



## Comparative life cycle assessment of bioenergy in Japan from residual biomass-based wood pellets produced in the US Pacific Northwest

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### ABSTRACT

The US Pacific Northwest (PNW) faces an increase in wildfires due to forest overcrowding and climate change, posing significant environmental and public health risks. Traditional methods of managing surplus biomass, including prescribed burning, have increased air pollution and global warming. While in the PNW, residual woody biomass is being treated as waste, Japan's growing demand for bio-based energy presents an opportunity to export value-added biomass as energy pellets. This study investigates whether producing wood pellets from the residual woody biomass from forest operations and sawmills for electricity generation in Japan is truly environmentally beneficial. Accordingly, we conducted a cradle-to-grave Life Cycle Assessment (LCA) to evaluate the environmental impact of residual pellets vs. coal for electricity generation. The assessment covered feedstock production, pellet processing, transportation, and combustion phases. Our findings indicate that replacing coal-based electricity in Japan with PNW residual pellet-based electricity can lower the Global Warming Potential (GWP) by about 90% for every unit of electricity displaced. Furthermore, the results show that repurposing the otherwise burnt harvest slash residues for pellet production would improve local air quality by reducing PM<sub>2.5</sub> and smog in the PNW. However, substituting coal with residual pellets marginally increased carcinogenic and ecotoxicity-related emissions. Based on these results, we conclude that substituting coal with residual wood pellets for electricity generation, particularly harvest-slash residual pellets, is environmentally beneficial across most impact categories, including the GWP. This research underscores how an export-oriented pellet industry can help address the environmental challenges within the regional US wood products industry and global renewable energy supply.

### Introduction

The US Pacific Northwest (PNW) has experienced more frequent and devastating wildfires in recent years. More than 1.1 million acres of wildlands burned in Washington in 2015 and 1.3 million acres in Oregon in 2012, becoming the worst wildfires ever recorded in these two states [1]. The historical practice of fire suppression has led to forest overcrowding, whereas climate change has diminished moisture levels and accelerated snowmelt [2]. These combined factors have created a perilous environment conducive to forest fires, directly threatening public health and well-being. These fires adversely impact air quality, the timber industry, and vital forest ecosystem services [3].

To reduce the wildfire risk, forest agencies recommend mechanical treatments to remove excess biomass through thinning and regeneration harvest. The residues generated from these treatments are typically piled and burned in a controlled manner [4]. This act of burning, also known as prescribed burning, has been traditionally used in North American forests [5,6]. However, this practice emits several chemicals that potentially impact global warming and local air quality [7,8] with significant emissions of PM<sub>2.5</sub> particles, which represent a potential public

health hazard, as they penetrate people's lungs, causing difficulty breathing and decreasing lung function in the short term [9,10]. Long-term exposure can also lead to an increase in hospital visits and possible death.

In addition to residual woody biomass from forest operations, large amounts of residues are produced by sawmills during lumber production. The sawmill processes generate co-products such as hog fuel, sawdust, wood chips, and bark. Hog fuel mainly includes irregularly sized branches and tops, whereas sawdust comprises homogenous fine wood dust particles. Wood chips consist of small-diameter wood particles. Some of these co-products are used by industries such as pulp and paper and particleboard; some portions are burned to provide heat for milling operations [11]. The remaining mill residues are typically discarded as waste in landfills, releasing potent greenhouse gases like methane during decomposition [12].

Repurposing these discarded waste residues to produce value-added products, such as bioenergy products, could be both environmentally and economically valuable. Wood (white) pellets are biofuels made from compacted biomass and are an excellent candidate for using the residues as a raw material. Any low-quality biomass, such as forest residues, can

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be compressed and bound together under high pressure to produce pellets. The natural plant lignin in the wood materials holds the pellets together without chemical additives [13]. Pellets have significantly lower moisture content compared to their original source materials, resulting in enhanced combustion efficiency [14]. Practical applications of wood pellets include renewable energy generation on small and large scales, ranging from residential heating to industrial combined heat and power facilities [15]. They can be used as a source of both electricity and heat. Premium and standard wood pellets are typically used for heating, while utility-grade wood pellets are used for electrical power generation. Pellets can also be co-fired with coal in power plants to reduce coal consumption and lower overall emissions. Wood pellets produced by cutting down trees have been a contentious issue among conservationists [16]. In 2021, a letter by 500 scientists [17] urged countries to stop cutting forests to produce pellets. Alternative raw materials, such as forest residues for pellet production, could alleviate the contention around the pellets.

While using residual woody biomass for wood pellet production can be a viable alternative to burning or discarding it in landfills, the domestic market for pellets in the US remains relatively small. Since the Fukushima nuclear disaster, Japan has been actively working to reduce its reliance on nuclear energy. Climate change adds further pressure to decrease fossil fuel consumption. Consequently, Japan has steadily increased the share of renewable energy in its electricity mix, with biomass being one of the primary sources [18]. Given Japan's dependence on biomass energy sources, there is an opportunity to establish international trade between the PNW and Japan [19]. However, the sustainability of creating a pellet supply chain between the PNW and Japan must be verified. A cradle-to-grave Life Cycle Assessment (LCA) that estimates the emission profile of the entire pellet supply chain is needed to evaluate the environmental impacts of pellets using an internationally standardized approach.

Several studies focused on evaluating the environmental impact of pellet supply chains using LCA and among those, most focus on the use of wood pellets for heat generation [20,21] using various feedstocks such as switchgrass [22], olive husk [23], and wood [24–26]. Fewer studies assessed the environmental impact on an international scale [21], and, among these studies, most looked at the pellet supply chain between the Southeastern US (US SE) and the United Kingdom (UK). A study analyzing the import of US SE pellets into the UK for electricity generation under 930 different scenarios, including different sawmill and forest residual feedstocks, found that the UK would benefit from a 50%–68% GHG emissions reduction compared to fossil fuels [27]. In comparison to coal, pellets resulted in an 86% reduction in climate change impacts [28]. However, another study estimated that the emission reduction potential of the US SE pellets produced from forest residues for electricity generation in the UK had an uncertainty between 80% and –70% based on different assumptions [29].

Japan uses a significant volume of pellets for domestic heat and electricity generation. Woody biomass utilization systems used for household heat generation in Japan offer the advantages of reduced costs and environmental impacts compared to petroleum-based heat generation [30]. However, the pellet production process was the largest contributor to the environmental impact of wood pellets produced in Hokkaido, Japan [31], indicating a need to improve the production process. Further, Yun et al., estimated the life cycle GHG emissions of torrefied pellets compared to white pellets made from forest residues in British Columbia and transported to different regions, including Japan. This study found that replacing coal with residual pellets for electricity generation may result in more than 85% greenhouse gas (GHG) emission reduction, with torrefied pellets having higher benefits than white pellets [32].

