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Research Trends and Future Direction for Utilization of Woody Biomass in Japan

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Abstract: After nearly a decade of rapid development, woody biomass has been widely used in Japan for power generation and heating. However, it has faced bottlenecks in recent years, leading to a decline in its popularity. This study aimed to elucidate the current status of woody biomass utilization in Japan by reviewing relevant research papers on upstream resource supply and downstream case studies in the supply chain. The supply potential of woody biomass estimated by reviewed articles ranges from 1.2 to 5.5 m^3/year/ha, yet a significant portion of this potential cannot be exploited. The utilization of government subsidies, mechanization, and aggregated forests can substantially enhance the availability. The utilization of woody biomass has garnered widespread attention from the Japanese government and private enterprises, presenting an economic impact ranging from 66 to 249 million JPY/t, along with a GHG emission reduction spanning from −17.29 to 202.44 kg-CO_{2eq}/GJ. However, balancing cost and scale remains the primary challenge facing woody biomass utilization in Japan.

Keywords: woody biomass; supply potential; production cost; power generation; heat utilization

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1. Introduction

Since the signing of the Paris Agreement, over 100 countries have pledged to achieve carbon neutrality by 2050 and are making concerted efforts to reduce reliance on fossil fuels to limit the global average temperature increase to 1.5 °C [1]. Woody biomass is a renewable energy source that is widely used in various fields, such as power generation and heating, and its importance is increasing daily [2]. Most European Union (EU) countries place growing emphasis on the use of woody biomass to meet their 2030 renewable energy targets [3,4]. In 2017, woody biomass accounted for approximately 40% of the EU's renewable energy share [5], and it is already the most significant renewable energy source in some EU countries with rich forest resources [6]. Despite the controversial effects of woody biomass on climate change mitigation, the EU still considers woody biomass an important component for achieving its renewable energy targets [7]. Several studies have predicted the gradual expansion of woody biomass utilization in Europe [8–10].

In contrast, the utilization of woody biomass in Japan is developing rapidly, although not on a large scale. Since the introduction of a Feed-in Tariff (FIT) for renewable energy in 2012, woody biomass power plants have been constructed throughout Japan, reaching approximately 130 by 2019, covering nearly the entire country [11]. However, in the Japanese power supply structure in 2019, biomass accounted for only approximately 2.6% of total power generation and 14% of renewable energy power generation. To address climate change issues, the Japanese government announced in 2020 its goal of achieving carbon neutrality by 2050. The share of biomass power generation is expected to increase from 2.6% in 2019 to 5% by 2030; however, the scale is not as extensive as that in countries with advanced woody biomass utilization, such as Finland [12].

In the Fifth Basic Energy Plan published in 2018, the Japanese government set a target to increase the share of biomass power generation to 3.7–4.6% by 2030 [13]. However, in the Sixth Basic Energy Plan released after the government announced its goal of achieving carbon neutrality, the share of biomass power generation increased only by 0.4%, whereas the share of other mainstream renewable energy sources, such as wind and solar power, roughly doubled [12]. Additionally, Japan's current domestic production of woody biomass is insufficient to meet demands, leading to a heavy reliance on imports. According to statistics from the Japan Forestry Agency, the import ratio of fuelwood reached 36.6% in 2021 and has been increasing in the past few years [14]. The use of large amounts of imported fuelwood undermines the original advantages of woody biomass utilization, such as regional revitalization and energy independence, and contradicts the Japanese government's aspiration to promote the use of woody biomass for energy [15]. Therefore, to clarify the current status of woody biomass utilization in Japan, this paper summarizes the research trends in Japan on woody biomass utilization using various regions of Japan in terms of both resource supply and case study and analyzes factors hindering the development of woody biomass utilization. It also discusses how Japan can optimize the utilization of woody biomass based on the experiences of countries with advanced woody biomass utilization.

2. Materials and Methods

This paper summarizes the methods and results of an analysis of research papers on woody biomass utilization in Japan, starting from both aspects of resource supply upstream of the woody biomass supply chain and a case study downstream. The study was conducted between 1 April and 1 July 2023.

Regarding resource supply, we searched for research papers in English and Japanese on Google Scholar and CiNii Research using five keywords: "woody biomass, potential, availability, cost, and Japan," within the timeline of 2000–2022, and we collected 24 research papers. From these studies, we extracted information on the supply of woody biomass in Japan, including estimation methods, results, and influencing factors related to supply potential and availability. Additionally, details on supply costs, including the production cost of woody biomass and its cost structure, are summarized. Finally, a concise statistical analysis was performed on the results of the supply potential, availability, and supply costs. It should be noted that the focus of this discussion is on woody biomass derived from forests, specifically the woody biomass produced from thinning and final felling. Residual wood from sawmills or construction is not included. Additionally, the quantification of woody biomass is based on the raw materials used to produce woody biomass fuels such as chips and pellets. This is due to the absence of a unified use standard for woody biomass fuels in Japan. Different regions and different fuel usage facilities use fuels with significant differences in quality, such as size and moisture content, making it difficult to measure them uniformly.

For the case study, the timeline was narrowed to 2012–2022, as there was little woody biomass utilization in Japan until the introduction of the FIT in 2012. Using the keywords "woody biomass, utilization, and Japan," we searched Google Scholar and CiNii Research for research papers in English and Japanese that evaluated woody biomass utilization in Japan and obtained 37 research papers. To comprehensively discuss the current status and issues of woody biomass utilization in Japan, we categorized the collected papers according to three perspectives: society, economy, and environment. We identified 14 research papers that focused on social aspects, 16 on economic aspects, and 12 on environmental aspects.

3. Supply Potential and Availability of Woody Biomass

3.1. Methods and Results of Supply Potential Estimation

3.1.1. Methods

Because some of the reviewed papers estimated multiple regions simultaneously, 32 cases were organized as one case of estimation results for each region (Table 1). The supply potential of woody biomass was estimated using government forestry survey data. However, there are differences between the long- and short-term estimates, depending on the period of estimation. Long-term estimation is based on the concept of a "normal forest" (i.e., a forest that undergoes sustainable management through the cutting down and replanting of trees at an amount equivalent to the annual growth) and estimates the supply potential for an entire harvest period, assuming that the forest can be harvested sustainably over a long period. Long-term estimation considers the growth of trees but cannot accurately estimate specific annual supply potentials, such as cases 1 to 24 in Table 1. On the other hand, short-term estimation is used to estimate the supply potential for a specific year in areas that have been either harvested or are planned. Short-term estimation provides relatively accurate estimates of the annual supply potential based on actual harvesting records, such as cases 25 to 32 in Table 1. However, this may underestimate the potential, as in some areas forest operational records only record harvesting activities subsidized by the government [16,17].

Table 1. Results of woody biomass supply potential and availability.

Case No.	Region and Year	Target Forest Type	Share of Target Forest [%]	Factors for Estimating Supply Potential				
				Biomass Rate [%]			Extraction Rate [%]	Yield Rate [%]
				Pre-Commercial Thinning	Commercial Thinning	Final Felling		
1	Yusuhara, Kochi Pref., 2009	Conifer plantations	41.9	N.A.	100	15	115	100
2	Nasushiobara, Tochigi Pref., 2013	Conifer plantations	10.2	100	55	26	109	100
3	Kanuma area, Tochigi Pref., 2013	Conifer plantations	76.7	100	55	26	109	100
4	Tochigi Pref., 2017	Conifer plantations	32.5	90	50	25	100	100
5	Tochigi Pref., 2019	Conifer plantations	37.9	90	50	25	100	100
6	Fukushima Pref., 2020	Conifer plantations	37.5	15	15	15	100	90
7	Ibaraki Pref., 2020	Conifer plantations	60.6	15	15	15	100	90
8	Tochigi Pref., 2020	Conifer plantations	46.9	15	15	15	100	90
9	Gunma Pref., 2020	Conifer plantations	41.1	15	15	15	100	90
10	Japan, 2021	Conifer plantations	41.3	15	15	15	100	90
11	Hokkaido, 2021	Conifer plantations	24.6	15	15	15	100	90
12	Tohoku region, 2021	Conifer plantations	42.5	15	15	15	100	90
13	Kanto region, 2021	Conifer plantations	48.8	15	15	15	100	90
14	Chubu region, 2021	Conifer plantations	36.1	15	15	15	100	90
15	Kinki region, 2021	Conifer plantations	60.2	15	15	15	100	90
16	Chugoku region, 2021	Conifer plantations	50.4	15	15	15	100	90
17	Shikoku region, 2021	Conifer plantations	52.5	15	15	15	100	90
18	Kyushu region, 2021	Conifer plantations	50.5	15	15	15	100	90
19	Tohoku region, 2021	Conifer plantations	43.7	15	15	15	100	90
20	Aomori Pref., 2021	Conifer plantations	45.2	15	15	15	100	90
21	Iwate Pref., 2021	Conifer plantations	45.5	15	15	15	100	90
22	Miyagi Pref., 2021	Conifer plantations	49.4	15	15	15	100	90
23	Akita Pref., 2021	Conifer plantations	48.8	15	15	15	100	90
24	Yamagata Pref., 2021	Conifer plantations	29.4	15	15	15	100	90
25	Tochigi Pref., 2014	Conifer plantations	32.6	90	50	25	123	100
26	Nasushiobara, Tochigi Pref., 2015	Conifer plantations	10.6	90	50	25	123	100
27	Takahara area, Tochigi Pref., 2015	Conifer plantations	35.4	90	50	25	123	100
28	Hokkaido, 2015	Conifer plantations	N.A.	70	28	28	100	100
29	Hokkaido, 2015	Conifer plantations	N.A.	70	17	17	100	100
30	Northern Chiba Pref., 2010	Broadleaf natural forest and Conifer plantations	N.A.	100	100	100	123	100
31	Western Saitama Pref., 2010	Broadleaf natural forest and Conifer plantations	N.A.	100	100	100	123	100
32	N.A., 2011	Broadleaf natural forest and Conifer plantations	N.A.	100	100	100	109	100

