Journal of Sustainable Development; Vol. 16, No. 2; 2023
ISSN 1913-9063 E-ISSN 1913-9071
Published by Canadian Center of Science and Education

Life Cycle Assessment of Power Generation from Imported Woody Biomass Fuels

Noriko Nishihara[1], Lisa Ito[1], Leticia dos Muchangos[2] & Akihiro Tokai[1]

[1] Laboratory of Environmental Management, Division of Sustainable Energy and Environmental Engineering, Graduate School of Engineering, Osaka University, Osaka, Japan

[2] The University of Tokyo Institute for Future Initiatives, Tokyo, Japan

Correspondence: Nishihara Noriko, Laboratory of Environmental Management, Division of Sustainable Energy and Environmental Engineering, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan. E-mail: nishihara@em.see.eng.osaka-u.ac.jp

Received: January 4, 2023 Accepted: February 9, 2023 Online Published: February 13, 2023

doi:10.5539/jsd.v16n2p50 URL: https://doi.org/10.5539/jsd.v16n2p50

Abstract

With the promotion of woody biomass power generation in Japan, wood fuel imports have increased yearly. However, the environmental impact of the transportation process is expected to increase compared to procuring the fuel domestically. Therefore, this study aimed to evaluate the environmental impact of biomass power generation using imported woody fuel. Human health, ecosystem, and global warming were evaluated using the life cycle assessment (LCA) method under four scenarios: three scenarios for importing woody fuel and one scenario for procuring woody fuel domestically. The results reveal that replacing heavy oil with liquefied natural gas (LNG) or ammonia as ship fuel at the time of importation could reduce the environmental impact to the same level or up to 86% compared to the case wherein wood fuel is procured domestically. Thus, using next-generation vessels to import wood fuel and generate biomass power effectively reduces environmental impact. Furthermore, the use of wood fuel—a renewable energy source whose generation can be adjusted—should be promoted toward achieving carbon neutrality.

Keywords: environmental impact, life cycle assessment, woody biomass, renewable energy

1. Introduction

The introduction of power generation from renewable energy sources is being promoted to achieve carbon neutrality by 2050. While the ratio of renewable energy in the power source composition was 19.8% in 2020, Japan’s Sixth Basic Energy Plan set an ambitious target of 36%–38% in 2030.

Among the various kinds of renewable energy sources, woody biomass power generation is considered carbon neutral—even if it is used as fuel and emits carbon dioxide—because forests absorb carbon dioxide through photosynthesis. However, unlike solar, wind, and other natural energy sources, woody biomass power generation requires the procurement of fuel. Thus, it requires environmental assessment throughout its life cycle, including the environmental impacts of logging the forests and transporting the fuel by truck.

According to Japan’s Forestry Agency (2021), in recent years, Japan’s imports of woody fuel have been increasing yearly to procure large quantities of fuel stably in line with the increase in biomass power generation. Imports from Vietnam, the number one importer, have increased 12.5-fold in the five years from 2017 to 2021, and are expected to continue to increase. Therefore, the environmental impact of the fuel transportation process is expected to increase compared to the use of domestic wood resources. In a previous study, Hitoe and Hattori (2011) conducted a life cycle assessment (LCA) of a scenario wherein sawmill residues are used as fuel for woody biomass power generation and evaluated the impact on global warming (Hitoe & Hattori, 2011). Komata et al, (2017) compared the environmental performance of wood biomass-based power generation and heat and power supply systems with fossil fuel-based power generation as well as heat and power supply systms, and then verified their superiority by comparing external costs (Komata, Ishikawa & Hondo, 2017). Heller et al, (2004) compared willow-fueled and coal-fired power generation and assessed their greenhouse and air pollution impacts (Heller, Keoleian, Mann & Volk, 2004). Röder et al, (2015) generated electricity by burning wood pellets from forest residues and examined the uncertainties associated with greenhouse gas (GHG) emissions, which are defined as the gas that works to trap heat emitted from the sun and warm the earth's surface (Röder, Whittaker & Thornley, 2015). Pieratti et al, (2020) performed an LCA on the use of forest and sawmill residues in a district heating plant and evaluated GHG emissions (Pieratti et al, 2020). However, few of the previous studies have conducted LCAs under the condition that wood fuel is sourced from abroad. In addition, few of them mention anything other than GHG emissions in their evaluation indicators. As imports of wood fuel increase, environmental assessment from a life cycle perspective becomes more important.

Based on the above, the objective of the present study is to conduct an environmental impact assessment of biomass power generation using imported woody fuels. In doing so, we will not only quantitatively evaluate the GHG reduction effect, but also compare three impact items, namely, global warming, human health, and ecosystems, in order to calculate the environmental impacts that occur in certain stages of the life cycle process and identify the appropriate measures that should be taken. The results of this study can provide guidelines for the spread of wood biomass power generation, in line with Japan's policy toward carbon neutrality, as well as inform proposals of future measures that can be used as a reference in countries similar to Japan.

2. Methods

2.1 LCA

This study used the LCA method for environmental impact assessment, which is a method to calculate and evaluate the environmental impacts of a product or service throughout its life cycle—from the procurement of materials to the manufacture and use of the final product. For the LCA calculations in this study, we used the software SimaPro, developed by the Dutch environmental consultant PReConsultants. We also used the Ecoinvent 3 inventory database and IDEA, a Japanese inventory database. The functional unit was defined as the environmental impact per kWh electricity generated. The system boundary was assumed to be from wood procurement to power generation.