Some studies found that long-distance ocean transportation adds a considerable environmental burden to the pellet supply chain. The long-distance ocean transportation between Canada and Sweden was the major contributor to the pellets produced in British Columbia and

shipped to Sweden [33]. Therefore, the location of ports and a short and efficient shipping route are essential to reduce the emission burden. The western part of North America, such as British Columbia in Canada and PNW ports in the US, is closer to Asian ports than to US SE ports. The strategic location of PNW ports makes them better suited to establish a trade relationship between the US and Japan.

Limited studies have examined the environmental impact of bioenergy products in the PNW. These studies examined the utilization of forest residues generated in the PNW to produce bioenergy products such as briquettes and biofuel, and found that the residual bioenergy products have less global warming impact, around 60% compared to petroleum-based jet fuel [34,35] and 94% compared to propane [36]. Since there is no well-established export-oriented wood pellet trade between the PNW and Asia-Pacific regions, no studies have explored the environmental impact of shipping these wood pellets from the PNW, and this study aims to fill this knowledge gap.

The objectives of this study are i) to evaluate whether wood pellets produced from the PNW forest and mill residues demonstrate a lower cradle-to-grave environmental impact compared to coal; ii) to determine the specific environmental contributions of production, shipping, and combustion phases to the overall environmental impact of wood pellets and coal; and iii) to evaluate the sensitivity of the environmental impacts to parameters such as residual feedstocks, species of the residues, and location of pellet mills.

## Methods

### Goal and scope

A comparative cradle-to-grave LCA was conducted in this study, where 'cradle' is defined as feedstock production and procurement, and 'grave' is defined as the combustion of wood pellets in a power plant for electricity generation. The LCA was conducted following the ISO 14040-44 standards, which have been widely used for the environmental impact assessment of product systems [37]. An LCA analysis typically includes four main phases: 1) goal and scope, which describe the purpose and breadth of the project; 2) life-cycle inventory (LCI), which covers data collection and quantification of inputs and outputs; 3) life-cycle impact assessment (LCIA), which uses characterization factors to estimate environmental and human health impacts based on LCI inputs and outputs; and 4) interpretation, which can be performed to identify strategies to reduce the environmental impacts and improve the environmental performance of the product. This study was conducted using the LCA software SimaPro Version 9.5.0.0 and the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) method, version TRACI 2.1 V1.05 / US 2008 for impact assessment. The environmental impacts were calculated based on a functional unit of 1 MJ of electricity produced by burning pellets.

### Study area

The pellet shipping route between the port of Longview in the PNW and the Sakata port in Japan was used in this study (Fig. 1). Although very few shipping activities occur between these ports, we identified Longview as an ideal port in the PNW due to its strategic location closer to the sawmills across both Washington (WA) and Oregon (OR). Additionally, the port of Longview, in its plans, is looking into ways to include wood pellet export [38]. The Sakata port was selected because it has already been used for importing wood pellets and is close to large biomass power plants.

Two hypothetical pellet facilities with a batch processing capacity of 1000 kg were modeled to be closer to Longview's port, with one facility in each state, WA and OR. The WA pellet facility was modeled in Cowlitz County, whereas the OR pellet facility was modeled in Columbia County, Oregon. An 80 km radius was set around these pellet facilities for feedstock procurement (Fig. 1).

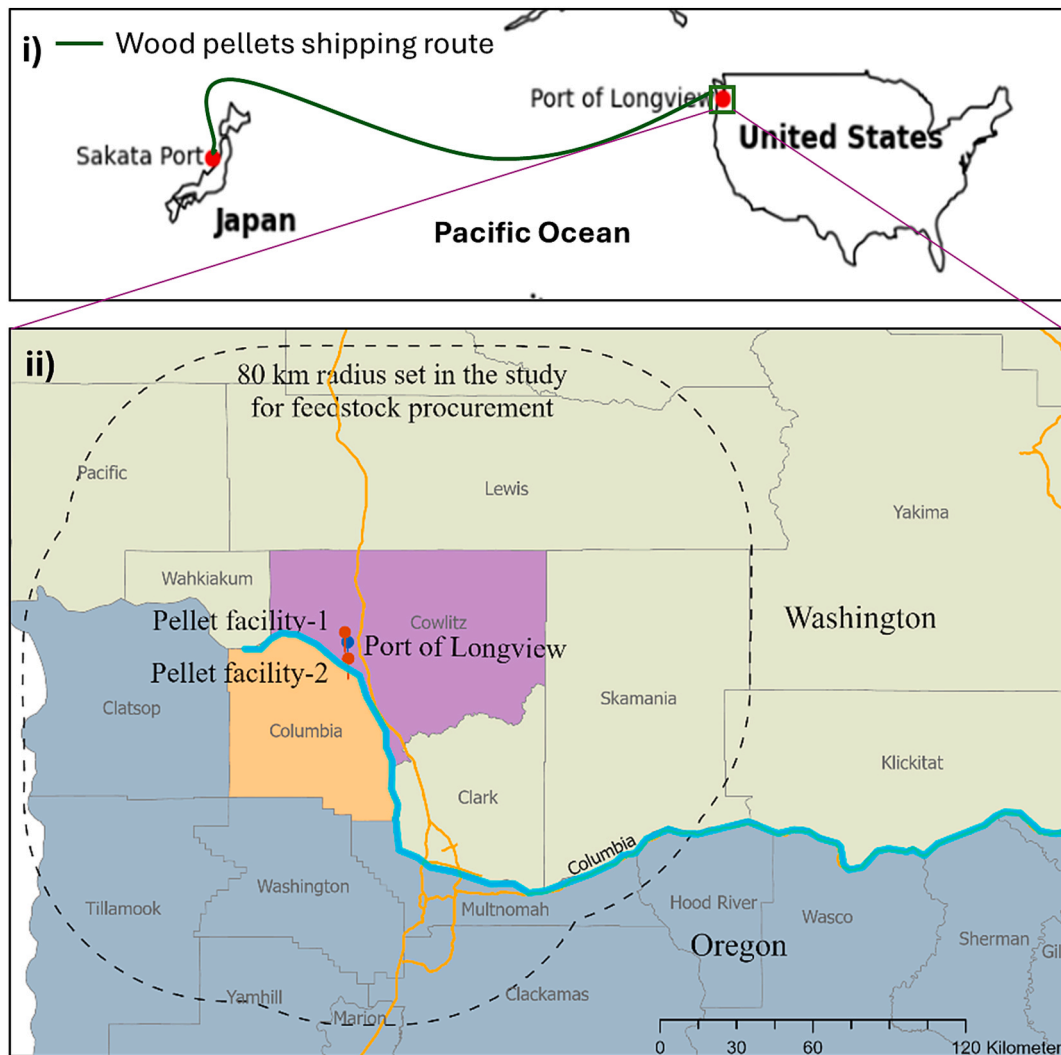


Fig. 1. i) Shipping route between the port of Longview, WA, US, and the Sakata port, Japan, via the Pacific Ocean; ii) A detailed view of the area surrounding the port of Longview depicts the two pellet facilities located in WA and OR. An 80 km radius has been designated around the facilities for feedstock procurement.