Table 1. *Cont.*

Case No.	Results of Supply Potential		Result of Availability				Reference
	Supply potential [m^3/year]	Supply potential per unit area [m^3/year/ha]	No subsidy [m^3/year]	Availability rate [%]	Maximum availability [m^3/year]	Availability rate [%]	
1	990,113	5.50	N.A.	N.A.	N.A.	N.A.	[18]
2	972,672	4.10	N.A.	N.A.	16,088	99	[19]
3	7,868,852	4.81	N.A.	N.A.	131,148	100	[19]
4	394,042	5.11	N.A.	N.A.	301,481	52	[20]
5	493,572	4.67	N.A.	N.A.	187,260	30	[21]
6	536,333	1.47	36,285	7	418,787	78	[22]
7	174,389	1.53	70,111	40	172,246	99	[22]
8	249,651	1.52	39,033	16	217,281	87	[22]
9	235,303	1.35	51,422	22	229,598	98	[22]
10	13,098,067	1.30	N.A.	N.A.	6,216,134	47	[23]
11	1,999,130	1.47	N.A.	N.A.	1,067,684	53	[23]
12	2,654,312	1.33	N.A.	N.A.	1,059,323	40	[23]
13	770,446	1.26	N.A.	N.A.	259,463	34	[23]
14	2,053,567	1.29	N.A.	N.A.	1,014,592	49	[23]
15	1,650,850	1.26	N.A.	N.A.	709,311	43	[23]
16	1,505,793	1.29	N.A.	N.A.	695,219	46	[23]
17	826,171	1.20	N.A.	N.A.	308,026	37	[23]
18	1,637,798	1.22	N.A.	N.A.	1,102,516	67	[23]
19	2,277,792	1.40	326,325	14	1,730,589	76	[24]
20	433,972	1.52	67,524	16	347,121	80	[24]
21	643,814	1.21	98,461	15	514,073	80	[24]
22	274,212	1.33	75,829	28	214,465	78	[24]
23	634,517	1.55	47,329	7	428,788	68	[24]
24	291,277	1.48	37,182	13	226,142	78	[24]
25	273,380	3.53	13,468	3	105,747	26	[16]
26	53,345	3.30	716	5	11,072	85	[17]
27	23,191	2.50	440	1	24,493	72	[25]
28	729,000	2.76	N.A.	N.A.	N.A.	N.A.	[26]
29	428,000	1.62	N.A.	N.A.	N.A.	N.A.	[26]
30	56,820	3.78	N.A.	N.A.	N.A.	N.A.	[27]
31	110,295	3.31	N.A.	N.A.	N.A.	N.A.	[27]
32	52,206	2.92	N.A.	N.A.	N.A.	N.A.	[28]

N.A.: Not applicable.

The estimation of woody biomass supply potential primarily relies on government forestry survey data (e.g., forest registers and forest management plans). The total supply potential is calculated by aggregating the supply potential of each sub-compartment within a study area. Utilizing Geographic Information Systems, the spatial distribution of supply potential for the sub-compartment can be visualized. The estimation method can be summarized using the following equation:

$$SP = \sum_{i=1}^{n} S_i \cdot Cr_i \cdot Er \cdot Br \quad (1)$$

where SP is the supply potential of woody biomass, i is the sub-compartment targeted for harvesting, n is the number of sub-compartments, S is the forest stock, Cr is the cutting rate, Er is the extraction rate, and Br is the biomass rate.

The interpretation of the variables in the above equation occurs as follows:

(1) Forest stock

Forest stock is the sum of the stem volumes of living trees in a sub-compartment and is usually recorded in forest registers for each region of Japan. While many studies directly utilize these data, some focus on long-term estimates and choose not to rely directly on them. Instead, they utilize tools such as yield tables [20,21], empirical growth curves [29], or other projection methods to estimate future forest stock considering tree growth [18].

(2) Cutting rate

The cutting rate indicates how much of the tree will be harvested during harvesting activities such as thinning and final felling. The value of this variable was always set to

100% in the final felling, representing complete harvesting of the targeted forest. Thinning is often determined according to the regional forest management plan and ranges from 10% to 40%, depending on forestry conditions such as tree species, age, and harvesting method.

(3) Extraction rate

The extraction rate indicates the share of harvested trees that are ultimately utilized. Because forest stock is generally recorded in the forest register in the form of stem volume in Japan, the extraction rate essentially represents the number of branches and leaves utilized. When the extraction rate exceeded 100%, branches and leaves were utilized, and the portion exceeding 100% represented the number of branches and leaves utilized. Different studies set different values for the extraction rate, which mainly include four situations. Cases 25 to 27, 30, and 31 in Table 1 adopted the biomass expansion factors published by the Japanese government, which is the ratio of aboveground area, including branches and strips, to the standing tree trunk [16,17,25,27]. Cases 1 to 3 and 32 utilized actual measurements from harvesting activities [18,19,28], whereas Cases 4, 5, 8, and 29 did not consider the use of branches and leaves [20,21,26]. Finally, Cases 6 to 23, besides not considering the use of branches and leaves, also account for losses in harvesting activities, resulting in a yield rate of less than 100% [22–24].

(4) Biomass rate

The biomass rate is a variable indicating the number of harvested trees that can be used as woody biomass, with its counterpart being the timber rate. Woody biomass mainly refers to unused wood, such as forest residues, which distinguishes it from traditional lumber used in construction or furniture. In the case of final felling, the biomass rate is often based on the actual harvesting activity in the study area, and typically ranges from 15% to 28%. However, in the case of thinning, the biomass rate varied widely, ranging from 15% to 100%. This variability is attributed to the lack of economies of scale, which stem from thinning yields being lower than those of final felling. In Japan, many forests are not well-maintained and require a certain scale of harvesting to be profitable. During thinning, when the scale of harvesting is typically small, harvested trees are often left unutilized in a forest. Cases 1 and 30 to 32 have considered this situation and set the biomass rate of thinning to a high value, assuming that the remaining wood can be fully utilized [18,27,28]. Incidentally, Cases 2 to 5 and 25 to 32 considered pre-commercial thinning separately and set the biomass rate of pre-commercial thinning to be higher than that of commercial thinning, ranging between 70% and 100%. Pre-commercial thinning is the initial thinning of relatively young stands for density control purposes and has a high probability of being left on forest land because the trees are small and have little or no utility value as timber at the time of harvest.

(5) Regionality

In addition to the four variables mentioned above, the age of the tree at the time of thinning and final felling, the number of thinnings, the tree species, and the site indexes also have a direct impact on the supply of woody biomass. However, the values of these variables vary greatly and cannot be presented succinctly. Almost all of the reviewed papers set the values of these variables based on forest registers and forest management plans issued by Japanese local governments, so we summarized them as regionality. In general, the impact of regionality on the supply potential of woody biomass is not very significant. Cases 11 to 18 in Table 1 use the same method to calculate the supply potential of woody biomass in several large regions in Japan, such as Tohoku and Kanto region, and the results range from 1.20 to 1.47 m^3/year/ha, which does not show a significant difference [23]. Similarly, the results of Cases 6–9 for the four prefectures in the Kanto region [22] and Cases 20–24 for the five prefectures in the Tohoku region [24] also do not show large fluctuations.

3.1.2. Results

(1) Target forest types

Woody biomass was originally a forest-derived resource, and theoretically, any forest can produce woody biomass. However, the reviewed papers covered only part of the forests in the study area, rather than the entire forest. Among them, all studies focused on privately owned coniferous-planted forests, with a few simultaneously examining privately owned natural hardwood forests or national coniferous-planted forests. We extracted the target forested area from each paper and calculated the share of the target forested area relative to the total forested area in the study area (Figure 1). It should be noted that some studies lacked specific data; therefore, the estimates were based solely on privately owned coniferous-planted forests.

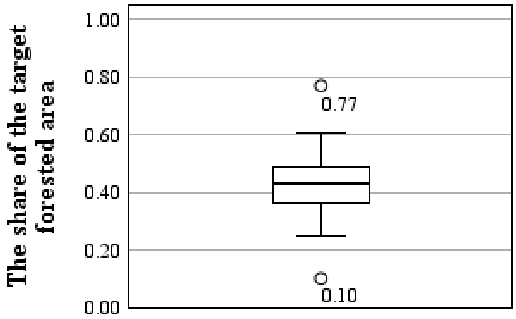

Figure 1. The share of the target forested area relative to the total forested area in the study area.

The results indicate that the target forested area in relation to the total forest area in the study area ranged from 10.2% to 76.7%, demonstrating significant variation depending on the characteristics of the forests within the study area. The maximum and minimum values in the box plots were identified as outliers owing to their representation of areas at the municipal level, showing prominent local forest characteristics. The maximum value of 76.7% corresponds to Case 3 in Table 1, where the forests in this area are predominantly privately owned. Conversely, the minimum value of 10.2% corresponds to Case 2 in Table 1, with the forests in this region being primarily national. The median and mean values in Figure 1 are 42.0% and 42.5%, respectively, which closely resemble the ratio of the total privately owned coniferous-planted forests to the total forest area in Japan (41.8%).

(2) Results and factors influencing supply potential estimation

The supply potential of woody biomass is directly related to forest area; a larger forest area corresponds to a greater supply potential. To compare the estimation results from the reviewed papers, the annual supply potential was divided by the target forested area. The results, illustrated in Figure 2, are widely distributed, ranging between 1.2 and 5.5 m^3/year/ha, with median and mean values of 1.5 and 2.3 m^3/year/ha, respectively. To identify the factors that significantly impact the estimation of the supply potential, the estimation conditions set by each study are tabulated (Table 1). The results shown in Figure 2 can be categorized into three groups based on the estimation period, biomass rate, and extraction rate (Figure 3).

