Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Beyond supply-chain risk: a three-tier social life cycle assessment of wood-based aviation fuel in Japan

Ziyi Han
The University of Tokyo
Heng Yi Teah
teah@platinum.u-tokyo.ac.jp

The University of Tokyo
Yuichiro Kanematsu
The University of Tokyo
Yasunori Kikuchi
The University of Tokyo

Article

Keywords:

Posted Date: November 24th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11692006/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Beyond supply-chain risk: a three-tier social life cycle assessment of wood-based aviation fuel in Japan

Ziyi Han[1], Heng Yi Teah[2*], Yuichiro Kanematsu[2], Yasunori Kikuchi[1,2,3,4*]

[1] Department of Chemical System Engineering, The University of Tokyo, 113-8656 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan

[2] Presidential Endowed Chair for "Platinum society", The University of Tokyo, 113-8656 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan

[3] Institute for Future Initiatives, The University of Tokyo, 113-8654 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan

[4] UTokyo LCA Center for Future Strategy, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan

* Corresponding authors: H.Y. Teah (teah@platinum.u-tokyo.ac.jp); Y. Kikuchi (ykikuchi@ifi.u-tokyo.ac.jp)

Abstract

Japanese policy promotes domestic feedstocks, including wood, for sustainable aviation fuel (SAF), partly to revitalize feedstock-producing regions. We apply a three-tier social life cycle assessment to Fischer–Tropsch SAF from sawmill residue: supply-chain risk screening, regional feasibility to 2120 and six companies' documented conduct. The route places more of its work in Japan than fossil jet, yet most screened risk lies overseas. Comparisons with fossil jet and used-cooking-oil SAF depend on the activity basis and residue mapping. Under business as usual, attributed forestry work gains weight in all 47 prefectures as labor forces contract, while the route's added value falls relative to regional output. Companies document supplier governance, most clearly for

forced labor, yet feedstock companies hold no assessable evidence on forestry safety. The domestic work thus gains weight while remaining the least evidenced part of the route. Its social performance depends on input procurement, host-region planning and supplier evidence.

Introduction

Domestic wood is among the feedstocks that Japan's policy for sustainable aviation fuel (SAF) is considering, and a government-funded demonstration has already produced Fischer–Tropsch jet fuel from wood chips (NEDO, 2021). Part of the case made for this feedstock is social. The national biomass plan commits ministries to coordinating the supply of domestic biomass as SAF feedstock and expects locally led biomass businesses to secure jobs and incomes in rural villages (MAFF, 2022). The annual forest report presents the energy use of wood as supporting regional economies and employment immediately before it introduces wood-based SAF (Forestry Agency, 2026a). The secretariat of the public-private council on SAF lists the economic revitalization of feedstock-producing and plant-host regions among the reasons for investing in domestic production (ANRE and MLIT, 2026). These statements attribute to a domestic feedstock social consequences that would remain in the country. This study examines what using domestic wood for SAF actually makes domestic in social terms.

The social case for such a use combines claims that rest on different kinds of evidence. One concerns the potential social risk along the supply chain, another the contribution of the activity to the regions that host it, and a third the conduct of the companies through which production would be carried out. The guidelines for social life cycle

assessment (S-LCA) distinguish the corresponding forms of evidence. Potential risks are flags derived mostly from country, sector or company information, performance is assessed against reference points, and claims of actual social impact require observed and verified primary data (UNEP, 2020). In this study, the first claim is examined as potential risk, the second through modeled regional quantities, and the third as documented performance against reference points. Each of these claims depends on more than the origin of the feedstock. The supply-chain risk depends on the full set of purchased inputs and the countries that supply them, and the regional contribution depends on the labor forces and economies of the host regions. The evidence on conduct depends on what the companies involved document about their own operations and their suppliers.

Existing approaches establish how each kind of evidence can be obtained, and each has limits that bear on this question. Database screening with the Social Hotspots Database or the Product Social Impact Life Cycle Assessment database (PSILCA) extends coverage to upstream suppliers at the resolution of countries and sectors, and its developers caution against using the resulting rankings to shift sourcing without site-specific information (Benoit-Norris et al., 2012). Applications have located much of the screened result abroad. In the assessment of Finnish wood products by Mattila et al. (2018), 56% of the total score occurred outside Finland. In their assessment of a biomass-to-liquid fuel, Zeug et al. (2023) concluded that global fossil-based supply chains shift most negative social and economic effects to other countries. Regional assessments resolve the places of production but represent future organizations through sector averages. In the assessment of a prospective Fischer–Tropsch fuel chain in Eastern Germany, biofuel production generated employment while working conditions

and workers' participation performed poorly, and the upstream chain was left to separate screening (Gan Yupanqui et al., 2024). Regional studies more generally do not consider effects outside the region in detail (Macombe et al., 2013). In Japan, local studies have estimated the employment and economic effects of woody biomass in particular localities without examining working conditions or organizational conduct (Moon et al., 2013; Miyamoto et al., 2022). Screening has also been used to select the concerns examined with more specific evidence, whether for named organizations (Tsalidis et al., 2023) or through stakeholder prioritization (Bouillass et al., 2021). The importance of social concerns has also been set through experts and stakeholders, as in the assessment of a pilot biorefinery producing biofuels for aviation and maritime transport (Kostidi and Lyridis, 2024). Such evidence depends in turn on what companies choose to disclose and on the coverage of their audits (Marquis et al., 2016; LeBaron and Lister, 2015). What remains unknown is how the three kinds of evidence relate to one another for a single route: whether the regional contribution, the screened risk and the evidence on conduct lie in the same part of the value chain, and how their relationship changes as the host regions change.