### System boundary

As shown in Fig. 2, the system includes four modules—feedstock, processing, transportation, and biomass burning. The feedstock module includes the emissions related to feedstock production, processing, and transportation to the mill gate. Three different types of feedstocks were studied: harvest slash residues, hog fuel, and sawdust. The harvest slash residue model includes the avoided emissions from slash pile burns. The processing module includes the emissions associated with pellet production, which includes drying, grinding (not for sawdust), and pelletization. The transportation module includes the transport of pellets to the port, intercontinental shipping, and road transport to the biomass power plant. Lastly, the biomass burning module includes all the emissions associated with burning the wood pellets. This study is based on the assumption of biogenic carbon neutrality, which asserts that carbon emissions from burning wood-based fuels are offset by the carbon sequestered by trees, resulting in a net neutral effect.

### Feedstock

This study tested three forms of residual biomass as pellet feedstock: harvest slash residues, sawdust, and hog fuel. Harvest slash residues are the leftover treetops and branches generated from commercial harvest operations. This paper adopts the base case logistics developed by Chen

et al. (2017) for harvest slash residues, representing an average scenario for the PNW region under consideration [39]. The harvest slash residues from Douglas-fir (*Pseudotsuga menziesii*), Western hemlock (*Tsuga heterophylla*), and Ponderosa pine (*Pinus ponderosa*) species, predominantly grown in the PNW, were used in this study.

Forest residues had an initial on-ground moisture content of 40% and were contaminated with soil and dirt. These residues were collected and loaded into bin trucks using an excavator loader to transport them to a centralized landing location. At the centralized landing site, the residues were ground and processed into chips that were further loaded using an excavator loader and transported to the bioenergy facility using a chip van. The total distance from the landing site to the pellet facility was assumed to be 80 km (160 km roundtrip) traveling on a road combination of 85% highways and 15% gravel road.

The harvested logs were cut and processed to lumber in sawmills, generating large amounts of sawmill residues in different forms. The sawmill residues can be fine dust called sawdust or have irregular wood pieces like branches called hog fuel. This study uses the sawdust and hog fuel logistics LCIs developed by Milota (2015), which consists of three systems – resource extraction, transportation, and production [40]. The extraction model was designed based on the WA government's sustainable harvesting rules. Productivity data developed by Oneil and Puettman (2017) for different logging equipment and equipment configurations were used to create the extraction model specific to the

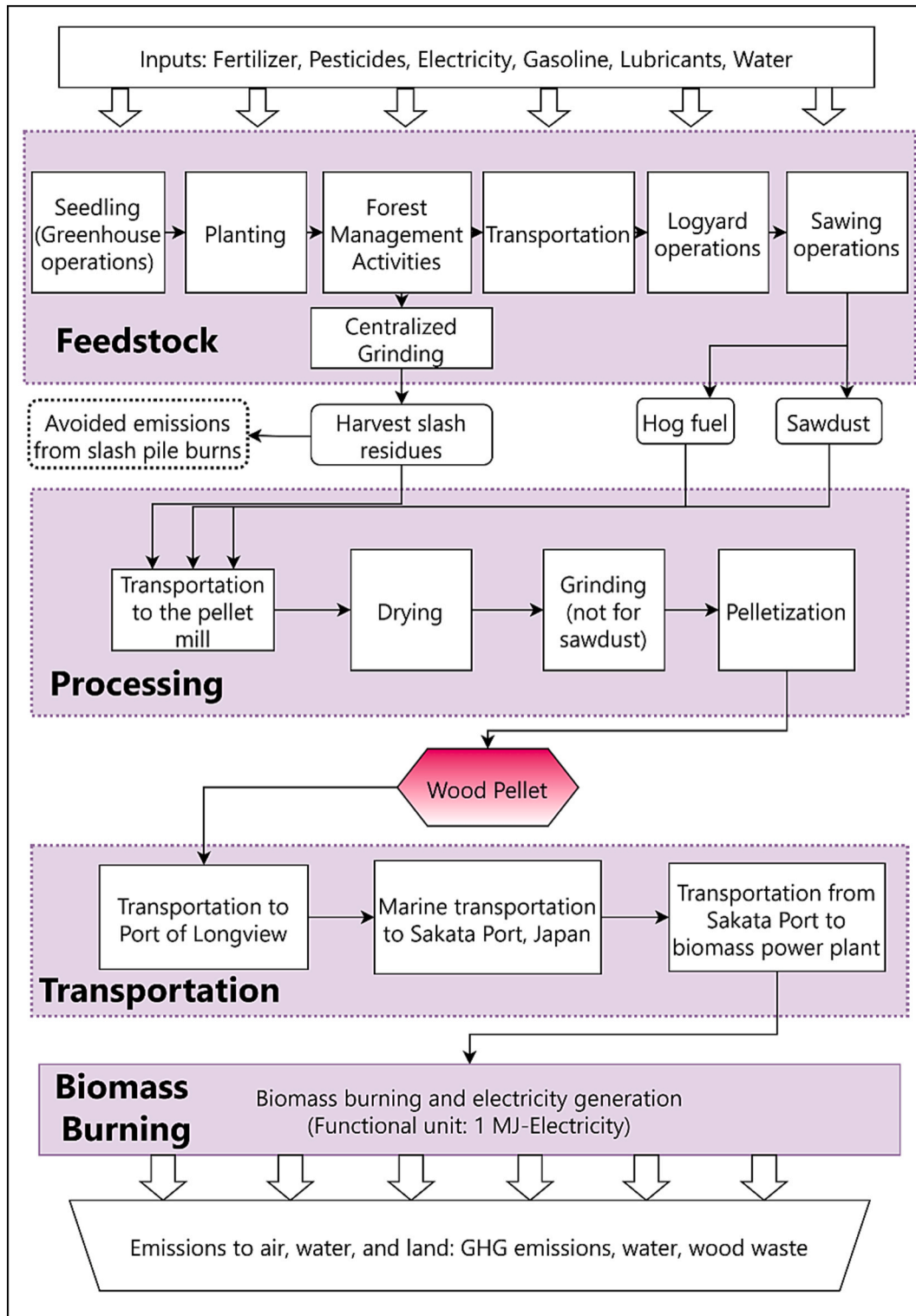


Fig. 2. System boundary of the residual biomass pellets' cradle-to-grave LCA. The supply chain was divided into four categories: feedstock, process, transportation, and biomass burning. The feedstock harvest slash and sawmill residues (hog fuel and sawdust) have different feedstock pathways, as shown in the feedstock box.