2.2 Impact assessment

Various countries have developed impact assessment methods, and there are differences in how the methodologies are constructed, including the impact items to be calculated and the calculation methods. In this study, we used IMPACT 2002+ (Jolliet et al., 2003) developed in Switzerland, which consists of 14 midpoints and 4 damage areas. It can assess human health, ecosystem quality, and climate change, which correspond to the objectives of the present study.

2.3 Damage category

The calculation of the evaluation indicators used in this study is described below. The units for the three indicators are listed in Table 1.

Table 1. Unit of damage category

Category	Unit
Human health	DALY (Disability Adjusted Life Years)
Ecosystem quality	PDF・m^2・yr (Potentially disappeared fraction of species over a certain amount of m^2 during a certain amount of year)
Climate change	kg-CO_2 eq

To assess human health risk, we used the indicator DALY, which is calculated by adding the number of years lost due to premature death and the number of years lost due to disability; according to WHO (2020), it is expressed in Equation (1).

$$DALY = YLL + YLD \tag{1}$$
$$YLL = N \times L$$
$$YLD = I \times DW \times C$$

where YLL = the years of life lost, YLD = the years lost due to disability, N = the number of deaths, L = a standard loss function specifying years of life lost for death, I = a number of incident cases, DW = disability weight, and C = average duration of the case until remission or death.

According to Ii (2008), the indicator PDF is used to assess ecosystems, representing the lost species percentage, and is expressed in Equation (2).

$$PDF = \frac{S_{ref} - S_{use}}{S_{ref}}, \tag{2}$$

where S_{ref}= the number of species in the reference state, and S_{use}= the number of species after modification or in occupation.

Climate change was evaluated based on GHG emissions. The global warming potential (GWP) was used to convert GHG emissions into CO_2 emissions in the atmosphere. The calculated coefficients for DALY and PDF in IMPACT2002+ are shown in Table 2.

Table 2. IMPACT2002+ midpoints and damage area units

Midpoint category	Factor	Unit
Carcinogens + Non-carcinogens	2.80×10^{-6}	DALY / kg_{eq} C_2H_3Cl into air
Respiratory (inorganics)	7.00×10^{-4}	DALY / kg_{eq} $PM_{2.5}$ into air
Ionizing radiations	2.10×10^{-10}	DALY / Bq_{eq} C-14 into air
Ozone layer depletion	1.05×10^{-3}	DALY / kg_{eq} CFC-11 into air
Respiratory organics	2.13×10^{-6}	DALY / kg_{eq} C_2H_4 into air
Aquatic ecotoxicity	5.02×10^{-5}	PDF・m^2・yr / kg_{eq} TEG into water
Terrestrial ecotoxicity	7.91×10^{-3}	PDF・m^2・yr / kg_{eq} TEG into water
Terrestrial acidification/ nitrification	1.04×10^{0}	PDF・m^2・yr / kg_{eq} SO_2 into air
Land occupation	1.09×10^{0}	PDF・m^2・yr / m^2 eq organic arable land year

2.4 Scenario

This study created four scenarios, and LCA was performed, focusing on wood fuel procurement and marine fuel. The overall flow is shown in Figure 1.

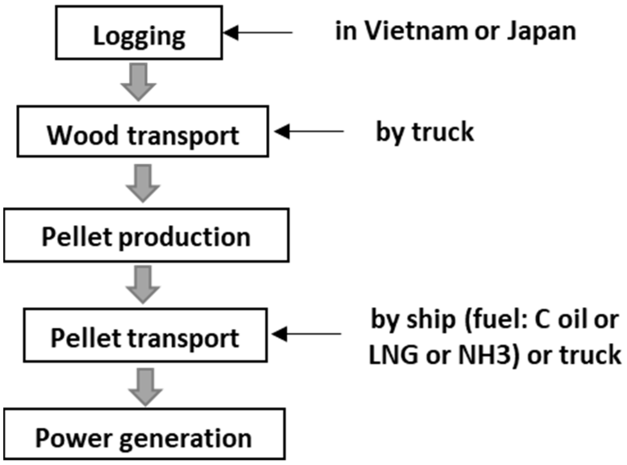

Figure 1. Flow of life cycle

Scenario 1: Wood fuel is imported from Vietnam. The fuel used for the transport vessel is C fuel oil, which is commonly used as marine fuel.

Scenario 2: Wood fuel is produced domestically. In the transportation process, we compare the case wherein fuel is imported with the case wherein fuel is procured domestically.

Scenario 3-1: Wood fuel is imported from Vietnam, and natural gas is used for marine fuel. In order to achieve decarbonization, the shipping industry plans to introduce a new fuel to replace C fuel oil. Depending on the size of the ship, small ships are segregated into electric, medium-sized ships into hydrogen fuel (fuel cell) and large ships into ammonia fuel (direct combustion). In addition, natural gas is planned to be used during the transitional period until hydrogen- and ammonia-fueled vessels are put into service.