Groups 1 and 2 represent the long-term estimation outcomes, with Group 3 corresponding to the short-term estimation results. Group 1 included the five cases from Table 1, namely Cases 1 through 5, which exhibited relatively large values. In these cases, the biomass rate was set to 50% or more for thinning and 25% for final felling (except for Case 1), resulting in larger values. Additionally, because the number of cases in Group 1 was small and the biomass rate was high, the utilization of branches and leaves did not have a significant impact on the results. Group 2 included 19 cases from Cases 6 through 24 in Table 1, with smaller values. The estimation method for these cases was nearly identical, as the biomass rate for both thinning and final felling was set at 15% and no consideration was given to the utilization of branches and leaves. This resulted in a relatively concentrated distribution of results. Finally, Group 3 resulted in short-term estimations and included eight cases from Cases 25 through 32 in Table 1, with values falling between those of Groups 1 and 2 and exhibiting a relatively wide distribution. Notably, although the study areas, estimation methods, and conditions were nearly identical for Group 3 Case 25 and Group 1 Cases 4 and 5, Case 25 produced larger estimates than Cases 4 and 5. This difference may be attributed to the contrast between the long-term and short-term estimates. As previously noted, long-term estimates are based on the entire forest studied, whereas short-term estimates rely on actual harvest records or harvest plans. In other words, even though the study area is similar, the actual forest area considered in the short-term estimation is smaller than in the long-term estimation, leading to correspondingly smaller estimation results.

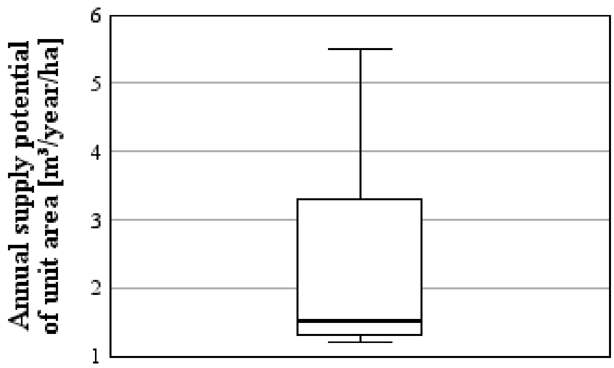

Figure 2. Annual supply potential of unit area.

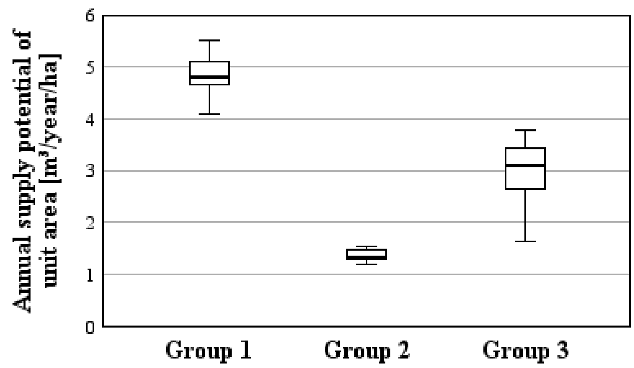

Figure 3. Annual supply potential of unit area under different conditions.

3.2. Methods and Results of Availability Estimation

3.2.1. Methods

Estimating woody biomass availability involves the selection of forests capable of supplying woody biomass through the imposition of restrictions. The estimation methods employed in each study share several similarities. There are two main types of restrictions: spatial and economic. Spatial restrictions involve selecting forests based on spatial information such as forest type and topography. For example, spatial restrictions include information on forest types that serve public functions, such as water source conservation and disaster protection, as well as topographical information, such as slope and distance from forest roads. Economic restrictions involve using harvesting-related economic calculations to select forests. Economic restrictions essentially lie in quantifying and expressing spatial restrictions in the form of income and expenditure balance calculations. For instance, in forests with steep slopes, challenging terrain prohibits large-scale mechanized operations, requiring more manpower and specialized equipment and resulting in even higher costs. Compared to spatial restrictions, economic restrictions screen available forests more accurately but are cumbersome and require many calculations.

3.2.2. Results and Influencing Factors of Availability Estimation

The availability of woody biomass, as estimated by the reviewed papers, is presented in Table 1, showing significant variations in results due to the different estimation methods. To facilitate comparisons among the studies, the availability rate was calculated by dividing the estimated availability by the respective supply potential (Figure 4). Notably, the restrictions considered in these studies were not uniform. The maximum availability rate was 40% in the absence of government subsidies, indicating that nearly half of the potential was inaccessible. It is nearly impossible to achieve self-sufficiency in many areas of Japan. However, with the implementation of appropriate improvement measures, the availability rate demonstrated notable improvements, with mean and median values reaching 65% and 70%, respectively, albeit with a wide range of variation. Furthermore, in certain areas of Japan, the full supply potential of woody biomass can be utilized effectively.

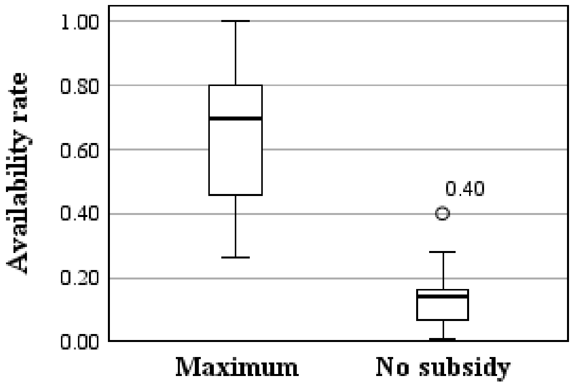

Figure 4. Availability rate relative to supply potential.

To identify ways to increase the availability of woody biomass, we summarized the improvement measures proposed by the reviewed papers and identified three measures, which are described below. It should be noted that some studies examined the availability in relation to changes in selling prices. However, because selling prices are typically determined by the market, an increase in selling prices was excluded from the improvement measures.

(1) Government subsidies

Government subsidies, the most intuitive improvement measures, directly offset the production costs of woody biomass and ensure profitability. The effects of subsidies are examined in the four examples presented in Table 1, Cases 6 through 9. Implementing government subsidies can significantly increase the availability rate, enabling the utilization of approximately 80% of the supply potential [22].

(2) Aggregated forests

In Japan, this sub-compartment is a fundamental unit for forest management and harvesting. The concept of Aggregated Forests revolves around economies of scale achieved by expanding the fundamental unit through the aggregation of smaller adjacent sub-compartments. This expansion enhances operational efficiency and reduces indirect costs. The overhead costs of woody biomass utilization include significant fixed expenses, such as machinery transportation and garage management costs (further discussed in Chapter 4). Because fixed expenses occur only once per harvest area, the overall fixed costs decrease with an increase in operational area. However, with the expansion of the operational area, the distance over which trees are forwarded also increases. Therefore, the scale of the Aggregated Forests should be carefully considered. Matsuoka et al. [30] investigated the optimum area of Aggregated Forests and recommended limiting the area of aggregated sub-compartments to 6 hectares or less because production costs would rise if the area exceeded 6 hectares.

Almost no studies consider only Aggregated Forests, but Cases 2 and 3 in Table 1 demonstrate that Aggregated Forests can increase the availability rate from 38% to 100% and from 48% to 99%, respectively, when subsidies are applied [19]. In Case 26 in Table 1, when no subsidies are applied and the selling price of woody biomass is 6000 yen/m^3, Aggregated Forests can enhance the availability rate from 6.6% to 9.6%. When the selling price is 10,000 yen/m^3, the availability rate increases from 25.0% to 56.1% [17]. Additionally, Cases 19 through 24 in Table 1, which consider regional trade, show that Aggregated Forests effectively improve woody biomass availability [24]. Notably, these studies considered only fixed expense reductions and omitted operational efficiency improvements when estimating the effects of Aggregated Forests. Therefore, the improvement effects of the Aggregated Forests may be even greater.

(3) Mechanization

Mechanization refers to the transition from a conventional low-efficiency, primarily manpower-dependent forestry operation system to a high-efficiency, primarily machine-dependent forestry operation system. This transition involves the selection of suitable machinery based on the topographical characteristics of the operational area. The essence of mechanization is to enhance operational efficiency and reduce production costs by appropriately selecting efficient machinery. Earlier studies have estimated the availability of woody biomass by comparing traditional and mechanized operation systems, revealing that in large-scale harvesting activities, mechanized operation systems significantly improve availability [18,19]. However, recent studies have tended to treat the operational system as a fixed condition for estimation, neglecting mechanization as a factor influencing availability. Cases 4, 5, 25, 26, and 27 in Table 1 establish five forestry operation systems based on information from harvesting sites in the study area. Additionally, Cases 6 through 24 in Table 1 set up more complex forestry operation systems based on the slope and relief volume in the study area. The selection of an appropriate forestry operation system has a substantial impact on reducing the cost of woody biomass production.

The choice of a forestry operation system is closely tied to topography, making it challenging to quantify the effects of mechanization. Cases 4, 5, and 8 in Table 1 investigated the availability of woody biomass in different forestry operation systems within the same location (Tochigi Prefecture, Japan). By comparing the results of these three cases, the impact of mechanization on increasing the availability can be elucidated. In contrast to Cases 4 and 5, Case 8 employed highly efficient machinery such as harvesters, with a more precise set of nine operation systems based on the local topography. As a result, when subsidies are applied, Cases 4, 5, and 8 estimate availability rates of 10%, 9%, and 87%, respectively, with Case 8 showing a significantly higher availability rate than Cases 4 and 5 [20–22].