**Table 1**  
Quantity of fuel and lubricant consumed for harvesting operations and crew transport.

	Harvesting operations	Crew transport
Fuel consumption (L/m <sup>3</sup> )	3.062	0.210
Lubricant consumption (L/m <sup>3</sup> )	0.055	0.0016

PNW [41]. Table 1 provides fuel and lubricant consumption for the overall harvest operations and crew transport. The weighted average for all harvest operations was used.

*The avoided impact from slash pile burns*

Leaving harvest slash residues on the forest floor is a potential fire

hazard that can fuel wildfires. Since there is no market for these residues, and as part of the forest treatment activities, these residues are typically piled and burned in Washington and Oregon. Studies show that burning woody biomass in forests through wildfires or prescribed burns is a significant source of emissions in the western US [7,8]. Utilizing these otherwise burned harvest slash residues for pellet production avoids the environmental impact associated with open burning. Hence, the avoided slash burn emission profile was added as a credit to the harvest slash feedstock module. The slash-pile burn LCI developed by the National Energy Technology Laboratory [42] was used to develop this avoided-impact burn module.

### Process

Wood pellets are produced by drying, grinding, and pelletizing the feedstock. This study uses the mass and energy balances developed by Kumar et al. [43]. Wood pellets produced from sawdust do not require the grinding step due to the homogenous and fine structure of the sawdust. The methods assume an overall dry weight loss of 0.1% and a steady reduction of moisture content (MC) from an initial 40% (feedstock) to 5% (pellets). Therefore, to produce one metric ton of wood pellets (dry weight basis), 1684 kg of green (40% MC) feedstock is required. The details of each of these steps are provided below.

### Drying

The initial drying step is common to all feedstocks. For a 1000 kg pellet-producing batch, 1668 kg of green feedstock (40% MC) is required. The drying process reduces the moisture content of the feedstock from 40% to 15%. Following the assumption reported by Kumar et al. [43], an energy requirement of 3.4 MJ per kg of water removed during drying was adopted in this study. Therefore, to reduce the MC of 1668 kg of feedstock from 40% to 15%, 1668 MJ of energy was required, and these energy requirements were met by burning wood fuel in an onsite boiler combustion. This amounted to burning 158 kg of green (40–50% MC) wood chips to generate heat for the dryer.

### Grinding

Grinding is the next step after drying, and the grinder requires 67 MJ of electricity for grinding every ton of dried feedstock. Since sawdust is homogeneous and refined, the pellets made from sawdust do not undergo grinding. The grinding stage typically does not emit any gases besides wood dust and water (released as moisture).

### Pelletization

The pelletization process modeled by Kumar et al. includes pelletizing, cooling, and screening pellets [43]. The electricity required for each stage varies based on its unique requirements. The electricity required to pelletize was the highest at 137 MJ for every ton of ground feedstock. It takes 22 MJ and 101 MJ of electricity to cool and screen every ton of pellets. Like grinding, pelletization does not emit gases besides wood dust and water (released as moisture).

### Transportation

The pellets are transported from the pellet facilities located in Longview, WA, to the Port of Longview, WA, covering 2.75 km. The pellets were modeled to be shipped in a Handymax vessel with a 40,000 Dead Weight Tonnage (DWT) (weight carried by the ship without including the ship's weight) capacity to reach Japan, as this is the industry standard [44]. Traveling at 14 knots/hr, the ship would cover 7485 km and take approximately 12 days to reach the Sakata Port in Japan.

The pellets are delivered to the power plant via truck traveling 5.4 km in Japan. The mass-distance parameter (tkm) of the truck and transoceanic freight LCIs from the US LCI database was modified to suit the needs of this study. Due to the unavailability of road transportation LCIs specific to Japan, the US truck LCI, designed based on the US input

parameters, was used to develop truck transportation.

### Biomass burning for electricity generation

The “electricity from pellets” LCI module in the U. LCI database was tailored to this study’s requirements. This LCI module models pellet combustion in a European power plant with a 90% system efficiency (the power plant’s productivity) and 23% electricity efficiency (total output power to input power ratio). However, the weighted average electricity efficiency for coal power generation globally is 35% [45]. Since biomass can be co-fired in coal power plants, this study assumes an electricity efficiency of 35%. Therefore, the “electricity from pellets” process from the US LCI was modeled for a 35% electricity-efficient system, keeping the system efficiency at 90%.

We calculated the environmental impact of generating 1 MJ of electricity by burning pellets in this modified system. Furthermore, under the biogenic carbon assumption, we did not account for the CO<sub>2</sub> emissions associated with burning pellets in this module, as these emissions were sequestered during the growth phase of the trees.

Table 2 provides the low heating value of different pellets produced from different feedstock. Considering the system that burns pellets to generate electricity is 90% efficient, and the conversion efficiency is 35%, the electricity generated by each pellet will be 31.5% of its low heating value.

### Coal supply chain and import to Japan

A cradle-to-grave LCA of coal includes the entire coal supply chain, including mining, transportation, and electricity generation. For mining and burning, we used LCIs from the US LCI database. Separate LCIs were made for shipping from Australia, Indonesia, and the US to Japan. We calculated a weighted average based on the quantity of coal imported to Japan from Australia (74%), Indonesia (20%), and the US (6%) [46]. Australia and Indonesia are the top two coal exporters to Japan. The US is fourth (Fig. 3). However, it is included as a comparison to the pellet supply chain.

### Pellet quality analysis

The PNW residual wood pellets, produced using the stated process, were tested in a laboratory at Washington State University to ensure their quality. The raw feedstocks for the pellets were collected from local sawmills and made into pellets at the lab. This lab-scale pellet production process includes operations used in the commercial process, such as drying the feedstock using a rotary drum dryer, grinding by shredding the raw feedstock followed by hammer milling using a 3.2 mm screen to achieve a uniform particle size, and pelletizing using a ring die pelletizer. However, the efficiency and scale of the lab-scale equipment are lower compared to commercial-scale operations.

