from the state average grid to all renewables [13].

Heat treatment is a widely accepted wood modification technology in China. Its annual output in 2018 was estimated to be 250 thousand m^3 [14]. However, the life-cycle-based environmental performance evaluation of HTW is still limited in China. Because of variations in heat treatment equipment, process, and energy mix, it would be inaccurate to evaluate the environmental performance of domestically made HTW based on LCA studies in other countries.

Moreover, China is currently in the stage of an energy policy transition. According to the Air Pollution Prevention and Control Action Plan issued by the State Council, coal-fired and wood-fired steam boilers with a capacity below 10 t/h should be phased out in urban areas, and those with capacity below 20 t/h were not allowed to be built by 2017, because most of them cannot meet the national standards for boiler thermal efficiency. The efficiency of most wood-fired boilers is less than 75%, and may be as low as 60% [15,16], far below the efficiency range of 80%–88% required by the national standard GB 24500-2020 [17]. Heat should either be centrally supplied by power plants or by cleaner alternatives. Previously, most Chinese wood heat treatment facilities were equipped with wood-fired boilers to supply heat, so wood residues could be used on-site by the means of energy recovery. Ever since the release of the new policy, these facilities have been in the process of switching over to new energy supply systems, but the influence of the new policy has yet to be quantitatively evaluated.

As a response to these unknown factors, an LCA of heat-treated radiate pine (*Pinus radiata*) lumber produced in East China was performed. Radiata pine is China's largest imported wood species and a typical species used in the wood modification industry. According to the General Administration of Customs of China, in 2024 alone, the import volume from New Zealand reached 17.2 million m^3, accounting for 27.4% of the total wood imports of the state. The majority of the imported radiata pine wood was shipped to the Jiangsu and Shandong provinces in East China [18].

2. Methodology

This study is a cradle-to-gate LCA quantifying the environmental performance of heat-treated radiate pine lumber produced in East China following the methodological guidance of ISO 14040:2006 [19] and ISO 14044:2006 [20].

2.1. Goal and Scope

2.1.1. Goal Definition

This study evaluated the environmental performance of heat-treated radiata pine lumber, which was imported from New Zealand as logs and processed in East China, by quantitatively calculating the material and energy inputs and outputs from the acquisition of raw materials to the production of the heat-treated lumber.

In addition, two heat supply scenarios, i.e., on-site heat from wood-fired boilers and off-site heat from power plants, were compared to investigate the impacts of the heat source on the environmental performance of the HTW.

2.1.2. System Boundary

A full LCA of a product includes all stages from raw material acquisition to end-of-life disposal. For HTW, it includes forest management, wood harvesting, log sawing, lumber drying, lumber heat treatment, product processing, product use, final disposal, and all the related logistics (Figure 1). As HTW is an intermediate product and has a wide range of possible applications, this study focused on the stages from raw material acquisition to lumber heat treatment, and the stages of HTW product processing, use, and final disposal were excluded. The manufacturing and maintenance of buildings and machinery were elements excluded in this study. Previous studies have suggested that, for wood-based products, the infrastructure of production facilities may not be taken into account because the infrastructure for the production of different wood products is similar and the differences are negligible compared to the overall environmental impacts of a product's life cycle [21].

2.1.3. Declared Unit

A functional unit is the basis on which the input and output data in the life cycle stages of a product system are collected and reported. HTW is an intermediate product that needs to be further processed before it is used in end products, meaning that it does not have a specific functionality. Therefore, the term declared unit was adopted in this study [22]. The declared unit in this study was 1 m^3 of heat-treated radiata pine lumber with a nominal thickness of 50 mm.