Scenario 3-2: Wood fuel is imported from Vietnam and ammonia is used as fuel for ships. Given that vessels for import are classified as large, it is assumed that ammonia is substituted for marine fuel. Transportation from Vietnam to Japan is set to be from Ho Chi Minh City to Tokyo, the respective capitals of each country. The characteristics of the four scenarios are shown in Table 3.

Table 3. Characteristics of each scenario

Process		Scenario 1	Scenario 2	Scenario 3-1	Scenario 3-2
Logging	location	Vietnam	Japan	Vietnam	Vietnam
Pellet transport	means	ship	truck	ship	ship
	fuel	C oil	diesel oil	LNG	NH3

2.5 Background Data

Background data are inventory data that cannot be manipulated by the LCA performer. In this study, the calorific value and consumption of fuels are obtained from existing publicly available data from the government and other sources. Details are given in the next and in subsequent sections.

2.5.1 Logging Process

In this study, assuming that wood pellets, whose importation is increasing year by year, are used as fuel for power generation, the weight of logs to be harvested is determined from the weight of pellets required to generate 1 kWh of electricity. Wood pellets are individual fuel particles made of dried logs, bark, and other wood materials that are compressed and formed into cylindrical shapes 6–8 mm in diameter and 5–40 mm in length. The weight of logs to be cut to generate 1 kWh of electricity is calculated using Equation (3) given by:

$$W_{log} = W_{pellet} \times \frac{(100 - M_{pellet})}{100} \div M_{log} \div C, \tag{3}$$

where W_{wood} = weight of logs [kg/kWh], W_{pellet}= weight of pellets [kg/kWh], M_{pellet}= moisture content of pellets [%], M_{wood}: = moisture content of logs [%], and C= combustion efficiency [%].

The characteristics of the pellets are determined to be 10% moisture content and 15.5 MJ/kg calorific value, based on data published by the Japan Wood Pellet Association. According to Japan Woody Bioenergy Association (2021), as the moisture content of raw wood chips that have not undergone the drying process ranges between 45% and 55%, the moisture content of the logs is taken as 50% on average. In the case of power generation, according to Tokyo University of Agriculture (2015), the combustion efficiency of wood fuel is said to be 10%–30%. Given that this study assumes large-scale power generation, the combustion efficiency is set to 30%, which is at the upper end of the range of this existing data (cited above).

2.5.2 Transport Process

The distance to transport logs from the forest to the wood fuel plant is set at 100 km, based on data published by Japan's Ministry of Internal Affairs and Communications. A truck with a 10-ton payload capacity is used as the means of transportation.

The distance from Vietnam to Japan for the fuel produced at the wood fuel plant is assumed to be 4,500 km, using the "Searoutes" route calculation website. The data from Ecoinvent3 are used for a 50,000 DWT transoceanic vessel, which is close to the size of the vessels used for the marine transport of pellets. The transport distance of wood fuel produced in Japan to the power plant is assumed to be 70 km, citing data published by the Japan Woody Biomass Energy Association.

2.5.3 Wood Fuel Manufacturing Process

The inventory data for wood pellet production are taken from Ecoinvent v3. However, in this study, the "wood" entry in the pellet production dataset is excluded because wood collection is calculated as a harvesting process. The inventory data table for wood pellet production are shown in Table 4.

Table 4. Inventory data for wood pellet production

Category	Product name	Quantity	Unit
Input	Water	3.0×10^{-5}	m^3
	Starch	5.0×10^{-5}	kg
	Wood Pellet Mill	4.0×10^{-10}	machine
	Display	1.6×10^{-8}	machine
	Lubricants	8.4×10^{-5}	kg
	Dust Collectors	2.0×10^{-9}	kg
	Pointing Devices	8.0×10^{-9}	kg
	Keyboards	8.0×10^{-9}	kg
	Computers	8.0×10^{-9}	kg
	Wood*	1.0×10^{0}	kg
	Packing film	2.3×10^{-3}	kg
	Heat	2.8×10^{-1}	MJ
	Electric Power	9.1×10^{-2}	kWh
Output	Water	3.0×10^{-5}	m^3
	Pellets	1.0×10^{0}	kg

* It was excluded from the pellet production process in this study.

2.5.4 Generation Process

The inventory database for woody biomass power generation is available from IDEA, which has data on woody fuels and equipment required per MJ of power generation and associated emissions. However, given that combustion efficiency is not considered, they are converted to the weight of woody fuel set in this study. The inventory data generated per MJ of woody biomass generated are shown in Table 5.

Table 5. Inventory data for wood biomass power generation

Category	Product name	Quantity	Unit
Input	Wood chips	5.86×10^{-2}	kg
	Construction of electric power facilities	4.48×10^{-13}	facility
Output	CH_4	2.90×10^{-5}	kg
	CO_2	1.09×10^{-1}	kg
	N_2O	3.80×10^{-6}	kg
	Energy for power generation	1.00×10^{0}	MJ

2.6 Next Generation Ships

2.6.1 Fuel Consumption and Emissions

The inventory data for the next-generation vessels are created based on the default data (Table 6) for transport by ocean-crossing vessels in SimaPro. Changes are made to the fuel used and the corresponding emissions. In the default data, heavy oil C is used as fuel for ocean crossing vessels. For the next-generation ships, Fuel Oil C is replaced with liquefied natural gas (LNG) and ammonia. The fuel substitution also changes the emissions from fuel combustion. The emissions are taken from IDEA and IMO regulations, while the consumption rates of LNG and ammonia are calculated from the calorific value of each fuel (Table 7).