The quality of these pellets was tested, and the measured quality parameters were compared to the existing ISO 17225 quality standards [47]. A thermogravimetric analysis protocol [48] was employed to determine the moisture content (MC%) and ash content (Ash%) of the three types of residual pellets. The ultimate analysis was conducted using a TruSpec CHN and S module to measure nitrogen (N%) and sulfur (S%) content. The pellets' high and low heating values were determined

**Table 2**  
Low heating value and amount of electricity generated by burning 1 kg of pellet.

Pellets	Low Heating Value (LHV) (MJ-energy/kg pellet)	Electricity generated (MJ-electricity/kg pellet)
Harvest	20.9	6.58
Slash		
Hog fuel	20.02	6.31
Sawdust	20.34	6.41

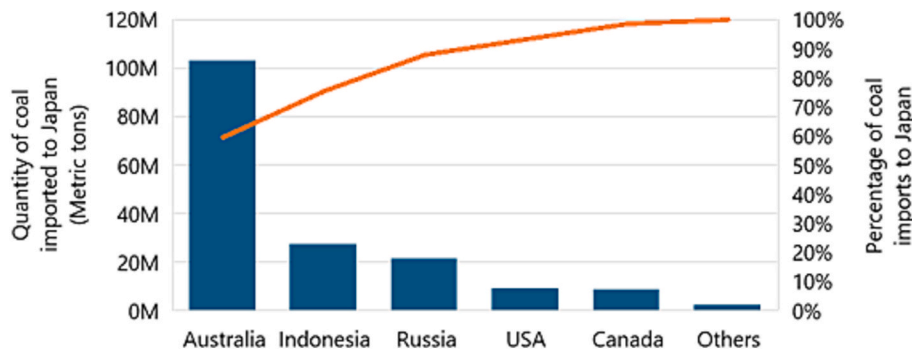


Fig. 3. Annual quantity and percentage of coal imported by Japan.

in MJ/kg units using a Parr 6100 bomb calorimeter. Additionally, the fine content and durability were evaluated following the standard specification for residential/commercial densified fuel by the Pellet Fuel Institute (PFI).

**Results**

*Pellet quality*

The results of the pellet quality test indicated that the pellets made from harvest slash and hog fuel had a higher quality compared to sawdust pellets, meeting or exceeding the ISO standards for six out of seven criteria (Table 3). Please note that we did not consider the pellet durability index, one of the ISO pellet standards criteria, in this paper, as that metric primarily depends on the equipment quality and the binders used, whereas this paper focuses on the feedstock type. The pellets made out of sawdust had a higher fine content of over 76% compared to the ISO standard, which could be because sawdust itself is a fine wood particle. Such high fine content can influence the emission profile of the pellets, particularly releasing more CO emissions [49].

*Coal vs. pellets*

Table 4 shows the results of the cradle-to-grave comparative LCA of producing 1 MJ of electricity from wood pellets and coal. Across the impact categories, pellets generated lower ozone depletion, global warming potential, smog, respiratory effects, and acidification. Pellet’s ecotoxicity value was higher than that of coal, and the contribution analysis revealed that 75% of pellet’s ecotoxicity was contributed by pellet combustion for electricity generation. Similarly, carcinogenicity was higher for pellets compared to coal. However, repurposing the slash residues for pellet production instead of burning reduced around 48% of the carcinogenicity load of the pellets.

Fig. 4 shows that replacing coal with pellets for electricity generation reduces global warming potential (Fig. A1 in Appendix) by 90% on

**Table 3**  
Pellet quality analysis vs ISO standards.

Tested for	ISO Standards	Pellets		
		Harvest Slash	Hog fuel	Sawdust
Fine content (%)	< 4	2.785	2.35	11.76**
Moisture Content (%)	< 10	5.517	7.5	6.98
Ash (%)	< 4	0.687	3.14	0.52
Nitrogen (%)	< 0.3	0.16	0.3	0.13
Sulfur (%)	< 0.05	<0.01	<0.01	<0.01
High Heating Value (MJ/kg)	> 18.6	21.42	21.43	21.84
Low Heating Value (MJ/kg)	> 16.5	19.81	20.02	20.34

\*\* Quality standard not met.

average, with the highest emission reduction coming from using harvest slash, which would otherwise be burned, as feedstock.

*Contribution analysis*

The LCA contribution analysis provides insights into the emissions generated at each point of the supply chain. Fig. 4 displays the results of the contribution analysis for pellets across eight impact categories. The supply chain is divided into distinct stages, including i) feedstock, which includes emissions from feedstock production and procurement; ii) process, which accounts for emissions generated during the pellet production process; iii) transportation, which encompasses the transport of pellets from the mill to the ports, pellet shipping, and transport from the port to the power plant; and iv) biomass burning, which represents emissions associated with burning the pellets for electricity generation.

Among the four stages, transportation and biomass burning are the predominant contributors to emissions in most impact categories for pellets. For coal, burning is the most significant contributor to all the categories. Conversely, the process module exhibits the lowest contribution to all impact categories. The transportation module accounts for the pellets’ largest share of global warming emissions, representing approximately 45%. Although burning pellets contributes less to global warming due to the biogenic CO<sub>2</sub> assumption, its contribution towards impact categories, carcinogenic, non-carcinogenic, respiratory effects, and ecotoxicity is significant. However, the contribution of biomass burning was lower compared to coal burning on most impact categories, particularly smog, respiratory effects, and acidification. The categories for which the contribution of biomass burning was greater than that of coal burning were ecotoxicity and carcinogenicity. There were no cases where the feedstock module was the largest contributor to the pellet’s overall emissions.