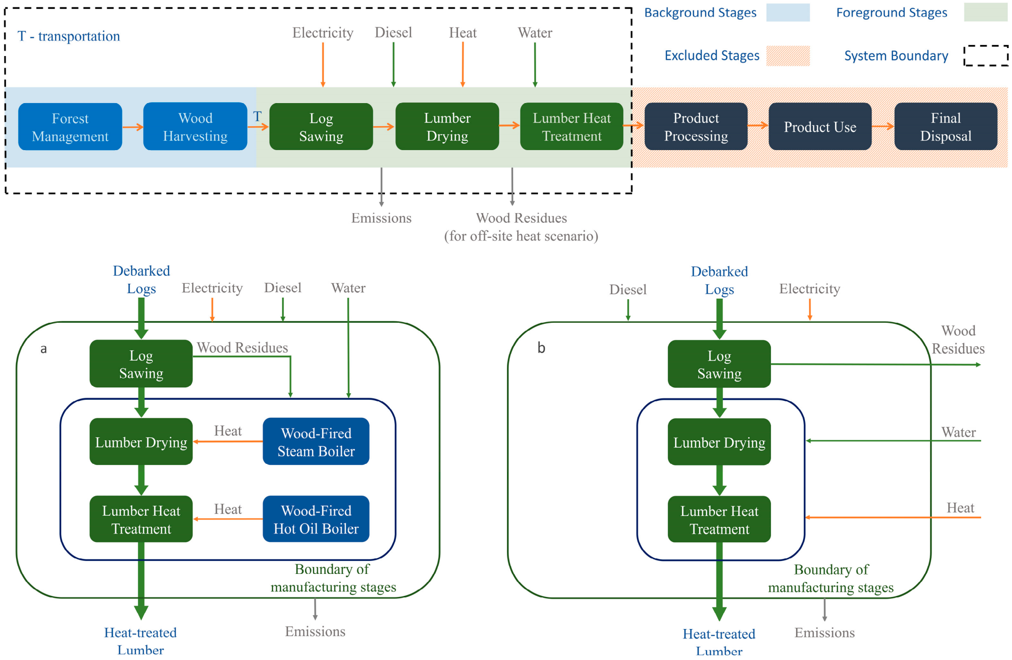

Figure 1. System boundary for the LCA of heat-treated radiata pine lumber in East China and modelled process flow for the foreground product manufacturing stages with (**a**) on-site heat supply from wood-fired boilers or (**b**) off-site heat supply from power plants.

2.1.4. Allocation Procedure

In the log sawing stage, rough-sawn lumber is the main product. Meanwhile, wood residues including sawdust, edgings, and trimmings are produced. They can either be used on-site as the fuel for wood-fired boilers or sold for off-site uses. Sawdust can be used for the raw material of wood pellets and edgings and trimmings can be cut to chips for pulp or wood-based panel industries. So, all the residues were treated as co-products in this study. According to ISO 14040:2006, allocation should be considered to assign specific quantities of inputs to the different products resulting from the process based on some mathematical relation. In this study, volume was used for allocation, with lumber accounting for 70% of the outputs and wood residues for the remaining 30% based on the assumption in the following section.

2.2. Inventory Approach

2.2.1. Forest Management and Wood Harvesting

According to the Ministry of Primary Industries, radiata pine is the predominant planted species in New Zealand, consisting of over 90 percent of forest area. New Zealand's government oversees the management of forests, and modern forestry practices have been introduced to ensure forest sustainability.

In this study, forestry practices from tree seedling to log debarking were considered in the forest management and wood harvesting stages. The equivalent process in Ecoinvent (Table 1) was chosen as secondary data for these stages.

2.2.2. Transportation

The logs were assumed to be shipped from the North Island of New Zealand, where radiate pine plantations are mainly distributed. The departure port was Tauranga, the largest wood export port in New Zealand, and the destination was Taichang Port bordering Shanghai in East China. The distance between the 2 ports is around 9500 km based on the data from: https://sea-distances.org/ (accessed on 27 March 2025). Logs were shipped by bulk carriers with a load capacity of around 40,000 t, and were assumed to be debarked before shipping as a phytosanitary measure.

Table 1. Data sources for background life cycle stages of heat-treated radiation pine lumber.

Process	Data Source	Equivalent Process
Forest management and wood harvesting (material extraction)	Ecoinvent	Sawlog and veneer log, softwood, debarked, measured as solid wood {RoW} ∣ debarking, softwood, in forest ∣ Cut-off, U
Transoceanic shipping	Ecoinvent	Transport, freight, sea, bulk carrier for dry goods {GLO} ∣ market for transport, freight, sea, bulk carrier for dry goods ∣ Cut-off, U
Land transport	Ecoinvent	Transport, freight, lorry >32 metric ton, EURO5 {RoW} ∣ market for transport, freight, lorry >32 metric ton, EURO5 ∣ Cut-off, U
Electricity in China	Ecoinvent	Electricity, high voltage {CN-ECGC} ∣ electricity, high voltage, production mix ∣ Cut-off, U
Off-site heat supply	Ecoinvent	Heat, district or industrial, other than natural gas {RoW} ∣ heat and power co-generation, lignite ∣ Cut-off, U Heat, district or industrial, natural gas {RoW} ∣ heat and power co-generation, natural gas, combined cycle power plant, 400 MW electrical ∣ Cut-off, U

After being imported to China, the logs were sawn to lumber, dried, and thermally treated. The data on these stages (product manufacturing stages) were primary information obtained by on-site investigation and questionnaires. The on-site investigation was performed in the wood processing facilities around the major wood import ports of Taichang, Zhangjiagang, and Jingjiang in Jiangsu Province. The log sawing, lumber drying, and heat treatment were investigated by process and machinery data recording and staff interviewing. It was assumed that the processing facilities were 300 km away from the port. The questionnaires were sent to Jiangsu Xinan Wood Drying Equipment Co. Ltd., a leading wood heat treatment equipment provider located in Jiangyin, China. Questions were asked about the specification of the wood heat treatment kiln, its operation parameters, and the typical treatment schedules.

2.2.3. Log Sawing

In China, log sawing is mostly organized on small scales. Bandsaws and gang saws are equipped for primary breakdown and re-sawing, but automatic control and conveying systems are usually absent. Such a manufacturing pattern limits capacity, but is in favor of a higher conversion efficiency, as operators manage to increase yield for a higher economic payback. The on-site investigation showed that the yield of log sawing ranged from 60% to 80% depending on the grades of the lumber produced. So, the lumber yield was assumed to be 70%, and the remaining 30% was assigned to wood residues.