4. Production Costs of Woody Biomass

4.1. Structure of Wood Biomass Production Cost

The details of the production costs considered by the reviewed papers are presented in Table 2, revealing significant differences and encompassing six main categories: direct, indirect, transportation, fuel conversion, forest road construction, and reforestation. Direct costs are expenses directly incurred during harvesting activities and can be subdivided into main and sub-operation costs. Main operation costs include labor and machinery costs related to harvesting activities, whereas sub-operation costs encompass the expenses of strip-road and landing establishments. Indirect costs encompass expenses incurred indirectly in harvesting activities, such as machinery transportation and overhead costs. Transportation costs account for the expenses associated with transporting woody biomass from forests to markets and energy-use facilities. Fuel conversion costs pertain to the expenses incurred when processing woody biomass into chips, pellets, and other fuels. Forest road construction costs represent expenses associated with constructing forest roads. Reforestation costs cover expenses incurred in activities such as site preparation, planting, and weeding after the forest has been cut.

Table 2. Results of woody biomass production cost.

Paper No.	Region and Year	Cost Structure							Production Cost [JPY/m^3]		Reference
		Direct		Indirect	Trans.	Fuel Conversion	Forest Road Construction	Reforestation	Main Product	By-Product	
		Main-Op	Sub-Op								
1	N.A., 2006	✓							N.A.	4092~8572	[31]
2	Toei-cho, Aichi Pref., 2006	✓							5492~9885	N.A.	[32]
3	N.A., 2006	✓			✓	✓			5311	N.A.	[29]
4	Sano, Tochigi, 2010	✓	✓	✓	✓				17,988	5370	[33]
5	Nasushiobara, Tochigi Pref., 2010	✓		✓					8711~8985	N.A.	[34]
6	Chichibu area, Saitama Pref. and Shimosa plateau, Chiba Pref., 2010	✓			✓	✓			4410~5141	N.A.	[27]
7	Nasushiobara, Tochigi Pref., 2011	✓	✓						4106~5236	N.A.	[35]
8	N.A., 2011	✓			✓	✓			4981	N.A.	[28]
9	Nasushiobara and Kanuma area, Tochigi Pref., 2012	✓	✓	✓	✓				11,887~14,048	5129~7995	[36]
10	Nasushiobara, Tochigi Pref., 2013	✓	✓	✓	✓		✓		28,840~29,940	5168~5644	[37]
11	Nasushiobara, Tochigi Pref., 2014	✓	✓	✓	✓				18,537	1322	[38]
12	Tokai region, 2017	✓						✓	9000~14,000	N.A.	[39]
13	Ibaraki, Fukushima, Tochigi and Gunma Pref., 2020	✓	✓	✓	✓			✓	3500~10,000	N.A.	[22]
14	Nasushiobara, Tochigi Pref., 2021	✓			✓	✓			N.A.	5206~8040	[40]
15	Japan, 2021	✓	✓	✓	✓			✓	3500~8500	N.A.	[23]

1 USD = 118.07 JYP (1 January 2006); 1 USD = 92.10 JYP (1 January 2010); 1 USD = 81.49 JYP (1 January 2011); 1 USD = 77.74 JYP (1 January 2012); 1 USD = 86.58 JYP (1 January 2013); 1 USD = 105.39 JYP (1 January 2014); 1 USD = 116.49 JYP (1 January 2017); 1 USD = 109.56 JYP (1 January 2020); 1 USD = 103.50 JYP (1 January 2021); 1 USD = 141.83 JYP (1 January 2024); N.A.: Not applicable.

4.2. Woody Biomass Production Costs

As mentioned previously, woody biomass primarily consists of unused wood, which is often left in large quantities in forests. In this context, we considered a scenario in which woody biomass is harvested independently as the main product and a scenario in which both timber and woody biomass are harvested simultaneously as by-products. In the case of the main products, woody biomass is rarely harvested only at the final felling stage, and for by-products, the costs of final felling and thinning are almost identical; therefore, thinning costs were used for analysis. Of note, the available data on fuel conversion costs, forest road construction costs, and reforestation costs are limited. Furthermore, because forest road construction and reforestation are typically financed by public government funds, these three costs were excluded.

The distribution of production costs for woody biomass is depicted in Figure 5; the production costs for the main product ranged from 3.5 to 29.9 thousand JPY/m^3, while those of by-products ranged from 1.3 to 8.6 thousand JPY/m^3. This phenomenon can be attributed to two factors. First, the production cost structures considered in each study differed. Second, the estimation results exhibited regional characteristics owing to varying factors of production in different regions, such as forestry operation systems and transportation distances. In the case of the main product, the mean and median production costs are 9.9 and 8.7 thousand JPY/m^3, respectively, which exceed the average price of 7 thousand JPY/m^3 for material for chips in Japan in 2022, rendering it less economically viable. On the other hand, for by-products, the mean and median production costs are 5.5 and 5.3 thousand JPY/m^3, respectively, falling below the average price and demonstrating a certain level of economic viability.

The distributions of the direct, indirect, and transportation costs of the main products and by-products are shown in Figures 6 and 7, respectively. Regardless of whether it is for the main product or by-products, the main operation costs constituted a substantial proportion of the total costs. For the main products, the proportion of indirect costs was significant and may even surpass that of the main operation costs. However, for by-products, in addition to the main operation costs, transportation costs also constitute a substantial portion. The higher transportation costs can be attributed to the larger volume of unused wood, such as branches and leaves, compared with logs, making transportation less efficient. In some studies that estimated the production cost of by-products, indirect cost items from the main product were often reduced, and by-operation costs were not included. Of note, many studies assumed short transportation distances, resulting in smaller estimated transportation costs. Goltsev et al. [41] found that the cost of using woody biomass is less than that of heavy oil when the transportation distance is 50 km or less, and Kamimura et al. [42] estimated that with an increase in transportation distance from 25 km to 100 km, the transportation cost increased by approximately 9000 JPY/t.

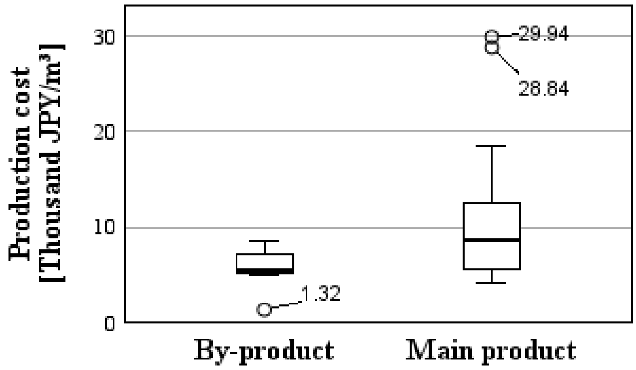

Figure 5. Production costs of woody biomass.

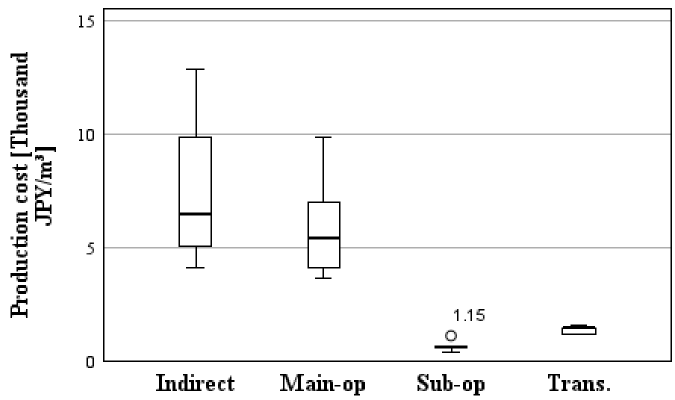

Figure 6. Production costs with main product.

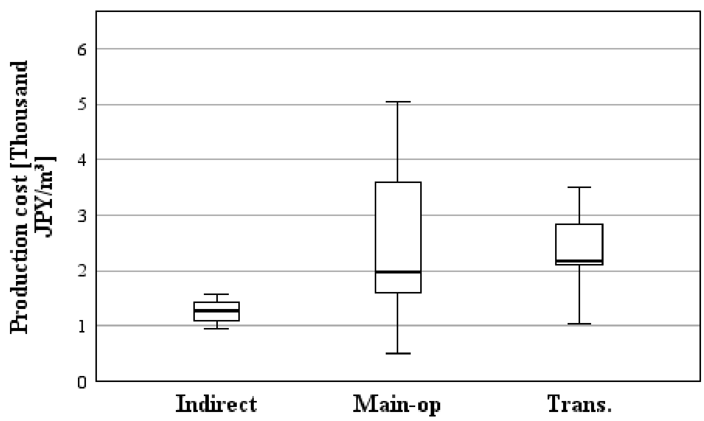

Figure 7. Production costs with by-product.

5. Social Impact Assessment of Woody Biomass Utilization

From a social perspective, the reviewed papers primarily focused on three aspects: issues related to woody biomass utilization, factors contributing to the success of the woody biomass utilization, and factors promoting collaboration in woody biomass utilization.

5.1. Issues with Wood Biomass Utilization

The issues related to the use of woody biomass for power generation and heating in Japan are presented in Table 3. Four issues concerning power generation were identified: high cost, securing feedstock supply, forest destruction, and a lack of technicians. The cost issue presents two primary challenges: dependence on FIT, where woody biomass power plants can sell electricity at a fixed price higher than the market price, and the lack of economic efficiency in small-scale power plants (further discussed in Section 6). Ensuring the supply of feedstock and the destruction of forests are interconnected and tend to create a vicious cycle. Since the introduction of the FIT in 2012, the number of woody biomass power plants in Japan has increased rapidly. However, the Japanese domestic wood market, which has been impacted for a long time by low-priced wood from overseas, has been in a prolonged slump, making a stable supply of feedstock a pressing issue. Simultaneously, supply scarcity drives imports and exacerbates illegal logging in both Japan and other exporting countries, perpetuating a vicious cycle. Finally, a lack of technicians is an urgent issue for small-scale power generation.