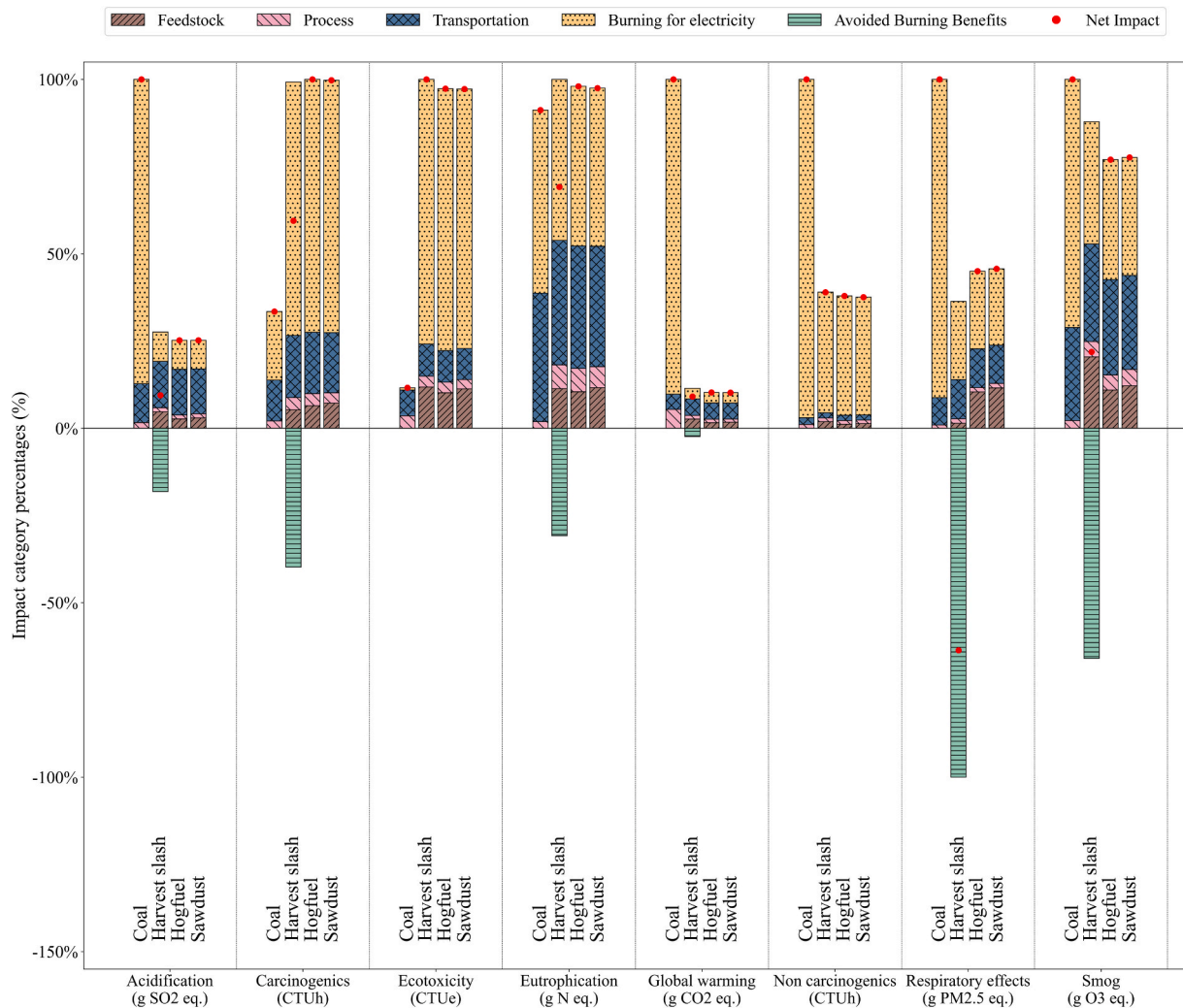
*Avoided burn benefits and local impacts*

Most unutilized harvest slash residues in Washington and Oregon are burned in prescribed fires due to the mandatory slash burn requirements in fire-prone regions. The slash that gets left behind on the forest floors or at harvest landings either decays or gets consumed by natural forest fires. This research targets only the slash that would have been burned, via prescribed burns, in the absence of an economically viable alternative. Using these resources for pellet production avoids the emissions from open prescribed burning. Fig. 4 shows the GWP of producing 1 MJ of electricity from harvest slash, including the avoided burning emissions.

Allocating the avoided burn benefits reduces the environmental impact of the harvest slash module on eight impact categories (Fig. 5). Since prescribed burning releases more emissions under five impact categories than pellet production, such as eutrophication, smog, acidification, carcinogenic effects, and respiratory effects, accounting for these avoided burn benefits resulted in a reduction of overall emission.

**Table 4**  
Emissions produced by coal vs. pellets per MJ of electricity generated.

Fuel	Feedstock	Acidification	Carcinogenic	Ecotoxicity	Eutrophication	Global warming	Non-carcinogenic	Respiratory effects	Smog
		g SO <sub>2</sub> eq	CTUh	CTUe	g N eq	g CO <sub>2</sub> eq	CTUh	g PM <sub>2.5</sub> eq	g O <sub>3</sub> eq
Pellet	Harvest Slash	0.61	2.16E-09	0.17	0.06	33.42	2.22E-08	0.06	13.76
	Hog fuel	0.56	2.18E-09	0.17	0.06	30.07	2.17E-08	0.07	12.18
	Sawdust	0.56	2.18E-09	0.17	0.06	29.89	2.15E-08	0.07	12.28
Coal		2.22	7.31E-10	0.02	0.05	292.67	5.71E-08	0.16	15.82



**Fig. 4.** Comparative assessment of coal vs. pellet-based energy, by impact categories (per MJ of electricity generated) and the contribution of each life cycle stage. The highest absolute value in each category is adjusted to 100% to compare all the impact categories at the same scale, and other values are normalized accordingly.

Respiratory effect (kg PM<sub>2.5</sub> eq.) showed the most significant percentage reduction due to the difference between the high content of PM<sub>2.5</sub> emitted from open burning and the low content emitted to produce pellets using harvest slash. In contrast, the emissions released by pellet production were higher than prescribed burning for categories of non-carcinogenic, ecotoxicity, and global warming. It is important to note that we applied the biogenic carbon assumption and did not account for the CO<sub>2</sub> emitted during prescribed burning. So, we considered only the residual CO<sub>2</sub> eq. emissions associated with other components of prescribed burning, such as transporting the slash and fossil fuel required to burn the slash. Although the overall emission load was reduced, significant residual emissions were still released for three of these categories.

This analysis provided insights into the local impacts of using otherwise burnt harvest slash residues to produce pellets, assuming that

the pellet mills are closer to the prescribed burning area. Our analysis indicates that the local community will primarily benefit from clean air and water from reduced PM<sub>2.5</sub> particles, smog, acidification, eutrophication, and carcinogenic substances by producing pellets instead of burning the residues. However, global warming, ecotoxicity, and non-carcinogenic substance emissions will increase in the local community since pellet mills emit more of these emissions than prescribed burning. Understanding these trade-offs is essential to making informed decisions on establishing a new industry.

*Sensitivity analysis*

A sensitivity analysis was conducted, varying three key parameters for pellet production: the feedstock, the tree species of the residues, and the location of pellet mills. As previously mentioned, the three

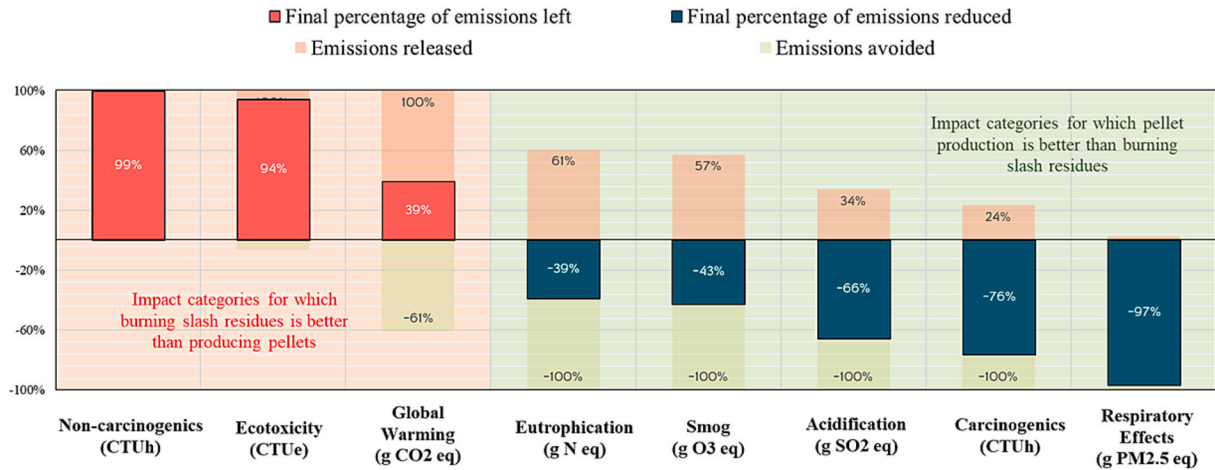


Fig. 5. Avoided emissions associated with diverting the slash piles to pellet manufacturing.

feedstocks tested were harvest slash residues, hog fuel, and sawdust. The three different tree species tested were Douglas fir (DF), Western hemlock (WH), and Ponderosa pine (PP), and the pellet mills were assumed to be located in WA and OR.