2.2.4. Lumber Drying

Radiata pine lumber is either subjected to high-temperature drying at around 110 °C or conventional drying below 100 °C. The latter is the mainstream drying process in China. Lumber is usually dried in steam-heated compartment kilns with a capacity of 100 m^3. In this study, the lumber MC was assumed to be 80% before drying and was down to 8% after drying. The density of the kiln-dried lumber was 465 kg/m^3, and the volumetric shrinkage from moisture saturation to oven drying was 10.7%.

2.2.5. Lumber Heat Treatment

Lumber heat treatment is carried out in atmospheric steam conditions. Steam is used as a heating medium and shielding gas. To modify the wood properties, the treatment temperature should be above 160 °C. In this study, the treatment temperature was assumed to be 210 °C. At this level, the biological durability of wood can be effectively improved, and is, therefore, applied to softwood used outdoors. The mass loss during the heat treatment was roughly 7.5%, and the density of the treated lumber was 430 kg/m^3. This mass loss is due to the degradation of wood cell wall components during the heat treatment. Volatile organic compounds (VOCs) are formed as a result. Low-molecular-weight components, such as acetic acid and formic acid, are typically released into the atmosphere, while others have the potential to condense before escaping from the kiln vents. As the steam in the kiln turns into water in the cooling down stage of heat treatment, many of the condensates will dissolve in it and are left in the kiln. Gaseous and liquid components can be treated by the means of wet scrubbing and septic systems. In this study, the VOCs were assumed to be released into the environment.

2.2.6. Heat Supply

For the on-site heat supply scenario, the moisture content of wood residues was assumed to be 60% with a heating value of 12 GJ/t [23], and the thermal efficiency of wood-fired boilers was 65%. Emissions from the boilers and other manufacturing processes, except VOCs from drying and heat treatment, were calculated according to the emission factors issued by the Ministry of Ecology and Environment of China [24]. Although the burning of wood also emits CO_2, it is treated as a carbon-neutral process in the energy sector by the Intergovernmental Panel on Climate Change because these emissions are counted in the agriculture, forestry, and other land use sectors [25].

Ever since the implementation of China's new energy policy, heat sources, in most cases, were switched to off-site power plants, which are assumed to be composed of 80% coal-fired boilers and 20% natural-gas-fired boilers because coal is the dominant energy source in China's energy mix [26]. In this scenario, heat is supplied in the form of steam, normally at 250 °C and 2 MPa. At the gate of the factory, the pressure is lowered to around 0.8 MPa and the temperature to around 170–180 °C. Such steam can raise the kiln temperature to around 140 °C, which is enough for lumber drying, but cannot meet the heat demand for lumber heat treatment. In industrial practice, auxiliary electric resistance heating units are installed in the kiln to raise the temperature further to around 200 °C.

The modeling of the manufacturing processes in the 2 heat supply scenarios is illustrated in Figure 1. The off-site heat and electricity supply data sources are listed in Table 1.

2.3. Impact Assessment Method

Several life cycle impact assessment methods exist for application. Some of them are country-oriented, such as TRACI in the US and LIME in Japan. In this study, the ReCiPe 2016 method was applied, as its characterization factors are representative of the global scale [27]. ReCiPe comprises 2 sets of impact categories, as follows: 18 problem-oriented categories at the midpoint level and 3 damage-oriented categories at the endpoint level. The endpoint characterization values are obtained by multiplying the midpoint characterization factors and damage factors. In this study, impact categories with normalized endpoint values lower than 0.2×10^{-3} were excluded, and seven midpoint impacts, i.e., global warming (GW), photochemical ozone formation (POF), fine particulate matter (FPM), terrestrial acidification (TA), human toxicity (HT), land use (LU), and fossil resource scarcity

(FRS) were considered. The 3 endpoint impact categories were human health, resources, and ecosystems.

3. Results and Discussion

3.1. Inventory Analysis for Wood-Fired Boiler Heat Supply Scenario

The on-site investigation showed that 1023.80 kg of radiata pine logs can produce 716.7 kg of green lumber (Table 2), corresponding to a conversion efficiency of 70%. Such a recovery rate is considerably high compared to that in some reports [28,29]. The electricity consumption was also low, because less powered chain or belt conveyors were equipped. The electricity consumed for 1 m^3 output of green radiate pine lumber averaged 11.76 kWh, while the values were 45.4 kWh and 35.5 kWh for the same volume of softwood lumber production in the western and southern US, respectively [30].

Table 2. The input and output inventory for the manufacturing of 1 m^3 heat-treated radiation pine with on-site heat supply from wood-fired boilers.