Table 3. Issues with wood biomass utilization.

Utilization Type	Paper No.	Year	Issues	Reference
Power generation	1	2015	1. Additional expenses incurred for the transportation of feedstock and the maintenance of transmission lines (High cost) 2. Lack of engineers for repair and maintenance (Lack of technician)	[43]
	2	2017	1. Depend on FIT (High cost)	[44]
	3	2021	1. Lack of feedstock due to the drastic increase in power plants (Securing feedstock supply) 2. Illegal logging due to the lack of feedstocks (Forest destruction)	[45]
Heat utilization	2	2017	1. High initial cost (High cost) 2. Price competition with fossil fuels at the operation stage (High cost) 3. Lack of heat demand (Ensure heat demand) 4. Lack of woody biomass suppliers (Securing feedstock supply)	[44]
	4	2019	1. Lack of operators of equipment related to woody biomass (Lack of technician) 2. Ensure the safety of users (Lack of technician)	[46]
	3	2021	1. Illegal logging due to the lack of feedstocks (Forest destruction)	[45]

The issues associated with heat utilization are similar to those associated with power generation, with a few distinctions. Regarding the cost issue, the initial cost of heat utilization is notably high and relies heavily on government subsidies. However, these subsidies do not cover the entire heat utilization supply chain and only address the initial costs. Consequently, there is an intense competition for fossil fuels during the operational phase. In terms of ensuring the supply of feedstock, the challenge lies more in the shortage of suppliers rather than the feedstock itself. The predominant heat utilization of woody biomass in Japan is low, resulting in dispersed locations that lack centralized utilization. This dispersion also contributes to a scarcity of suppliers and technicians. Finally, the most crucial issue for heat utilization is ensuring the heat demand. Given the high efficiency of heat utilization, the heat produced by large-scale utilization must be consumed over a wide area. However, district heating systems (DHSs) are scarce in Japan. Additionally, the high installation costs of these systems have hindered the widespread adoption of wood biomass for heat utilization.

5.2. Factors for Woody Biomass Utilization Success

The six main factors listed in Table 4 contribute to the success of woody biomass utilization.

Table 4. Factors for woody biomass business success.

Paper No.	Year	Factors	Reference
5	2013	1. Position forest management within the overall system of woody biomass production and utilization, and consider it as an integral part of demand creation (Forestry reformation) 2. Multi-agent and multi-scale forest management (Forestry reformation) 3. Reinforcement of regional economic circulation (Regional revitalization) 4. Proper utilization of private Energy Service Company (Collaborative activities)	[47]
2	2017	1. Utilization of government subsidies (Cost reduction) 2. Combination of wood biomass business with existing timber business (Cost reduction) 3. Security of multiple suppliers and buyers (Elasticity of supply and demand) 4. Creation of supply chains through collaborative activities among private companies, local government, and local organizations (Collaborative activities) 5. Government-coordinated action (Collaborative activities) 6. Quality control of woody biomass fuel such as dimensions and moisture content (Quality control of woody biomass fuels)	[44]
6	2018	1. Improvement of transportation infrastructure (Cost reduction) 2. Combination of wood biomass business with existing timber business (Cost reduction) 3. Building trust among stakeholders in the supply chain (Collaborative activities) 4. Promotion of regional revitalization (Regional revitalization) 5. Respect for the values and traditions of the forest owner (Forestry reformation) 6. Quality control of woody biomass fuel such as dimensions and moisture content (Quality control of woody biomass fuels)	[48]
4	2019	1. Ensure diversity among members of organizations promoting woody biomass utilization (Collaborative activities)	[46]

(1) Collaborative Activities

Collaborative activities among stakeholders in the woody biomass industry play a crucial role in the formation of the supply chain, and nearly all the reviewed papers list it as a key factor in the successful utilization of woody biomass. Paper 2 in Table 4 argues that the government's coordinating role is essential for promoting the development of the woody biomass industry. Paper 4 in Table 4 suggests that liaison meetings between stakeholders in the local woody biomass industry should highlight existing problems and facilitate their resolution, which is key to the smooth development of the local woody biomass industry [46]. A survey of stakeholders in the woody biomass industry in Paper 6 of Table 4 found that improving relationships and trust among stakeholders is crucial because strong business relationships can maintain the stability of collaboration. It also emphasizes the importance of cross-departmental collaboration, asserting that strategies and incentives related to woody biomass should be unified across the entire industry and intelligence transmission in the supply chain should be strengthened [48]. Paper 5 in Table 4 suggests that collaboration among stakeholders in the woody biomass industry can effectively address barriers to its advancement, such as financial (e.g., fundraising and management) and technical issues (e.g., equipment introduction and maintenance) [47].

(2) Cost reduction

High costs are one of the core issues hindering the promotion of woody biomass utilization. There are two main ways to address this issue: government subsidies and internal cost-reduction efforts by the woody biomass industry. Government subsidies include both direct subsidies and the development of forest-related infrastructure such as the construction of forest roads. A well-developed infrastructure can effectively reduce the costs of harvesting and transporting woody biomass [48]. Although infrastructure development cannot be classified as a subsidy, it is typically spearheaded by the government. Regarding how the woody biomass industry can reduce costs, Papers 2 and 6 in Table 4 propose measures that integrate woody biomass businesses with traditional timber businesses. Specifically, they advocate that businesses engaged in traditional wood activities, such as lumber and plywood production, diversify into woody biomass businesses based on existing wood operations. This integration allows for a more efficient reduction in the initial costs associated with woody biomass utilization [44,48].

(3) Regional revitalization

Regional revitalization is a key initiative in Japan's environmental policies. The utilization of woody biomass involves tapping into regional forest resources, which can effectively stimulate the development of forested areas. In Paper 6 of Table 4, upstream stakeholders of the supply chain believe that the woody biomass business can revitalize regional forestry and create job opportunities, whereas downstream stakeholders argue that regional economic development can be effectively promoted through the local production and consumption of woody biomass [48]. The results from Paper 5 in Table 4 demonstrate that the utilization of woody biomass can repatriate funds flowing out of the region and contribute to the effective promotion of the regional economic cycle [47].

(4) Forestry reformation and quality control of woody biomass fuel

Forestry reformation and quality control of woody biomass fuel were grouped in the same section owing to their emphasis on upstream and downstream stakeholders in the supply chain, respectively. Upstream stakeholders deem it crucial to utilize forest resources sustainably through long-term planning [44,48]. Additionally, Paper 6 in Table 4 suggests adopting different management systems for various forests to optimize resource utilization efficiency [47]. Many upstream stakeholders in Japan—often forest owners who have inherited their forests for generations—possess a strong attachment to them, making them likely to perceive forestry reformation as a key success factor. Conversely, downstream stakeholders in the supply chain focus more on the quality control of woody biomass fuels, recognizing their significant impact on the efficiency of power generation and heating [44,48].

(5) Elasticity of supply and demand

Paper 2 in Table 4 discusses the elasticity of woody biomass supply and demand, emphasizing the importance of securing multiple suppliers and buyers simultaneously to ensure stability in the woody biomass business [44]. With the increasing use of woody biomass in Japan, ensuring a stable supply of feedstock has gradually become a core issue. Therefore, ensuring multiple suppliers will help stabilize the feedstock supply. Additionally, ensuring that multiple buyers primarily target heat utilization is a suggested solution to the lack of heat demand.

5.3. Factors Contributing to Collaborative Behavior towards Woody Biomass Utilization

The factors promoting cooperation in the utilization of woody biomass are summarized from three perspectives—government, companies, and the public—and the results are presented in Table 5.

Table 5. Factors contributing to collaborative behavior towards woody biomass utilization.

Perspective	Paper No.	Year	Factors	Reference
Government	7	2012	1. New energy vision from the Kyoto Protocol (Climate change)	[49]
	5	2013	1. Measures to create a recycling-oriented society (Recycling-oriented society) 2. Forestry revitalization initiatives (Regional revitalization)	[47]
	8	2015	1. Creation of a forest low-carbon society (Climate change) 2. Reduction of fuel costs from fossil fuel substitution (Climate change) 3. Measures to promote forestry and an aging society (Regional revitalization) 4. Improvement of energy self-sufficiency (Recycling-oriented society) 5. Contribution to the local economy (Regional revitalization) 6. Creation of local employment (Regional revitalization)	[50]
	1	2015	1. Local production and consumption of energy resources (Recycling-oriented society) 2. Revitalization of the town (Regional revitalization)	[43]
	3	2021	1. Regional industry promotion and job creation (Regional revitalization)	[45]

Table 5. *Cont.*

Perspective	Paper No.	Year	Factors	Reference
Company	7	2012	1. Reduction of fuel costs (Company development) 2. Utilization of wood residues from its own mills (Company development) 3. Establishment and operation of a woody biomass research group (Collaborative activities)	[49]
	9	2013	1. Cognition of the potential of woody biomass business (Company development) 2. Cognition of the regional effects of woody biomass utilization (Regional revitalization) 3. Collaborative activities among companies (Collaborative activities) 4. Improvement of the company image (Company development) 5. Awareness of woody biomass utilization (Awareness of the woody biomass business) 6. Awareness of local initiatives (Awareness of the woody biomass business)	[51]
	10	2014	1. Business expansion (Company development) 2. Regional collaboration (Collaborative activities) 3. Contribution to the region (Regional revitalization) 4. Expenditure reduction (Company development) 5. Human resource capacity development (Company development)	[52]
Public	7	2012	1. High satisfaction with performance as a heating equipment 2. Reduction in fuel costs and CO_2 emissions	[49]
	9	2013	1. High intention for direct utilization, but low actual number of users 2. Intention of indirect utilization is much higher than direct utilization	[51]
	11	2017	1. Low intention for direct utilization and low actual number of users 2. Utilization in public facilities is desirable, such as hot springs and hospitals	[53]
	12	2019	1. High intention for direct utilization, but low actual number of users	[54]
	13	2019	1. High intention to use hot spring fueled by woody biomass 2. High awareness of region, environment, and forests	[55]
	14	2022	1. High intention to use hot spring fueled by woody biomass 2. Frequent visits to forests 3. High awareness of forests	[56]
	4	2019	1. High satisfaction with performance as a heating equipment	[46]

From a government perspective, the reviewed papers focused primarily on local governments in Japan. Regional revitalization has emerged as a key factor driving the participation of local governments in the woody biomass business, addressing issues commonly observed in Japanese localities such as population decline and industrial downturns. Furthermore, the involvement of woody biomass businesses aligns with the recent environmental policy of the Japanese government, which is primarily characterized by its commitment to addressing climate change, fostering regional revitalization, and promoting a recycling-oriented society.