Table 6. Inventory data for transoceanic vessels on board SimaPro

Items	Value	Unit
Ship Maintenance	1.54×10^{-5}	time/tkm
Cargo Vessels	1.54×10^{-5}	ship/tkm
Port Facilities	1.2×10^{-14}	place/tkm
C heavy oil	2.49×10^{-3}	Kg/tkm

Table 7. Heat value of each fuel

Items	Value	Unit
C heavy oil	43.5	MJ/kg
LNG	54.7	MJ/kg
Ammonia	22.4	MJ/kg

The consumption of LNG or ammonia is determined using Equation (4) as follows: For heat generation, we cited data published by Japan's Ministry of Economy, Trade and Industry (2020) and New Energy and Industrial Technology Development Organization (2020).

$$U_{LNG\ or\ NH_3} = U_{fuel\ oil\ C} \times H_{fuel\ oil\ C} \div H_{LNG\ or\ NH_3}, \tag{4}$$

where $U_{LNG\ or\ NH_3}$ = LNG or ammonia usage [kg/tkm], $U_{fuel\ oil\ C}$= C fuel oil consumption [kg/tkm], $H_{fuel\ oil\ C}$ = calorific value of C fuel oil [MJ/kg], and $H_{LNG\ or\ NH_3}$ = calorific value of LNG or ammonia [MJ/kg].

Data on the emissions released during LNG combustion are taken from data provided in IDEA (Table 8).

Table 8. Inventory data from IDEA's LNG combustion (per 1 MJ burned)

Category	Product name	Quantity	Unit
Input	LNG	1.82×10^{-2}	kg
Output	CH_4	2.30×10^{-7}	kg
	CO_2	5.13×10^{-2}	kg
	N_2O	1.70×10^{-7}	kg
	NO_x	1.52×10^{-5}	kg
	$PM_{2.5}$	7.82×10^{-7}	kg
	Combustion energy	1.00×10^{0}	MJ

Data regarding the NO_x emissions to the atmosphere during ammonia combustion are taken from NO_x limits published by the International Maritime Organization (2016). Ammonia emits NO_x during combustion, so control technologies are currently being developed. In this study, we assumed that the IMO regulation values are met and are obtained from Equation (5), which is expressed as:

$$E_{NO_x} = U_{NH_3} \times H_{NH_3} \times R_{NO_x}, \tag{5}$$

where E_{NO_x}= NO_x emissions [kg], U_{NH_3}= ammonia usage [kg/tkm], H_{NH_3}= ammonia calorific value [kWh/kg], and R_{NO_x}= regulation value of NO_x [g/kWh]. Here, 1.96 NO_x g/kWh is used for R_{NOx}.

2.6.2 Green Ammonia

The inventory data on ammonia production in SimaPro are created assuming that they will be produced by conventional methods that consume large amounts of fossil fuels. However, the ammonia to be utilized in the future will replace green ammonia, which is made of green hydrogen. Therefore, among the inventory data on ammonia production in SimaPro, the fossil fuels consumed for hydrogen production are converted to solar and wind power generation to create the inventory data for future ammonia production.

As the amount of electricity consumed to produce green hydrogen ranges from 4.5 to 6.5 kWh/Nm3, this study takes an average of 5.5 [kWh/Nm3]. Liquid ammonia's hydrogen content (weight %) was assumed to be 17.8%.

Table 9. Inventory data for green ammonia production

Category	Product name	Quantity	Unit
Input	Chemical plant	4.0×10^{-10}	plant
	Water	1.4×10^{-1}	m3
	Solvent	3.0×10^{-5}	kg
	Nickel	3.5×10^{-4}	kg
	Wind power generation	5.4×10^{0}	kWh
	Solar power generation	5.4×10^{0}	kWh
Output	Ammonia	1.0×10^{0}	kg

3. Results

3.1 Calculation Results

The results calculated from Equations (3)–(5) are shown in Table 10.

Table 10 Calculation results

Process	Values	Unit
amount of logging	1.38×10^{0}	kg/kWh*
fuel consumption (LNG)	4.28×10^{-6}	kg/tkm**
fuel consumption (NH_3)	4.78×10^{-3}	kg/tkm**
NO_x emissions from NH_3	5.83×10^{-5}	kg/tkm**

* The mass of logs required to generate 1 kWh of electricity

** The mass of material consumed or emitted when 1 ton of material is transported 1 km.

3.2 Human Health

The impact of each process on human health is shown in Figure 1. As can be seen, Scenario 3-1 has the smallest impact of 2.22×10^{-7} DALY/kWh compared with the other four scenarios. The reason for the larger impact for ammonia vessels is that ammonia emits NO_x during combustion. Compared with DALY/kWh from coal-fired power generation, woody biomass power generation is 48%–61% smaller. Thus, replacing coal-fired power with woody biomass can lead to a reduction in health risks.