Unit Process		Item	Unit	Value
Log sawing	Inputs	Debarked logs	kg	1023.80
		Electricity	kWh	11.76
		Diesel	L	0.42
	Outputs	Green rough-sawn lumber	m^3	1 (716.70 kg)
		Wood residues	kg	307.10
		Particulate matter	kg	0.002
Lumber drying	Inputs	Green rough-sawn lumber	m^3	1.08
		Heat	GJ	2.67
		Diesel	L	0.13
		Water	kg	50
		Electricity	kWh	28.8
	Outputs	Kiln-dried rough -awn lumber	m^3	1
		VOCs	kg	0.16
Heating by wood-fired steam boiler	Inputs	Wood residues	kg	83.31
		Electricity	kWh	3.26
		Water	kg	173.68
	Outputs	Heat	GJ	1
		Ash	kg	0.25
		NO_x	kg	0.09
		SO_2	kg	0.0003
		Particulate matter	kg	0.04
		COD	kg	0.003
Wood heat treatment	Inputs	Kiln-dried rough-sawn lumber	m^3	1
		Heat	GJ	0.60
		Electricity	kWh	25.10
		Water	kg	5000
	Outputs	Heat-treated lumber	m^3	1
		VOCs	kg	35
Heating by wood-fired hot oil boiler	Inputs	Wood residues	kg	83.39
		electricity	kWh	28.24
	Outputs	Heat	GJ	1
		Ash	kg	0.25
		NO_x	kg	0.08
		SO_2	kg	0.0003
		Particulate matter	kg	0.05
		COD	kg	0.003

During this process, minor quantities of VOCs were emitted into the atmosphere. According to Pang [31], the VOCs emitted during radiata pine drying were mainly pinenes with a quantity of about 0.024–0.162 kg/m^3 when conventional kiln schedules (dry-bulb temperature 90 °C) were applied. This emission level is rather humble compared to that of 35 kg/m^3 in the heat treatment process (Table 2).

The VOCs emitted during wood heat treatment can be classified into the following two categories: the volatile extractives in the wood and cell wall degradation products. For softwood species, the former mainly includes pinenes [31]. The latter consists of carboxylic acids and furans from hemicelluloses, and fewer quantities of phenolics from lignin [32–34].

Although the emission level during lumber drying is low, it is an energy-costing process. Kiln drying may account for 85% to 90% of the total sawmill energy consumption [15]. The on-site investigation showed that the heat and electricity consumption in wood drying were 2.67 GJ/m^3 and 28.8 kWh/m^3, respectively. The heat consumption was lower than the levels in New Zealand and Chile, two main producers of radiate pine lumber. According to Ananias et al. [35], the value was around 3 GJ/m^3 in these two countries. They attributed the higher heat consumption to the predominant sapwood content, with a typical initial MC as high as 150%. In China, partly due to long-distance transoceanic shipping and outdoor storage, the initial MC of radiate pine lumber can be lowered to around 80%. This may be the main factor responsible for the lower drying energy consumption, as heat for water evaporation is among the major energy consumption components in wood drying.

The electricity and heat consumption for wood heat treatment were 25.1 kWh/m^3 and 0.60 GJ/m^3, respectively. The energy consumption level for wood heat treatment varies with wood species, treatment process, and location. In this study, the treatment process under investigation was performed in atmospheric steam conditions. For the Thermowood process, a Finnish wood heat treatment technology performed in the same condition, the energy consumption in drying and heat treatment processes plus transport was around 2.16 GJ/m^3, among which, drying accounted for 80% of the heat energy [36]. Jartek, a Thermowood heat treatment kiln provider, claimed that the energy consumption levels for wood drying and heat treatment were 0.72–1.44 GJ/m^3 and 0.36–0.72 GJ/m^3, respectively [37]. A case study of Thermowood energy and its environment profile showed that a Spanish company consumed 1.47 GJ to dry and thermally treat 1 m^3 of maritime pine boards, and a Portuguese company consumed 4.38 GJ/m^3 for the same product [5]. For the same species, the energy consumption was 1.27 GJ/m^3 when the Retification process, a French wood heat treatment technology, was applied [34].

The data from this study and the above sources indicate that wood drying consumes the majority of the energy in the manufacturing stage of HTW, and heat treatment, performed at much higher temperatures, demands much less fuel.

3.2. Inventory Analysis for Power Plant Heat Supply Scenario

When heat is supplied by off-site power plants, on-site boilers are no longer needed, so all the related equipment and their energy consumption are avoided. As a result, the overall electricity consumption in the manufacturing system from log sawing to lumber heat treatment was reduced by 32.4%. Meanwhile, the heat consumption for lumber drying and heat treatment also decreased by 30.3% and 26.7%, respectively, due to the higher efficiency of off-site heat supply (Table 3).

Table 3. The input and output inventory for the lumber drying and heat treatment processes of 1 m^3 heat-treated radiation pine with off-site heat supply from power plants.

Unit Process		Item	Unit	Value
Lumber drying	Inputs	Green rough-sawn lumber	m^3	1.08
		Heat	GJ	1.86
		Diesel	L	0.13
		Water	kg	50
		Electricity	kWh	28.8
	Outputs	Kiln-dried rough-sawn lumber	m^3	1
		VOCs	kg	0.16
Wood heat treatment	Inputs	Kiln-dried rough-sawn lumber	m^3	1
		Heat from steam	GJ	0.16
		Heat from electric resistance heater	GJ	0.28
		Electricity	kWh	25.1
		Water	kg	5000
	Outputs	Heat-treated lumber	m^3	1
		VOCs	kg	35

3.3. Life Cycle Impact Assessment Results

3.3.1. Midpoint Impacts

Table 4 shows the midpoint impacts of heat-treated radiata pine lumber, based on which Figure 2 shows the percentage contribution of each life cycle stage to the environmental impacts of heat-treated radiata pine lumber. A similarity can be found between Figure 2a for the on-site heat supply scenario and Figure 2b for the off-site heat supply scenario. The impacts of material extraction, including forest management and log harvesting, were mainly on land use. The contributions from log sawing and land transportation were limited in all categories. Lumber heat treatment was also a moderate impact contributor in both heat supply scenarios. Its impact shares in almost all the midpoint categories were below 20%. Wood heat treatment is commonly carried out at around 200 °C, a temperature much higher than that for lumber drying. But a typical wood heat treatment only lasts tens of hours [38], which is rather short compared to the drying time, and is supposed to be the main reason for its modest energy consumption and environmental impacts.