Fig. 6 provides the sensitivity analysis results for all eight impact

categories. The baseline for each parameter is the average of the other parameters, excluding the one tested. For example, to find the sensitivity of sawdust, the baseline would be the average of all scenarios for the feedstocks hog fuel and harvest slash, and the bar would represent the difference imparted by switching to sawdust. The results show that

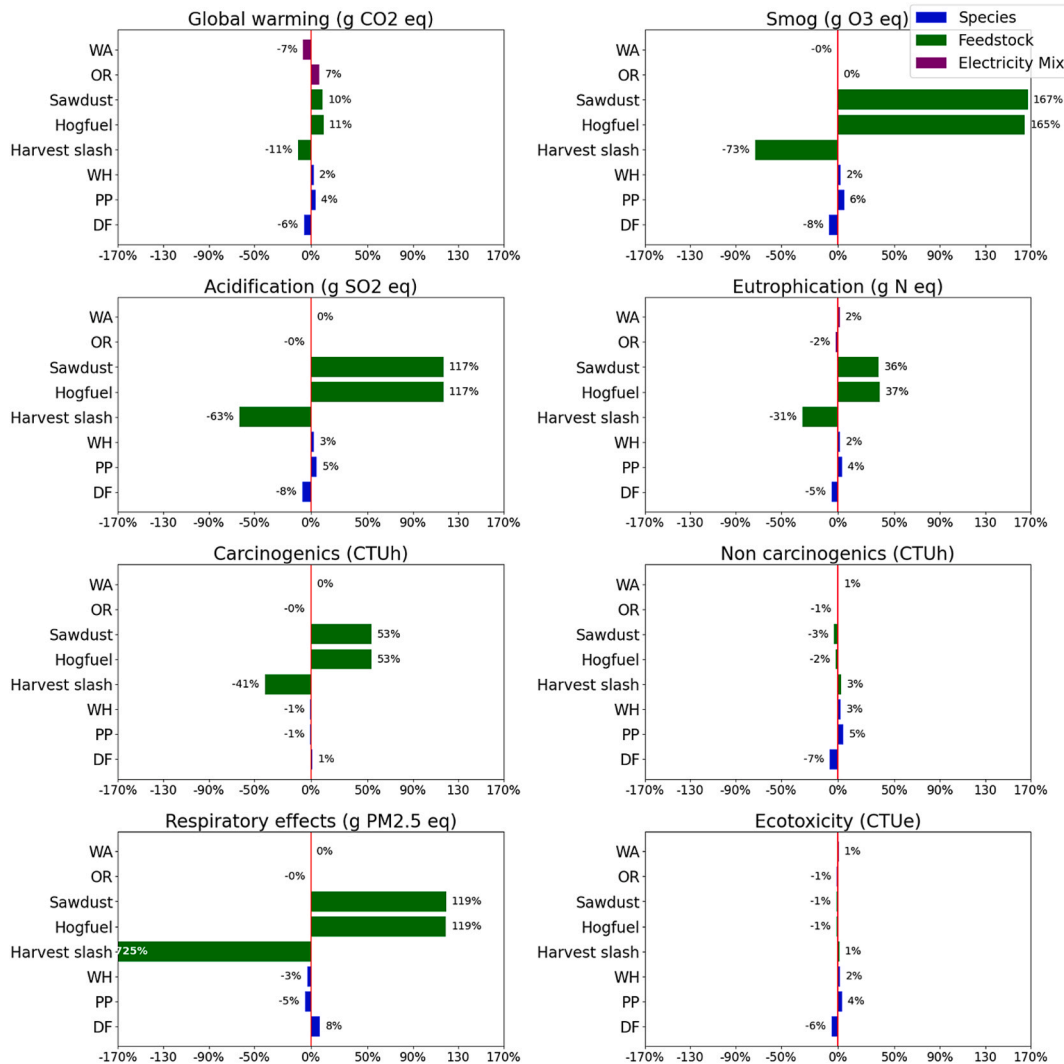


Fig. 6. Sensitivity analysis of energy produced by feedstock types and impact categories.

feedstock remains the most sensitive parameter, particularly between the sawmill and harvest slash residues. The added benefit of avoiding the burning of the harvest slash residues is an important reason for its sensitivity. We evaluated the species parameter only for the harvest slash feedstock and found that using DF slash residue produces a slight reduction in impact across all categories except respiratory effects. This agrees with the literature that found that DF burning produces more particulates than pine and hemlock. However, there is limited understanding of the species-specific emission profile for other impact categories.

Finally, the sensitivity analysis of the pellet mill location, which was influenced by the electricity used for pellet production, revealed that since WA has more clean energy in its electricity mix, locating the pellet mills in WA had a lower GWP compared to OR.

## Discussion

Wood pellets and their potential as a renewable energy source have been controversial. Several groups, including governments and the wood industry, promote pellets as a climate-friendly alternative to fossil fuels, especially coal [50]. Others view pellets and bioenergy as a potential “transition” fuel that could help when solar and wind are not scalable [51]. Several environmental groups argue that pellets are worse for the climate and could be more polluting than fossil fuels. Their main concerns include the assumption that whole trees are harvested for pellet production, leading to deforestation; the time lag between biomass combustion and forest regrowth, which creates a carbon debt; and the energy-intensive processes required for pellet production and long-distance shipping [16]. These debates and assumptions around pellets warrant a deeper understanding of this renewable energy source.

In this study, we started from the fundamental assumption that not all wood pellets and their supply chains are the same. While harvesting fully grown trees for wood pellets has been shown to have negative environmental impacts [52], pellets produced from forest residues have been shown to be better for the environment than fossil fuels. Particularly if the fate of the residues is set to be burnt or disposed of, repurposing them to higher-value products is beneficial. Nevertheless, even with residual pellets, the choice of residues between harvest and sawmill residues (sawdust and hog fuel), the species of the residues, the location from which the residues are procured, and the location of the pellet mills elicit a difference in their environmental footprint.