Comparing Scenarios 2 and 3, the environmental impact is the same or about 10% higher in the former. Therefore, if marine fuels are replaced by LNG and ammonia, the impact on human health will not change much, regardless of whether wood fuel is procured domestically or imported. Furthermore, when the pellet transport distance exceeds 19,300 km, the human health impact is greater than that in Scenario 2, even if LNG vessels are used. Thus, although Northern Europe and South America are large wood producers, importing wood fuel may increase human health impacts more than sourcing it domestically.

In addition, the impacts of the logging and pellet production processes on the life cycle are relatively large at 40% each. Dust from wood and $PM_{2.5}$ emitted during fuel processing are also thought to have an impact. Thus, it is necessary to establish emission regulations and other measures to protect forestry workers, pellet mill employees, and residents living near the mills.

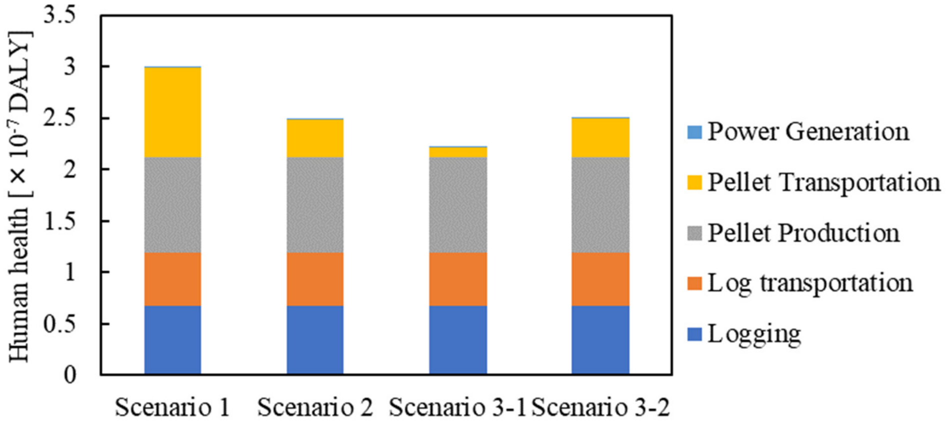

Figure 2. Human health effects from each process per 1kWh

3.3 Ecosystem Quality

The degree of impact of each process on ecosystem quality is shown in Figure 2. As can be seen, Scenario 3-1 has the smallest impact at 0.721 PDF・m^2・yr/kWh. About 90% of the impact in all cases come from the logging process, with 0.624 PDF・m^2・yr/kWh. Thus, by importing wood fuel, instead of avoiding the impact on the Japanese ecosystem, Japan is affecting the ecosystems of the countries from which we procure the fuel. In addition, in comparing this with the ecological impact of coal-fired power generation at 0.0788 PDF・m^2・yr/kWh, the former is about nine times higher, indicating that the ecological impact increases when coal is replaced by woody biomass.

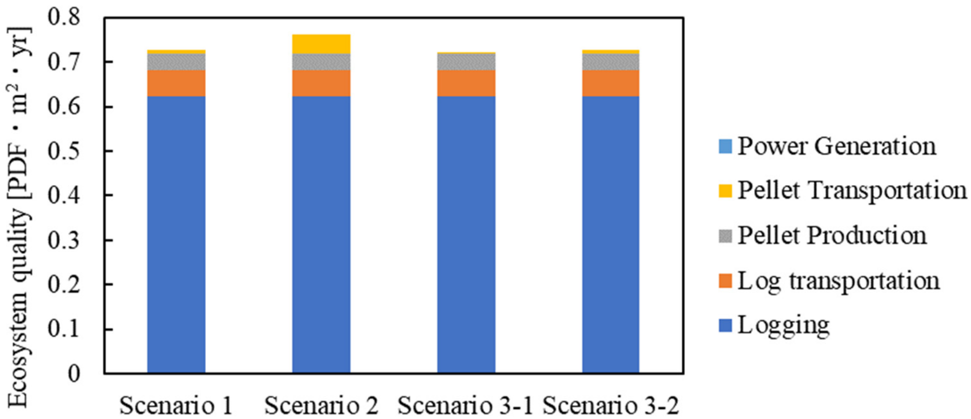

Figure 3. Impacts from each process on ecosystem quality per 1kWh

3.4 Climate Change

The impact of each process on climate change is shown in Figure 3. Upon comparing the five scenarios, we can see that, on the one hand, Scenario 3-2 has the smallest impact of 0.201 kg CO_2 eq/kWh. Using LNG and ammonia as marine fuel for wood fuel imports results in lower GHG emissions than domestic wood fuel procurement. On the other hand, when the transport distance exceeds 7,850 km, the value of Scenario 2 is exceeded even if ammonia ships are used. Thus, even if woody biomass power generation is promoted for GHG reduction, it may not be effective as a measure against global warming if the woody fuel is imported from a country farther away than Canada, the second largest importer of woody fuel.

Compared to fossil fuel power generation, the result is a reduction of about 0.9 CO_2 kg/kWh, and because the target annual power generation from woody biomass in 2030 is about 9.9 billion kWh, replacing coal-fired power generation would result in a reduction of about 9 million tons per year. This is 0.87% of the GHG reduction target for 2030 based on 2013. In addition, the logging and pellet production processes account for about 40% and 30% of the total, respectively. This can be attributed to light oil being consumed in the logging process for agricultural vehicles, among others.