Table 4. Comparison of midpoint impacts of heat-treated radiata pine lumber between 2 heat supply scenarios.

Impact Category	Heat Supply Scenario	Life Cycle Stages						
		Material Extraction	Land Transport	Transoceanic Shipping	Log Sawing	Lumber Drying	Lumber Heat Treatment	Total
GW ($kg\ CO_2$ eq)	On site	14.16	26.95	69.77	16.88	69.86	45.08	242.71
	Off site	14.16	26.95	69.77	16.88	177.14	56.57	361.48
POF ($kg\ NO_x$ eq)	On site	0.23	0.15	2.34	0.26	1.54	0.50	5.03
	Off site	0.23	0.15	2.34	0.26	0.65	0.23	3.87
FPM ($kg\ PM_{2.5}$ eq)	On site	0.02	0.02	0.40	0.05	0.28	0.10	0.87
	Off site	0.02	0.02	0.40	0.05	1.14	0.28	1.91
TA ($kg\ SO_2$ eq)	On site	0.05	0.04	1.25	0.13	1.08	0.34	2.90
	Off site	0.05	0.04	1.25	0.13	0.78	0.23	2.48
HT (kg 1,4-DCB)	On site	1.19	9.30	3.28	2.41	27.15	12.39	55.72
	Off site	1.19	9.30	3.28	2.41	28.89	10.77	55.84
LU (m^2a crop eq)	On site	499.71	0.01	0.01	40.54	155.32	35.23	730.81
	Off site	499.71	0.01	0.01	40.54	0.45	0.20	540.91
FRS (kg oil eq)	On site	4.21	8.08	19.56	4.48	17.34	9.88	63.53
	Off site	4.21	8.08	19.56	4.48	40.99	12.61	89.92

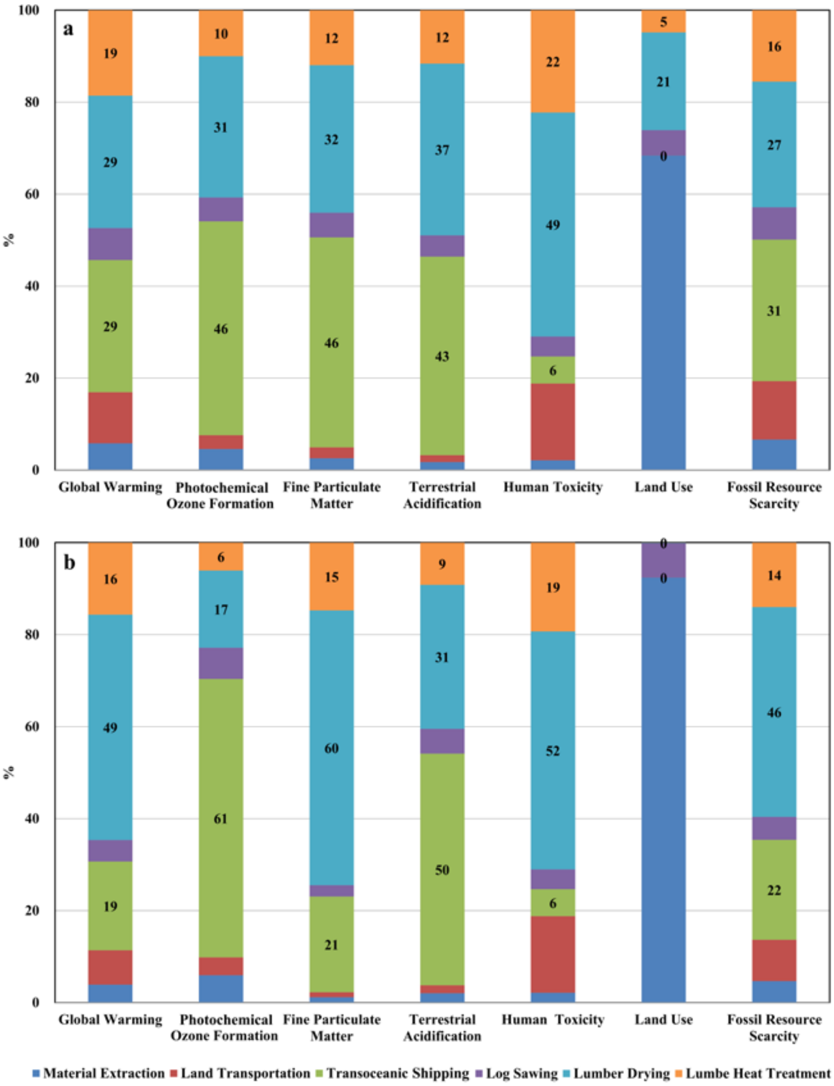

Figure 2. Contribution of each life cycle stage of the heat-treated radiata pine lumber to the midpoint impacts in the scenario of (**a**) heat supply from on-site wood-fired boilers and (**b**) heat supply from off-site power plants.