This study compared the environmental impact of pellets produced from three different types of forest residues in the Pacific Northwest against coal, with both fuels burned for electricity generation in Japan. The results of this study show that substituting coal with PNW residual pellets reduced the GWP by an average of 90%. This estimate assumes biogenic carbon neutrality—that CO<sub>2</sub> from biomass combustion is offset by subsequent regrowth. While critics note that neutrality can overlook the time lag between immediate emissions and delayed sequestration (i. e., carbon debt), in this study, the feedstock consists of forest residues (harvest slash and sawmill byproducts) that would otherwise be openly burned or disposed of. Diverting these short-lived residues to energy displaces coal without inducing additional harvesting or long-term reductions in forest carbon stocks, making the neutrality assumption reasonable for this pathway. The feedstock was the most sensitive parameter influencing the baseline impact by more than ±30% across five of the eight categories, with the highest impact reduction occurring when using the harvest slash residues due to the additional benefits of diverting these residues from burning to pellet production. Furthermore, using the harvest slash residues for pellet production would reduce the local air pollution by significantly reducing the smog and PM<sub>2.5</sub> particles.

Finally, a contribution analysis revealed that the intercontinental shipping contributed most to the overall GWP footprint of the pellets, but for coal, the burning of fuel contributed the most. So, reducing the emissions associated with shipping will consequently reduce the GWP of

pellets. In this study, we modeled the pellets to be shipped in a 40000-dwt ship, as those are the typical fleet of ships seen in Longview. Choosing a vessel size bigger than 40,000 dwt to transport pellets could further reduce its overall environmental impact [32]. Furthermore, recent policy initiatives by the International Maritime Organization have established a framework for member countries to decarbonize the shipping sector. These measures are expected to lower shipping emissions, thereby reducing the embodied carbon of transported commodities such as pellets [53]. Alternatively, if the pellets are used domestically, the additional pollution burden of long distances, which will be much higher than local transport, could be alleviated.

In this study, we relied on literature-based data representing typical pellet operations in the U.S. PNW. The accuracy of calculations could be improved by incorporating actual operational data from commercial pellet mills. At the time of this study, the PNW did not have any commercial-scale pellet mills; however, two new facilities have recently received approval and are expected to begin operations in the short term [54]. Future work could enhance model accuracy and reduce uncertainty by incorporating primary data from these commercial operations.

Overall, our study found that starting a residual-based pellet trade between Japan and the Pacific Northwest (PNW) would benefit both regions compared to the current situation. For Japan, the main advantages are lower fossil fuel emissions and a more diverse energy supply. Opening a new market for renewable energy could also boost competition and help lower pellet prices, easing some of the financial strain from the Feed-in Tariff program. Although this study focuses on Japan, the model could be adapted to other export destinations, such as South Korea, where supportive policies and demand for pellet imports create favorable conditions for implementation. Developing an export-oriented wood pellet industry in the PNW would improve local air quality by reducing PM<sub>2.5</sub>, smog, eutrophication, acidification, and carcinogenic-related pollution from slash burning. However, our study indicates that global warming potential, ecotoxicity, and non-carcinogenic emissions could increase with pellet production. Beyond environmental impacts, new pellet industries could deliver significant socio-economic benefits, such as job creation, increased tax revenue, and additional income streams for landowners to support sustainable forest management. At the same time, challenges like noise, infrastructure demands, and community impacts remain. These broader trade-offs are complex, context-specific, and beyond the scope of this study, but they should be carefully evaluated when considering future development prospects.

## Conclusion

In this study, we examined the environmental impact of using residual woody biomass to produce pellets in the US Pacific Northwest for electricity generation in Japan. We compared the emissions from pellets and coal across various environmental categories using a cradle-to-grave life cycle assessment. Our results show that replacing coal with PNW residual pellets has significant ecological benefits across four out of eight impact categories tested, including a 90% reduction in GWP. Additionally, using residual woody biomass that would otherwise be burned in prescribed fires offers notable local environmental advantages, such as better air quality and reduced smog and PM<sub>2.5</sub>. A contribution analysis revealed that the environmental impact of pellets was largely due to transportation and biomass burning. Lastly, a sensitivity analysis, testing various parameters of feedstock, electricity mix, and tree species, showed that the feedstock was the most sensitive parameter, mainly due to the additional benefits from avoiding slash pile burn.

## CRedit authorship contribution statement

**Hemalatha Velappan:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation. **Francesca Pierobon:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **Indroneil Ganguly:** Writing – review & editing, Supervision,

Methodology, Funding acquisition, Conceptualization.

### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Indroneil Ganguly reports financial support was provided by USDA Forest Service Pacific Northwest Research Station. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### Appendix

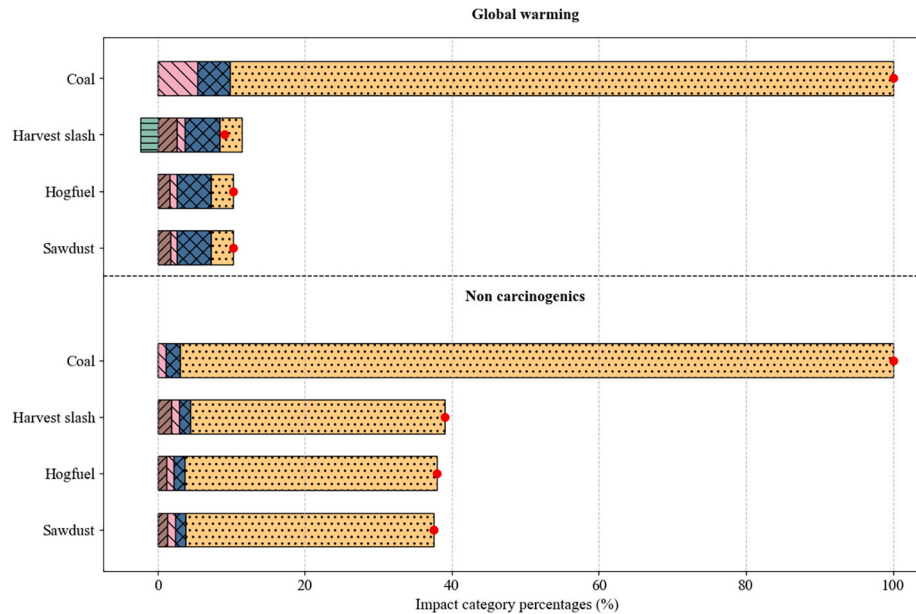


Fig. A1. Larger version of the impact category percentages with contribution percentages for global warming and non-carcinogenic. Substituting coal with pellets results in an average 90% GWP reduction.

### Data availability

Data will be made available on request.

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