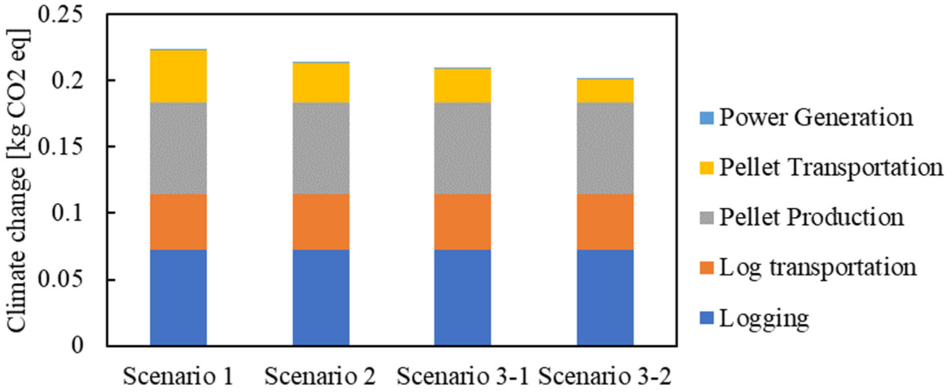

Figure 4. Impacts from each process of climate change per 1kWh

4. Discussion

4.1 Procurement of Wood Fuel

In all three damage areas, it can be seen that, on the one hand, the impact of the logging process accounts for a relatively large proportion of the damage. This may be because the wood procurement method used in this study is harvesting from forests. If wood fuel is produced from forest residues, sawmill residues, or construction waste, the logging process can be removed from the life cycle system boundary, thus reducing the total environmental impact. In Japan, as of 2018, 98% of sawmill residues and 96% of construction waste are being utilized, while 26% of forestland residues are unutilized. These figures highlight the importance of the maximization of unutilized wood.

On the other hand, the amount of carbon dioxide absorbed by trees decreases with age. In Japan, 50% of planted forests are over 50 years old, and the amount of carbon dioxide absorbed is less than half of the peak level. Therefore, GHG reductions can increase if older trees are actively harvested and forests are regenerated.

4.1.1 Unused Materials

In 2018, the amount of wood left over from forest lands was about 9.8 million tons, of which unused wood comprised 7.25 million tons. The Japanese government has set a goal of increasing the amount of electricity generated from woody biomass by about 15 billion kWh between 2020 and 2030. Based on the calculation results of this study, the amount of wood needed to generate 1 kWh of electricity is 1.38 kg. This means that 5.2 billion kWh of electricity can be generated from 7.25 million tons of unused wood, which covers about 30% of the increase in electricity generation. Thus, to reduce the potential environmental impact, it is important to use wood from unutilized materials that exist in Japan.

4.1.2 Reforestation

The amount of forest stock in Japan is increasing at a rate of about 52.3 million tons per year, which can be converted into 38 billion kWh of power generation in terms of pellets. Therefore, almost all of these can be covered by the increase in Japan’s forest stock. Theoretically, if trees are harvested from older trees, reforestation will be possible without reducing the amount of forest stock. The reasons for the increase in wood fuel imports despite the abundance of forest resources in Japan can be attributed to the decline of the Japanese forestry industry and the high cost of wood itself. We believe that among others, the government must work on the restoration of the forestry industry as a countermeasure against global warming.

4.2 Other Renewable Energy

A comparison of this study’s Scenario 3-2, power generation fueled by forest residues in Japan, wind power, and solar power, is shown in Figures 5–7. As can be seen, woody biomass power generation has a larger environmental impact than other renewable energy sources because of the need to procure and produce fuel. Even with the use of forest residues, the environmental impact is two to three times larger than that of solar power generation. However, we believe that the differences in environmental impacts between wood biomass and other renewable energies can be narrowed by promoting the use of electric vehicles in transportation trucks. Woody biomass power generation has the advantage of stable power generation that is not affected by climate. Thus, renewable energies must be promoted in consideration of the need to balance between environmental impact and electricity supply and demand.