According to Figure 2, the environmental performance of heat-treated radiata pine lumber was more dominated by two life cycle stages, i.e., transoceanic shipping and lumber drying. In the on-site heat supply scenario, transoceanic shipping was the unique biggest contributor to POF, FPM, TA, and FRS, with percentages of 46%, 46%, 43%, and 31%, respectively. It was also the No.1 contributor to GW along with lumber drying (Figure 2a). In the off-site heat supply scenario, it contributed most to POF and TA, and second to GW, FPM, and FRS. Transportation has been proven to be a significant source of the environmental impacts of wood products [8,29,39,40]. Ocean transport is actually the most energy-efficient transportation mode [41] and has environmental advantages over land transport in several environmental impacts, but its environmental influence will rise when the transport distance increases. In this study, the high impacts from transoceanic shipping derived from the approximately 10,000 km distance from New Zealand to China.

The impacts of transportation are mainly caused by the burning of fossil fuels in internal combustion engines. A bulk carrier with a capacity of 50,000 t consumes as much as 30.2 tons of fuel a day for its main engine [42]. Typical marine fuel includes heavy fuel oil, marine gas oil, and marine diesel oil. When burned, they emit CO_2, SO_x, NO_x, and particulate matter into the atmosphere as the major emissions. Both SO_x and NO_x are acidic chemicals responsible for acid precipitation, and the latter is also the essential substance to form photochemical ozone in the troposphere. The incomplete combustion of fuel produces large amounts of black smoke, which contains unburned oil mist, carbon particles, etc. The size of the particulate matter generated in the burning process is at the micrometer or sub-micrometer level and can be easily inhaled by humans, making it a health-threatening environmental issue.

In the on-site heat supply scenario, lumber drying was the dominant contributor to HT, the No.1 contributor to GW along with transoceanic shipping, and the second contributor to the rest of the impacts (Figure 2a). In the off-site heat supply scenario, it surpassed transoceanic shipping and contributed the most in four of the seven impact categories. As discussed above, lumber drying is a major energy consumption stage in the wood processing industry. Although the burning of wood residues can be treated as a carbon-neutral process, the impacts on GW and FRS can still be pronounced because of the electricity consumed by the drying system. It has been reported that the GHG emissions derived from electricity account for 74%–94% of the total in lumber drying [43]. Although the low sulfur content in wood greatly decreased the SO_x emissions during wood burning, NO_x and particulate matter were among its typical emissions and responsible for the impacts on POF, FPM, and TA.

When the heat source was switched to off-site power plants, the highs and lows of the impacts can be observed in Figure 3, illustrating the complex environmental consequences of the heat source change. The decreases in POF and LU may have been due to the more efficient heat generation and the simplified manufacturing system, while the increases in GW and FRS are supposed to be the direct result of substituting the wood residues with fossil-based fuels, as the per functional unit life cycle CO_2 emissions from natural gas and coal, which are around 10 to 20 times as much as those from wood [44]. The significant share increase in FPM can most probably be attributed to the much higher ash content of coal than wood, which is commonly more than 10% for coal and less than 1% for wood.