From the companies' perspective, there is a strong likelihood that they will consider collaborative woody biomass activities as part of their business expansion. Many companies aim to increase their revenue through the development of woody biomass businesses, either by expanding their operations or reducing costs. Moreover, heightened awareness of woody biomass and regional development are pivotal factors that encourage companies to engage in woody biomass utilization. Increased awareness of woody biomass can motivate companies to participate more actively, and regional revitalization can enhance the local economy and attract companies with a regional focus.

From a public perspective, we classified the factors into three categories: intention to use, reasons for utilization, and factors influencing cooperative activities for woody biomass utilization. Private utilization of woody biomass is primarily for heating in households or public facilities and can be classified into direct utilization, which involves the purchase of heating equipment fueled by woody biomass, and indirect utilization, which involves the use of public facilities fueled by woody biomass. Public willingness for direct utilization is not particularly strong, while in some regions, more than half of the respondents expressed a willingness for direct utilization, and the actual number of users remained small [51,54]. Furthermore, the majority of respondents expressed reservations about the drawbacks associated with heating equipment fueled by woody biomass, such as its complex operation and high costs [53]. In contrast, public willingness for indirect utilization was remarkably high, especially in public facilities such as hot springs and welfare facilities [55,56]. Additionally, the unique capabilities of woody biomass heating equipment [46,49] and awareness of forests, the environment, and local regions [55,56] are the primary reasons why the public is willing to utilize woody biomass.

6. Economic Evaluation of Woody Biomass Utilization

From an economic perspective, the reviewed papers were mainly concerned about three aspects: feasible conditions for woody biomass power generation, cost analysis of woody biomass heat utilization, and the economic impacts of woody biomass utilization.

6.1. Feasible Conditions for Woody Biomass Power Utilization

The cost structure of a wood biomass power generation plant and the relevant factors of feasible conditions for wood biomass power generation are shown in Tables 6 and 7, respectively. Feedstock, depreciation, and maintenance costs account for more than 90% of the total cost of wood biomass power generation. Additionally, nearly half of the total cost comprises feedstock costs, and the effective reduction of fuel costs is considered the key to improving the economic efficiency of wood biomass power generation. However, the economics of woody biomass power generation are influenced by many factors. Studies often keep certain variables constant and analyze the impact of changes in other variables on the viability of the project through scenario analysis when assessing the economics of woody biomass power generation. There are three main criteria for judging the feasible conditions for wood biomass power generation: the internal rate of return (IRR), payback period, and balance of income and expenditure. In general, eight percent of the estimated value published by the Japan Agency for Natural Resources and Energy was used for the IRR. In many cases, the payback period is based on the 15-year legal life of a power generation facility or the 20-year FIT project period [57,58]. The evaluation of the balance between income and expenditure is relatively simple, and a business is judged viable if it does not generate a deficit [59].

Table 6. Cost structure of wood biomass power generation plant.

Paper No.	**Year**	**Utilization Type**	**Cost Structure [%]**				
			Feedstock	**Depreciation**	**Fixed Property Tax**	**Labor**	**Maintenance**
1	2015	PG	64.0−76.6	8.5−12.6	0.9−1.3	1.6−5.7	5.0−7.4
2	2021	PG	69	15	1	3	7
3	2022	CHP	59	22	2	5	10

Paper No.	Cost structure [%]					Reference
	Insurance cost	General administrative cost	Ash disposal	Utility cost	Repayment for interest on borrowing	
1	0.7−1.0	0.4−1.4	0.6−0.8	2.2−4.6	2.3−3.4	[59]
2	1	1	1	2	N.A.	[57]
3			2			[60]

N.A.: Not applicable.

Table 7. Relevant factors of feasible conditions for wood biomass power generation.

Paper No.	**Year**	**Utilization Type**	**Fuel Type**	**Annual Operating Hours [h]**	**Fuel Price [JPY/t]**	**Moisture Content of Fuel**
1	2015	PG	Chip	7920	Variable	Variable
4	2017	PG & CHP	Chip	7920	9000	50% W.B.
5	2018	PG	Chip	7920	Variable	15% W.B.
2	2021	PG	Chip	8760	Variable	30% W.B.
3	2022	CHP	Pellet	Variable	26,000	7% W.B.

Table 7. *Cont.*

Paper No.	Selling price of heating [JPY/kWh]	Scale of power generation [kW]	Scale of heating [kW]	Judgment criteria for feasible conditions	Reference
1	N.A.	Variable	N.A.	Balance of income and expenditure	[59]
4	5.2	Variable	Variable	Payback period & IRR	[58]
5	N.A.	40	N.A.	IRR	[61]
2	N.A.	Variable	N.A.	Payback period & Fuel price	[57]
3	6	1815	Variable	Payback period & IRR	[60]

PG: Power generation; W.B.: Wet basis; 1 USD = 116.49 JYP (1 January 2017); 1 USD = 115.02 JYP (1 January 2022); 1 USD = 141.83 JYP (1 January 2024); N.A.: Not applicable.

Although many factors influence the feasible conditions of wood biomass power generation, many studies have indicated that wood biomass power generation has the characteristics of economies of scale. Paper 4 in Table 7 showed that, when using woody chips with a moisture content of 50% W.B. and a unit cost of 9000 JPY/t, small-scale power generation below 1600 kW is unprofitable [58]. Additionally, Paper 1 in Table 7, by calculating the break-even point for wood biomass power generation, showed that small-scale power generation requires the purchase of feedstock at lower prices to ensure economic viability [59]. In addition to economies of scale, combined heat and power (CHP) positively affect the economics of wood biomass power generation. Papers 3 and 4 in Table 7 examined the conditions under which CHP is feasible and showed that CHP greatly improves utilization efficiency and is more economical than only power generation at the same scale. However, as mentioned previously, large-scale heat utilization is difficult to fully utilize because of the large amount of heat produced. Paper 4 in Table 7 found that, if the produced heat cannot be completely sold, the effect of improved economic efficiency is not considerable. Moreover, in the case of Paper 3 in Table 7, half of the heat produced is disposed of [58,60].

6.2. Cost Analysis of Woody Biomas Heat Utilization

Woody biomass heat utilization is primarily focused on the small-scale utilization in public facilities. Various types of facilities and fuels were available. Therefore, qualitative economic evaluation is challenging. Existing research has mainly focused on the cost analysis of heat utilization. The initial and running costs of wood biomass heat utilization, as estimated in the reviewed papers, are shown in Table 8 (where multiple scenarios exist, each scenario is considered as one case). The initial and running costs per unit output scale were calculated to compare the results of each study.

Table 8. Cost structure of wood biomass heat utilization.

Case No.	Year	Utilization Facilities	Scale [kW]	Fuel Type	Fuel Price [JPY/t]	Running Cost [k JPY/year]	Unit Running Cost [k JPY/t]	Initial Cost [k JPY]	Unit Initial Cost [k JPY/t]	Reference
1	2012	Hot spring	200	Chip	10,000	4060	20.8	23,400	117.0	[62]
2	2012	Hot spring	200	Chip	12,000	5808	19.8	28,900	144.5	[62]
3	2012	Nursing home	290	Chip	10,000	1629	21.9	28,950	99.8	[62]
4	2012	Nursing home	290	Chip	12,000	2294	20.5	34,950	120.5	[62]
5	2012	Agricultural facilities	116	Chip	10,000	554	26.6	16,000	137.9	[62]
6	2012	Agricultural facilities	116	Chip	12,000	740	23.6	20,500	176.7	[62]

Table 8. *Cont.*

Case No.	Year	Utilization Facilities	Scale [kW]	Fuel Type	Fuel Price [JPY/t]	Running Cost [k JPY/year]	Unit Running Cost [k JPY/t]	Initial Cost [k JPY]	Unit Initial Cost [k JPY/t]	Reference
7	2017	Hotel	570	Chip	12,000	23,770	15.7	100,000	175.4	[63]
8	2017	DHS	810	Chip	12,000	23,060	15.3	465,200	574.3	[63]
9	2020	Residence	200	Chip	10,000	3735	13.2	85,410	427.1	[64]
10	2012	Hot spring	200	Pellet	35,000	6638	40.5	15,270	76.4	[62]
11	2012	Nursing home	290	Pellet	35,000	2610	41.9	22,570	77.8	[62]
12	2012	Agricultural facilities	116	Pellet	35,000	829	47.6	6870	59.2	[62]
13	2014	Hot spring	225	Firewood	13,500	5030	25.8	35,460	157.6	[65]
14	2017	Hotel	570	Firewood	11,300	29,470	19.5	40,400	70.9	[63]
15	2017	DHS	810	Firewood	11,300	23,880	15.8	433,000	534.6	[63]

1 USD = 77.74 JYP (1 January 2012); 1 USD = 105.39 JYP (1 January 2014);1 USD = 116.49 JYP (1 January 2017); 1 USD = 109.56 JYP (1 January 2020); 1 USD = 141.83 JYP (1 January 2024).