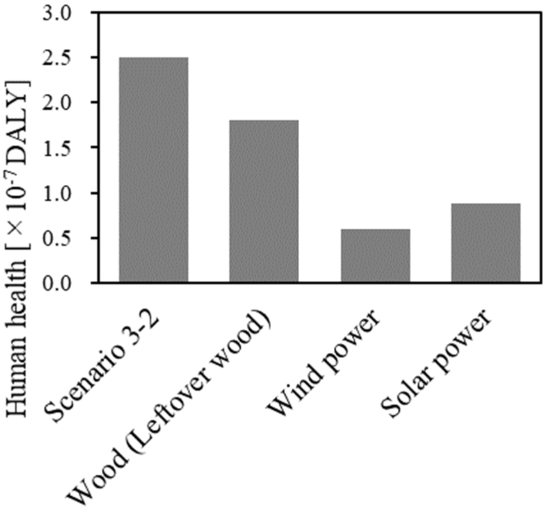

Figure 5. Impacts on human health of renewable energy generation

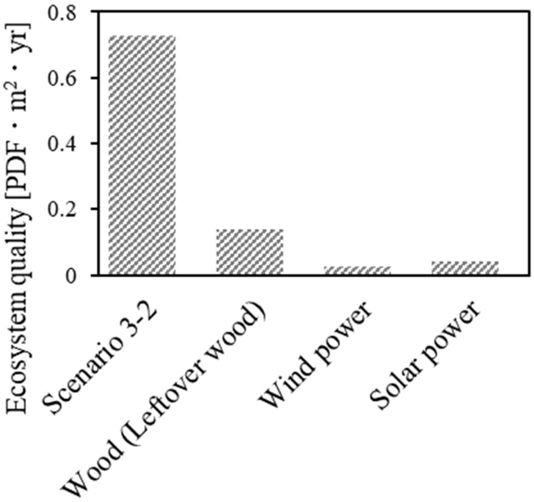

Figure 6. Ecological impacts of renewable energy generation

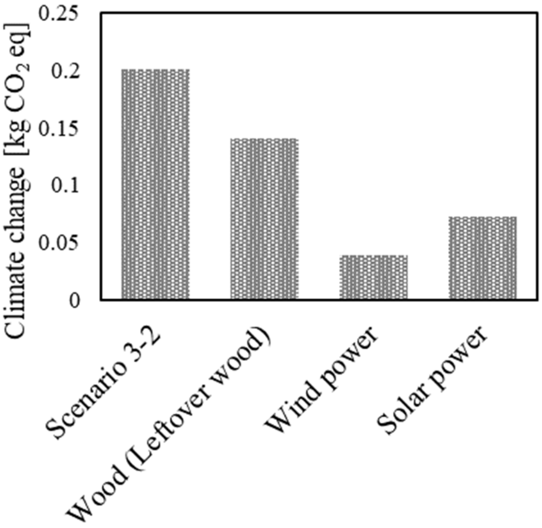

Figure 7. Impacts of renewable energy generation on climate change

5. Conclusions

In this study, we conducted LCA by creating four scenarios: three scenarios of biomass power generation using imported woody fuels and a scenario of power generation using domestically procured woody fuels. The results of the assessment in terms of three indicators, namely, human health, ecosystem quality, and climate change, show that the use of LNG/ammonia as marine fuel for imports reduced the environmental impact by about the same or 15% as that of domestically procured wood fuel. In terms of GHG emission reductions, the amount of GHG emission reductions reached 5% of the targeted reductions by 2030. Therefore, biomass power generation, even with the importation of wood fuel, is an effective way to achieve carbon neutrality.

Furthermore, looking at each process of the life cycle, the environmental impacts of logging and pellet manufacturing processes account for 30%–40% of the human health and climate change items, and 90% of the ecological quality is accounted for by the logging process alone. Thus, leftover wood must be used as material for pellets, and measures should be taken to address increased health risks for people living near manufacturing plants. Unlike other renewable energy sources, woody biomass power generation requires the procurement of fuel and thus has a greater environmental impact than wind and solar power generation. However, this type of power can be adjusted in terms of generation and has a smaller impact on human health and climate change than coal-fired power generation. Thus, by substituting hydrogen and ammonia as fuels for transportation and by limiting the transportation distance to approximately 8,000 km, this power source should be promoted while considering the balance between environmental impact and power supply and demand.

Acknowledgments

This research was performed by the chemical substance safety measures of the Ministry of Economy, Trade and Industry in FY 2022, "Chemical Substance Management Advancement Promotion Project in Collaboration with Universities and Public Research Institutions- Chemical substance management based on life cycle assessment perspective-".

References

Agency for Natural Resources and Energy. (2020). *Explanation of Standard calorific value by energy source・Carbon Emission Factor.* Retrieved from https://www.enecho.meti.go.jp/statistics/total_energy/pdf/stte_028.pdf

Agency for Natural Resources and Energy. (2021). *Ammonia as fuel? (Part 2)*. Retrieved from https://www.enecho.meti.go.jp/about/special/johoteikyo/ammonia_02.html (accessed on 12/1/2023)

Agency for Natural Resources and Energy. (2021). *Study to develop a clean energy strategy*. Retrieved from https://www.meti.go.jp/shingikai/sankoshin/sangyo_gijutsu/green_transformation/pdf/001_02_00.pdf

Agency for Natural Resources and Energy. (2022). *About biomass power generation*. Retrieved from https://www.meti.go.jp/shingikai/santeii/pdf/074_02_00.pdf

Agency for Natural Resources and Energy. (2022). *Future Renewable Energy Policy*. Retrieved from https://www.meti.go.jp/shingikai/enecho/denryoku_gas/saisei_kano/pdf/040_01_00.pdf

DAIHATSU DIESEL. *Environmental Regulatory Compliance*. Retrieved from http://www.dhtd.co.jp/ja/products/marine/nox.html

ecoinvent, *ecoinvent v3.0.* Retrieved from https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-0/

Hitoe, K., & Hattori, N. (2011). Evaluation of Green House Gas Emissions from Sawmill Residues Usage for Energy. *Journal of Japan wood research society, 57*(2), 63-71. https://doi.org/10.2488/jwrs.57.63

IDEA. Retrieved from https://idea-lca.com/

Ii, R. (2008). Theories and Indicators in Life Cycle Impact Assessment on Ecosystem. *Journal of Life Cycle Assessment, Japan, 4*(4), 408-413. https://doi.org/10.3370/lca.4.408