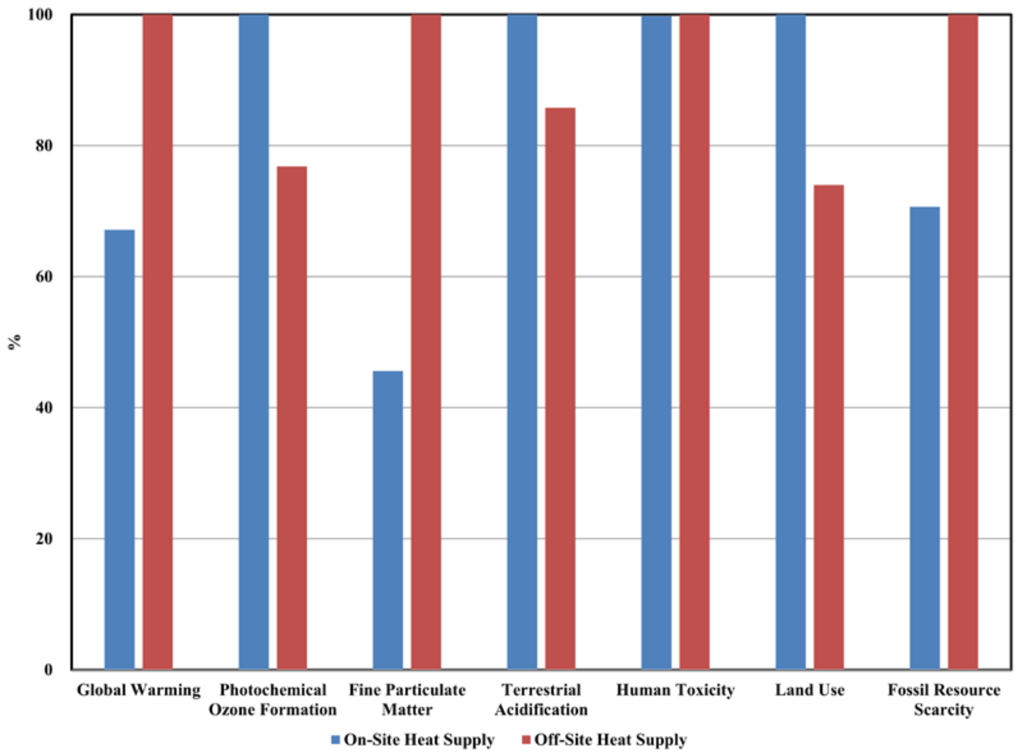

Figure 3. Comparison of midpoint environmental impacts of heat-treated radiata pine lumber between on-site and off-site heat supply scenarios.

The discussion above clearly shows that the main efforts should be made regarding transoceanic shipping and lumber drying to lower the environmental impacts of heat-treated radiata pine lumber. Great attention has been paid to the energy and environmental aspects of wood drying. Elustondo and Oliveira [15] summarized the opportunities for reducing energy consumption in softwood lumber drying. With respect to kiln schedule, they suggested that higher drying temperatures would yield lower energy costs because insulation and ventilation losses could be reduced due to faster drying. Riley and Sargent [45] also concluded that a combination of the highest dry-bulb temperature and lowest web-bulb depression is usually an optimized process for radiata pine kiln drying. Our on-site investigation revealed that high-temperature drying could dramatically shorten the duration to just 3 days. But higher initial investment, caused by higher installed capacity and insulation requirements for the drying system, was the major obstacle hindering the population of the high-temperature drying of radiata pine lumber.

With respect to transoceanic shipping, the distance from New Zealand to China can be treated as a constant. But what if we change the form of the shipped wood from green logs to kiln-dried lumber? To conduct an evaluation, an alternative log sawing and drying scenario was assumed, where radiate pine lumber was sawn and dried in New Zealand and shipped to China in the form of kiln-dried lumber.

In this case, the inventory data of "Sawnwood, softwood, raw {RoW} | sawing, softwood | Cut-off, U" in Ecoinvent were used to include the log sawing process. The electricity and heat consumption for lumber drying were set to 60 kWh/m^3 and 3 GJ/m^3 according to Ananias et al. [35]. The electricity mix was determined according to the electricity country mix of New Zealand in Ecoinvent. It was assumed that the heat for lumber drying and heat treatment was supplied by on-site wood-fired boilers.

Table 5 shows that the heat-treated radiata pine lumber sawn and dried in New Zealand had lower environmental impacts on GW, POF, FPM, TA, and FRS. The impacts of land and transoceanic shipping fell significantly in all impact categories thanks to the weight decrease in wood per unit volume, which could be as high as 54% when the wood MC was down from 150% to 10%. Although the energy consumption level of lumber drying was much higher in New Zealand, its impacts on five of the seven mid-point categories, i.e., GW, POF, FPM, TA, and FRS, was found to be reduced. This reduction can be attributed to the change of electricity mix. Electricity in New Zealand mainly comes from hydro (60.6%) and deep geothermal power (17.4%). On the contrary, 70.2% of the electricity in East China comes from coal. Such a difference means much less fossil fuel consumption and a corresponding positive environmental influence during electricity generation in New Zealand.

Table 5. Comparison of midpoint impacts of heat-treated radiata pine lumber between 2 lumber manufacturing (log sawing and lumber drying) scenarios in China and in New Zealand.

Impact Category	Country	Life Cycle Stages				
		Land Transport	Transoceanic Shipping	Log Sawing	Lumber Drying	All Stages
GW ($kg\ CO_2$ eq)	CN	26.9	69.8	16.9	69.9	241.9
	NZ	11.3	27.8	25.0	32.0	152.8
POF ($kg\ NO_x$ eq)	CN	0.2	2.3	0.3	1.5	5.0
	NZ	0.1	0.9	0.2	1.1	3.1
FPM ($kg\ PM_{2.5}$ eq)	CN	0.021	0.398	0.047	0.280	0.9
	NZ	0.009	0.159	0.048	0.215	0.6

Table 5. *Cont.*

Impact Category	Country	Life Cycle Stages				
		Land Transport	Transoceanic Shipping	Log Sawing	Lumber Drying	All Stages
TA ($kg\ SO_2$ eq)	CN NZ	0.043 0.018	1.251 0.498	0.134 0.084	1.081 0.275	2.9 1.2
HT (kg 1,4-DCB)	CN NZ	9.3 3.9	3.3 1.3	2.4 3.0	27.1 64.4	55.4 86.1
LU (m^2a crop eq)	CN NZ	0.009 0.004	0.011 0.004	40.538 280.010	155.317 168.599	730.8 983.8
FRS (kg oil eq)	CN NZ	8.1 3.4	19.6 7.8	4.5 6.6	17.3 8.3	63.4 39.4

Notes: 1. CN: China, NZ: New Zealand; 2. Heat is supplied by on-site boilers in both lumber manufacturing scenarios.