The initial and running costs of wood biomass heat utilization vary significantly, depending on the facility and fuel type. The initial costs for DHSs and residences were notably high—approximately three times higher than those for other facilities. This is attributed to the substantial piping expenses associated with DHSs and residences. In Cases 8 and 15 shown in Table 8, the piping costs constituted more than 90% of the initial cost. In contrast, the running costs for DHSs and residences were lower than those for other facilities, primarily because of economies of scale resulting from large-scale heat utilization [63]. Additionally, the initial cost of facilities using firewood or pellets is lower than that of facilities using chips. This is because boilers for chips are more expensive than those for other fuels and require the construction of dedicated fuel storage silos. Lastly, the running costs for facilities using pellets are higher because the price of pellets is approximately three times higher than that of other fuels [62].

6.3. Economic Impacts of Woody Biomass Utilization

The economic impact of woody biomass utilization is presented in Table 9. While all these studies utilized the input−output (IO) table to calculate economic impacts, significant variations existed owing to differing conditions in the woody biomass industry across regions and variations in the IO tables used in each study. In general, the results indicate that greater economic impacts were generated by increased woody biomass inputs. For instance, in Case 11 of Table 9, the largest economic impacts of 2905 million JPY were obtained by assuming the total annual woody biomass supply potential to be available in the western region of Tottori Prefecture, Japan [66]. To normalize the economic impact of woody biomass utilization, the economic impacts per unit input were calculated, revealing that the production of one ton of woody biomass had economic impacts ranging from approximately 66 to 249 million JPY/t for the region.

Table 9. Economic impacts of woody biomass utilization.

Case No.	Region and Year	Total Impact [mil. JPY]						Economic Impacts Per Unit Input [mil. JPY/t]	Reference
		Total Output	Multiplier	Value-Add	Multiplier	Income Effect	Multiplier		
1	Kouchi Pref., 2012	349.0	1.65	169.0	1.89	90.0	1.63	N.A.	[67]
2	Yusuhara city, Kochi Pref., 2012	49.0	1.40	22.0	1.58	13.0	1.35	N.A.	[67]
3	Maniwa city, Okayama Pref., 2013	447.7	1.70	208.1	1.90	90.6	1.80	231.97	[68]
4	Iwaki city, Fukushima Pref., 2013	1387.0	N.A.	N.A.	N.A.	N.A.	N.A.	194.02	[69]
5	Maniwa city, Okayama Pref., 2013	1062.0	N.A.	364.0	N.A.	N.A.	N.A.	127.49	[70]

Table 9. *Cont.*

Case No.	Region and Year	Total Impact [mil. JPY]						Economic Impacts Per Unit Input [mil. JPY/t]	Reference
		Total Output	Multiplier	Value-Add	Multiplier	Income Effect	Multiplier		
6	Nishiwaga town, Iwate Pref., 2014	7.8	1.28	N.A.	N.A.	N.A.	N.A.	N.A.	[71]
7	Maniwa city, Okayama Pref., 2015	179.5	1.50	102.1	1.50	N.A.	N.A.	75.71	[72]
8	Maniwa city, Okayama Pref., 2015	203.9	1.50	117.3	1.50	N.A.	N.A.	108.85	[72]
9	Maniwa city, Okayama Pref., 2015	123.9	1.60	60.3	1.80	N.A.	N.A.	248.95	[72]
10	Western Tottori Pref., 2017	1234.0	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	[66]
11	Western Tottori Pref., 2017	2905.0	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	[66]
12	Kamaishi City, Iwate Pref., 2020	1.9	1.23	N.A.	N.A.	0.3	N.A.	66.08	[64]

1 USD = 77.74 JYP (1 January 2012); 1 USD = 86.58 JYP (1 January 2013);1 USD = 105.39 JYP (1 January 2014); 1 USD = 120.55 JYP (1 January 2015); 1 USD = 116.49 JYP (1 January 2017); 1 USD = 109.56 JYP (1 January 2020); 1 USD = 141.83 JYP (1 January 2024). N.A.: Not applicable.

7. Environmental Impact Assessment of Woody Biomass Utilization

From an environmental perspective, the reviewed papers have predominantly explored the reduction effect of greenhouse gas (GHG) emissions resulting from woody biomass utilization. To facilitate a comparison of the findings of these studies, GHG emission reductions were standardized per gigajoule (GJ).

7.1. GHG Emission Reduction Effect of Woody Biomass Power Generation

The reviewed papers did not employ uniform estimation methods; instead, they utilized four distinct approaches: substitution effects, energy flows, life cycle assessment (LCA), and IO analysis. Substitution effect and energy flow are relatively simple estimation methods. The substitution effect calculates the GHG emissions produced by fossil fuels replaced by woody biomass, using it as the GHG emission reduction resulting from woody biomass utilization. Energy flow considers fossil fuel consumption in the process from woody biomass raw material collection to energy utilization, building upon the calculations made in the substitution effect. In contrast, LCA and IO analysis are more comprehensive estimation methods. LCA evaluates the environmental impact of the entire process, from raw material mining to the final disposal of waste, whereas IO analysis estimates the environmental impacts from an economic perspective by analyzing the inputs and outputs of a target sector.

The reduction in GHG emissions resulting from the utilization of wood biomass power generation is presented in Table 10 (where multiple scenarios exist, each scenario is considered as one case). Due to variations in the estimation methods employed by different studies, the calculated GHG emission reductions exhibit a wide distribution, ranging from −17.29 to 131.87 kg-CO_{2eq}/GJ. Among them, Case 1 in Table 10 calculates the utilization of woody biomass power generation using thinned wood, with a power generation efficiency of 20%, and finds that the GHG emission reduction is negative. In other words, woody biomass power generation results in greater GHG emissions than existing fossil energy power generation. This situation arises because Case 1 assumes the use of thinned wood as fuel with low power generation efficiency. Case 3 in Table 10 explores a scenario in which the power generation efficiency is increased to 30% under the same conditions as in Case 1, resulting in a positive GHG emission reduction [73]. In addition, Case 11 in Table 10 conducted an assessment of the construction and operation of the woody biomass power plant and found that, compared with traditional thermal power plants, the GHG emissions generated by the woody biomass power plant would be reduced by 25.08 kg-CO_{2eq}/GJ [74]. In the field of CHP, Cases 9 and 10 in Table 10 used different research methods, and estimated GHG emission reductions are 202.44 kg-CO_{2eq}/GJ and 44.21 kg-CO_{2eq}/GJ, respectively. The evaluation results for Case 10 show a larger GHG emission reduction effect, surpassing any of the cases listed in Table 10. This difference may be attributed to Case 10 not considering the GHG emissions generated during the resource collection process [75].

Table 10. GHG emission reductions of woody biomass power generation.

Case No.	Year	Utilization Type	Power Generation Efficiency [%]	Fuel Type	Method	Displaced Fossil Fuel	GHG Emission Reduction [kg-CO_{2eq}/GJ]	Reference
1	2013	PG	20	Chip	LCA	Grid electricity	−17.29~66.63	[73]
2	2013	PG	20	Chip	LCA	Grid electricity	34.01~117.93	[73]
3	2013	PG	30	Chip	LCA	Grid electricity	41.82~97.86	[73]
4	2013	PG	30	Chip	LCA	Grid electricity	76.11~131.87	[73]
5	2018	PG	40	Pellet	Energy flow	Coal	63.61	[76]
6	2018	PG	40	Chip	Energy flow	Coal	70.00	[76]
7	2019	PG	N.A.	N.A.	Substitution effects	Grid electricity	55.06	[55]
8	2021	PG	21.8	Chip	Substitution effects	Grid electricity	3.69	[75]
9	2016	CHP	N.A.	Chip	IO Analysis	Grid electricity	202.44	[77]
10	2021	CHP	N.A.	Chip	Substitution effects	Grid electricity	44.21	[75]
11	2015	Power Plant Construction	N.A.	N.A.	IO Analysis	Thermal power plant	25.08	[74]

N.A.: Not applicable.

7.2. GHG Emission Reduction Effect of Woody Biomass Heat Utilization

The environmental impact assessment of woody biomass heat utilization covers various facilities, with estimated GHG emission reductions ranging from 2.57 to 75.93 kg-CO_{2eq}/GJ (Table 11). The evaluation method for woody biomass heat utilization is essentially the same as that for power generation, but the range of variation is smaller. With the exception of Cases 1, 7, 8, 9, and 18 in Table 11, the estimated results fall within the range of 60 to 80 kg-CO_{2eq}/GJ. Among these, Cases 7, 8, and 9 discuss GHG emission reductions when replacing different types of fossil fuels based on the same heat utilization facility. The estimated results of these three cases were relatively small because the set heat utilization efficiency was low, at only 29%. Case 10 from the same study explored a scenario in which the heat utilization efficiency increased to 75%, resulting in a GHG emission reduction effect of 65.3 kg-CO_{2eq}/GJ [78]. Case 1 only calculated the GHG emission changes caused by the two processes of fuel production and equipment manufacturing without considering the energy conversion process, leading to smaller calculated values [77]. In general, compared to power generation, the GHG emission reduction brought about by woody biomass heat utilization is more stable, likely owing to its smaller scale and higher energy-conversion efficiency.

Table 11. GHG emission reductions of woody biomass heat utilization.