Japan Woody Bioenergy Association. (2018). *Quality Standards for Fuel Wood Chip*. Retrieved from https://jwba.or.jp/library/woodbiomass-chip-quality-standard/

Japan Woody Bioenergy Association. (2021). *Utilizing Domestic Wood Estimation of GHG Emissions from Wood Biomass Power Generation*. Retrieved from https://www.meti.go.jp/shingikai/enecho/shoene_shinene/shin_energy/biomass_sus_wg/pdf/012_03_00.pdf

Komata, H., Ishikawa, Y., & Hondo, H. (2017). Assessment of Life Cycle Environmental Impacts and External Costs for Woody Power Generation and Cogeneration. *Journal of Life Cycle Assessment, Japan, 13*(1), 73-83. https://doi.org/10.3370/lca.13.73

Martin, C. H., Gregory, A. K., Margaret, K. M., & Timothy, A. V. (2004). Life cycle energy and environmental benefits of generating electricity from willow biomass. *Renewable Energy, 29*, 1023-1042. https://doi.org/10.1016/j.renene.2003.11.018

Ministry of Agriculture Forestry and Fisheries of Japan. (2021). *Production Volume of Woody Granular Fuel (Wood Pellets) in 2021.* Retrieved from https://www.rinya.maff.go.jp/j/riyou/biomass/w_pellet.html

Ministry of Agriculture Forestry and Fisheries. (2020). *White Paper on Forest and Forestry*. Retrieved from https://www.rinya.maff.go.jp/j/kikaku/hakusyo/R2hakusyo/

Ministry of Agriculture, Forestry and Fisheries of Japan. (2022). *Japan's Wood Imports in 2021*. Retrieved form https://www.rinya.maff.go.jp/j/boutai/yunyuu/attach/pdf/boueki-77.pdf.

Ministry of Agriculture, Forestry and Fisheries. (2022). *Forestry and Forest Products Statistics Handbook.* Retrieved from https://www.rinya.maff.go.jp/j/kikaku/toukei/youran_mokuzi2022.html

Ministry of Economy, Trade and Industry of Japan. (2022). *Japan's Sixth Basic Energy Plan*. Retrieved form https://www.meti.go.jp/press/2021/10/20211022005/20211022005-2.pdf

Ministry of Internal Affairs and Communications. (2021). *Surveys on Wood Biomass Power Generation Fact-finding Survey on the Supply-Demand Situation of Wood.* Retrieved from https://www.soumu.go.jp/main_content/000761074.pdf

Ministry of Land, Infrastructure, Transport and Tourism. (2021). *Toward the Realization of a Green Society Environment-Related Policies and Projects in the Field of Land, Infrastructure and Transportation.* Retrieved from https://www.mlit.go.jp/policy/shingikai/content/001389404.pdf

Ministry of the Environment. (2022). *About Forest Sinks.* Retrieved from https://www.env.go.jp/content/900446213.pdf

Mirjam, R., Carly, W., & Patricia, T., (2015). How certain are greenhouse gas reductions from bioenergy? Life cycle assessment and uncertainty analysis of wood pellet-to-electricity supply chains from forest residues. *Biomass and Bioenergy, 79*, 50-63. https://doi.org/10.1016/j.biombioe.2015.03.030

New Energy and Industrial Technology Development Organization. (2015). *NEDO White Paper on Hydrogen Energy*. Retrieved from https://www.nedo.go.jp/library/suiso_ne_hakusyo.htm

New Energy and Industrial Technology Development Organization. (2020). *Ammonia Co-firing Technology.* Retrieved from https://www.nedo.go.jp/content/100932835.pdf

Pieratti, E., Paletto, A., Atena, A., Bernardi, S., Palm, M., Patzelt, D., Romagnoli, M., Teston, F., Grega, E. V., Grebenc, T., Krajnc, N., & Schnabel, T., (2020). Environmental and climate change impacts of eighteen biomass-based plants in the alpine region: A comparative analysis. *Journal of Cleaner Production*, 242. https://doi.org/10.1016/j.jclepro.2019.118449

TCO2 Co., *SimaPro LCA Software*. Retrieved form http://tco2.com/app/com/page/SimaProTop.action

The Japanese Shipowners' Association. *Ship's fuel.* Retrieved from https://www.jsanet.or.jp/qanda/text/q2_14.html

Toda, N., Yatabe, T., & Shiozawa, B. (2021). C*arbon neutral implementation strategy: electrification and hydrogen, ammonia* (1st ed.). Energy Forum, Japan

Tokyo University of Agriculture. (2015). *A Guide to Community Revitalization Using Renewable Energy*. Retrieved from http://nousanson.jp/data/tebiki_ene2015.pdf

Toyo Keizai Online. (2022). *Serious concern over Japan's large imports of "wood pellets."* Retrieved January 12, 2023 from https://toyokeizai.net/articles/-/605269

World Health Organization. (2020). *WHO methods and data sources for global burden of disease estimates 2000-2019*. Retrieved from https://cdn.who.int/media/docs/default-source/gho-documents/global-health-estimates/ghe2019_daly-methods.pdf

Copyrights