According to the data in Table 4, one can suggest that using kiln-dried lumber from New Zealand could earn heat-treated radiata pine lumber environmental benefits. But trade data show another picture. In 2019, China only imported 557 thousand m^3 of radiata pine lumber from New Zealand. This figure was dwarfed by over 17 million m^3 of logs imported in the same year. Price was suggested to be the main obstacle preventing more lumber import from New Zealand [18]. This, along with the selection of the kiln schedule discussed above, could be treated as a typical demonstration showing that environmental performance is not only influenced by technical factors, but also economic considerations.

3.3.2. Endpoint Impacts

According to Figure 4a, the heat-treated radiata pine lumber in the off-site heat supply scenario showed more damage to human health, but less damage to ecosystems and resources (Figure 4a). Human health is the endpoint impact category related to four of the seven midpoint impacts considered, i.e., PMF, POF, HT, and GW. Figure 4b shows that it made an overwhelming contribution to the final score of the environmental performance, which finally led to the superiority of the on-site heat supply compared to the off-site one.

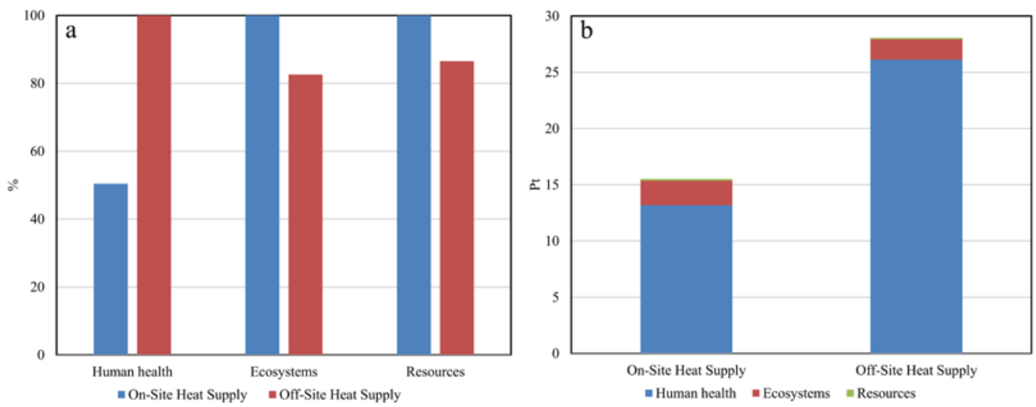

Figure 4. Endpoint impacts comparison between heat-treated radiata pine lumber in different heat supply scenarios: (**a**) damage assessment and (**b**) single score.

The combined results of inventory analysis and impact assessment suggest that heating centrally by a power plant can lower the on-site energy consumption level due to a higher energy efficiency and simplified manufacturing system. But the environmental impacts of the heat source switching are far more complex. The type of off-site heat source is a critical factor that makes a difference. In this case, the non-fossil and carbon-neutral nature of wood treated with on-site heat supplies environmental advantages over the solution of coal-fired power plants. Such an advantage has also been demonstrated by the comparison between lumber manufacturing in China and in New Zealand. The sawing and drying processes in New Zealand demand more energy, but lead to lower environmental impacts thanks to a more sustainable electricity mix.

According to the International Energy Agency [26], the share of renewable energy in China had risen to 23.4% by 2021, and 40% of global renewable capacity expansion between 2019 and 2024 is expected to occur in China. It is estimated that the share of renewable energy and electricity will, respectively, rise to 41.91% and 81.83% by 2050 [46], and installed coal-fired generators are expected to drop to 0 by 2060 [47]. It could be anticipated that the central heat supply scenario will not show its superiority until the electricity mix is continuously optimized this way.

3.3.3. Limitations and Challenges

Although LCA is a comprehensive environmental impact assessment method, limitations and challenges exist in terms of its practice and methodology in this study. As LCA is a data-intensive method, it is always a challenge to obtain representative data for the case under investigation. In this study, efforts were made to obtain more localized data, but some equivalent processes were applied to fill the gaps. Some assumptions were made to model the unit processes. Although they were built on a theoretical or investigation basis, more scenario analyses are still needed to check the sensitivity of the results to the consumption changes.

4. Conclusions

A cradle-to-gate LCA of heat-treated radiata pine lumber in East China was performed to identify the environmental performance of HTW produced in China. Transoceanic shipping and lumber drying, rather than heat treatment itself, were found to be the life cycle stages dominating the environmental impacts, which mainly cause human-health-related damage. The long transport distance from New Zealand to China and high energy consumption in lumber drying were responsible for the significance of these two stages. If only environmental factors are considered, it is a better practice to import kiln-dried lumber for heat treatment or apply a high-temperature kiln schedule for lumber drying.

Two heat supply scenarios, i.e., on-site wood-fired boilers and off-site coal-fired power plants, were compared. It was found that less energy was consumed in the off-site heat supply scenario due to the simplified manufacturing system and higher energy efficiency. However, the impact assessment showed the environmental superiority of the on-site solution thanks to the non-fossil and carbon-neutral nature of wood. It is, therefore, concluded that the impacts of switching heat sources are quite complex. Central heat supply could increase thermal efficiency, but its overall environmental performance heavily relies on the structure of the energy mix.

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