Case No.	Year	Method	Utilization Facilities	Heat Utilization Efficiency [%]	Displaced Fossil Fuel	GHG Emission Reduction [kg-CO_{2eq}/GJ]	Reference
1	2016	IO Analysis	Household	N.A.	Light oil	2.57	[77]
2	2012	LCA	Household	N.A.	Heating oil	60.53	[79]
3	2012	LCA	Household	N.A.	Heating oil	78.65	[79]
4	2015	LCA	Factory	N.A.	Kerosene	72.36	[72]
5	2015	LCA	City hall	N.A.	Kerosene	79.53	[72]
6	2015	LCA	Household	N.A.	Kerosene	58.58	[80]

Table 11. *Cont.*

Case No.	Year	Method	Utilization Facilities	Heat Utilization Efficiency [%]	Displaced Fossil Fuel	GHG Emission Reduction [kg-CO_{2eq}/GJ]	Reference
7	2016	LCA	DHS	29	LPG	21.60	[78]
8	2016	LCA	DHS	29	Kerosene	23.10	[78]
9	2016	LCA	DHS	29	Heavy oil	25.70	[78]
10	2016	LCA	DHS	75	LPG	65.30	[78]
11	2022	LCA	Hot spring	90	City gas	60.00	[56]
12	2022	LCA	Hot spring	90	heavy oil	76.30	[56]
13	2022	LCA	Hot spring	90	Kerosene	69.60	[56]
14	2014	Substitution effects	Household	63	Kerosene	68.25	[71]
15	2019	Substitution effects	Hot spring	N.A.	heavy oil	62.47	[55]
16	2019	Substitution effects	Hot spring	N.A.	Diesel	60.49	[55]
17	2020	Substitution effects	Residence	80	LPG	59.22	[64]
18	2021	Substitution effects	DHS	80	City gas	46.11	[75]

N.A.: Not applicable.

8. Discussion

Building on previous discussions on the current state of research on woody biomass utilization in Japan, several significant issues have been identified. This chapter delves into the primary causes of these issues and proposes solutions by drawing upon the experiences of countries with advanced woody biomass utilization.

8.1. More Detailed Forest Inventories

Most studies estimating the supply of woody biomass in Japan have adopted a long-term macroeconomic perspective, with only a few relying on short-term estimates derived from actual harvest records. Furthermore, short-term estimates often deviate significantly from actual timber supply and demand records. One potential explanation for this discrepancy is the limited availability of detailed records of forest management and operations in Japan. Compared to the empirical growth models used to estimate changes in forest conditions, such as stocks and area, matrix models based on transition probabilities offer a more precise estimation of short-term changes through scenario analysis [81]. However, the application of matrix models requires a foundation of detailed forest management and operational records spanning several years, which are not readily available in Japan. Forests in Japan are managed by different entities based on ownership, and many management entities, including the national government, local governments, and private individuals, disperse their forest management and operations. This dispersion makes it challenging to obtain accurate and comprehensive forest management and operational records. The absence of such records not only hinders the accurate measurement of the current forest status, but also undermines the ability to provide a reliable basis for future projections.

Many countries promote the establishment of National Forest Inventories to enhance forest surveys and monitor forest status at the national level [81]. Notably, the United States initiated The Forest Inventory and Analysis (FIA) research program in 1928. Over nearly 100 years of development, the FIA has evolved with various functions, ranging from early timber resource assessment to current forest ecosystem observations [82]. Numerous studies have been conducted on FIA across a wide range of fields, including forest resources assessment [83], forest management [84,85], and forest disasters [86]. It is evident that detailed forest management and operational records are essential not only for Japan, but also for any country that values its forest resources.

8.2. More Comprehensive Forest Projection Systems

Although most of the timber supply in Japan comes from planted forests, natural forests still constitute approximately 57% of the country's total forest area and 36% of its total forest stock. From the perspective of resource existence, their significance cannot be overlooked [87]. However, owing to the lack of projection systems, only a few studies have been conducted on natural forests, with the majority focusing on planted forests. Furthermore, most studies utilize yield tables as projection tools. These yield tables were developed in the 1950s or 1960s and often cover forests less than 100 years old [88]. However, following the postwar period, the Japanese government initiated a massive reforestation program, resulting in many forests between 60 and 80 years old, with expectations to exceed 100 years old in the next few decades [87]. Existing projection systems cannot adequately address this evolving situation.

In Europe, where woody biomass is widely utilized, many countries have established national-level projection systems [81]. Prediction systems for the entire EU have also undergone rapid development in recent years [89–91]. Some prediction systems have incorporated new functions, such as addressing climate change [92], forest disasters [93], and carbon sequestration [94], in addition to traditional resource estimations. In Japan, existing forest prediction tools are outdated, and a more comprehensive prediction system needs to be developed at the national level.

8.3. Balancing Cost and Scale of Wood Biomass Business

In Japan, woody biomass utilization has already reached a significant level and contributed to regional revitalization to some extent. However, the high cost of woody biomass utilization is a pressing issue that requires prompt resolution, despite substantial government subsidies. FIT and economies of scale play crucial roles in the success of woody biomass power generation: FIT enables power plants to sell electricity at prices above market rates, while economies of scale reduce the costs associated with constructing and operating power plants. Nevertheless, the increased prices resulting from FIT are ultimately borne by the Japanese public in the form of taxes. Additionally, as the scale of woody biomass power generation has expanded, the demand for woody biomass fuels has increased. Owing to the prolonged slump in Japan's domestic wood industry, supply has not been able to keep up with the rapid increase in demand, consequently causing the price of woody biomass fuel to skyrocket. Fuel costs account for nearly 60% of the total cost of woody biomass power generation and significantly impact the success of the woody biomass business. Furthermore, owing to the decentralization and fragmentation of Japanese forests, the cost of wood harvesting is relatively high [95]. Therefore, although the FIT and economies of scale have temporarily promoted the widespread use of woody biomass for power generation, they do not represent a fundamental solution. On the other hand, government subsidies play a crucial role in the establishment of wood biomass heat utilization, with many heat utilization businesses benefiting from subsidies that reduce or exempt about half of their initial costs, including equipment and construction costs [96]. However, it is important to note that government subsidies typically cover only the initial costs. Consequently, many heat utilization businesses remain susceptible to fluctuating fuel prices, causing instability [44]. While economies of scale also apply to heat utilization, challenges such as the lack of infrastructure and difficulties in ensuring sufficient heat demand hinder the potential for cost reduction through scale increases.

Many studies have considered CHP as an excellent solution for reducing the cost of woody biomass utilization because the high efficiency of heat utilization enhances the overall energy utilization efficiency, resulting in significant cost savings [75,97,98]. However, as mentioned earlier, CHP generates a substantial amount of heat, and the key challenge lies in its effective utilization. In countries with advanced woody biomass utilization, such as Finland and Estonia, government subsidies support the utilization of woody biomass, whereas a stable heat demand is ensured through DHSs by integrating CHP facilities with residential and industrial areas [6]. Nevertheless, DHSs are rare in Japan, and the high cost of constructing DHSs makes it nearly impossible for the private sector to promote them. Therefore, when promoting CHP, it is important not only to conduct urban planning to ensure sufficient heat demand but also to encourage the construction of heat utilization infrastructure and DHSs with public funds.

9. Conclusions

This paper summarizes research papers on woody biomass utilization in Japan, covering both the resource supply upstream of the woody biomass supply chain and a case study downstream. On the resource supply side, most studies have estimated the supply potential and availability of woody biomass for privately owned coniferous-planted forests. The calculated annual supply potentials ranged from 1.2 to 5.5 m^3/year/ha and were strongly influenced by the availability of branches and leaves, as well as the rate of woody biomass from final felling and thinning. The availability of woody biomass is primarily influenced by topographical limitations, such as the average slope and forwarding distance of the harvested area. In the absence of subsidies, the amount of woody biomass available ranged from 1.3% to 40.0% of the supply potential. Measures to increase the percentage of available volume include government subsidies, mechanization of forestry operation systems, and aggregation of forests. Concerning the case study, initially, from a social perspective, development was the primary factor driving cooperation in the woody biomass business for both local governments and companies. However, for the public, indirect utilization is preferred over direct utilization. Second, from an economic standpoint, the woody biomass industry can generate economic impacts of 66–249 million JPY/t in local regions. However, the high cost of woody biomass utilization remains a problem that must be promptly addressed. Finally, from an environmental perspective, the distribution of GHG emission reductions estimated in each study is broad, but overall, the substitution of woody biomass for fossil fuels in power generation and heating can lead to GHG emission reductions of -17.29 to 202.44 kg-CO_{2eq}/GJ and 2.57 to 79.93 kg-CO_{2eq}/GJ, respectively.

Looking forward to the future, understanding the future changes in woody biomass resource amounts and production factors is extremely important for achieving environmental goals. However, due to the lack of forest projection systems and detailed forestry statistical data, most current research focuses on the present, making it difficult to discuss the future. Therefore, building a detailed forestry database and a comprehensive projection system is an urgent issue that needs to be addressed. Additionally, research in many areas other than Tochigi Prefecture has not been verified. Given the scattered forestry statistics in Japan, this task may seem relatively large, but it should be implemented in the future. Finally, most studies focus on woody biomass derived from forests. However, in Japan, the most common use is woody biomass chips, accounting for about 90% of the total. As for the raw materials for chip production, only 45% come from logs harvested in forestry activities, while the remaining 40% come from sawmill residues, 14% from construction waste, and 1% from forest residues [14]. Further discussion is needed on the impact of sawmill residues and construction waste on woody biomass supply. Regarding the case study, although CHP is highly regarded in most studies, its effective application in Japan remains a challenge. In addition to traditional environmental and economic issues, it is also necessary to address DHSs, urban planning, and other factors, starting with the energy utilization system of the entire region, to enable a more comprehensive discussion in the future.

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