Japan's wood-based SAF route makes this relationship a demanding test. Its feedstock is a domestic, land-based resource whose supply is distributed across prefectures, whereas its conversion requires chemicals and other inputs purchased on wider markets. The regional labor forces against which the attributed work would be measured are projected to contract over the coming century (Methods), and forestry already has the highest annual rate of work-related casualties per 1,000 workers of any industry in Japan (Forestry Agency, 2026b). The annual forest report also notes that rising demand for fuelwood for power has led to competition with existing users of wood (Forestry

Agency, 2026a). The route thus joins a regionally distributed resource and changing regional economies to inputs and organizations located beyond those regions. The relationship among the three kinds of evidence bears on decisions taken at different points of the route: the purchase of conversion inputs, the planning of host regions and the evidence required from suppliers.

This study examines the route through three tiers that keep these forms of evidence separate (Fig. 1). Tier 1 screens the potential social risk of Fischer–Tropsch jet fuel from domestic sawmill residue (Wood-FT) against fossil jet fuel and against SAF produced in Japan from used cooking oil (UCO-HEFA). Tier 2 follows the work, regional added value and chip resource attributed to the route in Japan's 47 prefectures from 2025 to 2120 under four socioeconomic scenarios. Tier 3 examines the documented conduct of six companies whose functions are relevant to the route, on concerns identified by Tier 1. Each tier is reported in its own units, and the tiers are not combined into a single score.

Here we show that Wood-FT places a large share of its supply-chain work in Japan, although most of this work, and most of its screened risk, lies in overseas supply chains. Its screened comparison with fossil jet and with UCO-HEFA depends on the activity basis and on the sector to which the sawmill residue is assigned. The attributed forestry work gains weight in the supplying regions mainly because their labor forces contract, and most of it lies in prefectures where incumbent demand for chips exceeds eligible domestic supply. Under business as usual, the route's added value declines relative to regional output. The supplier governance documented by the assessed companies partly follows where the screened concerns lie, and the documents of the feedstock companies

contain no assessable evidence on the health and safety of the forestry work. The results of our framework indicate that domestic wood-based SAF places a large share of its work in Japan while relying on overseas supply chains for most of it, and that the weight of the domestic work depends on the host regions and on forestry conditions beyond the documented conduct of the assessed companies.

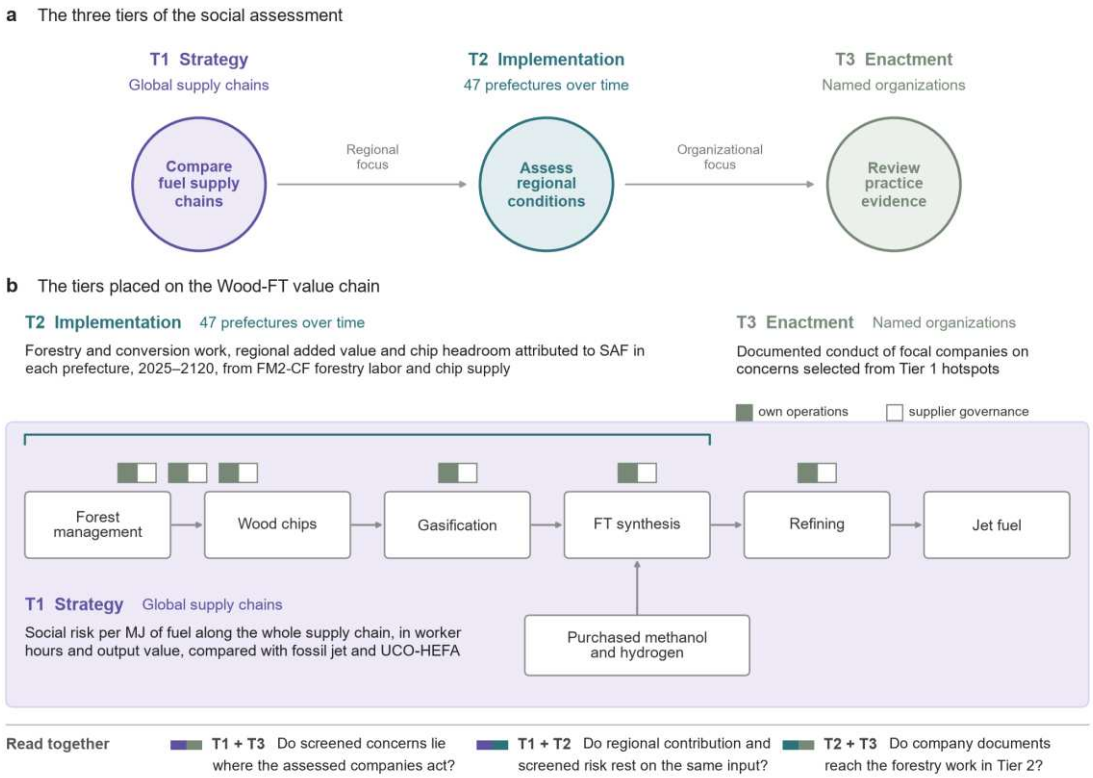


Figure 1 Three-tier framework for the social assessment of domestic wood-based SAF. a, The three tiers and their scales: global supply chains (Tier 1), 47 prefectures over time (Tier 2) and named organizations (Tier 3). **b**, The tiers placed on the Wood-FT value chain. Tier 1 covers the whole supply chain, including the methanol and hydrogen purchased by the FT plant. Tier 2 covers the domestic stages from forest management to FT synthesis. Tier 3 assesses focal companies at their functional positions, each for its own operations and for its governance of suppliers. The pairs at the bottom name the

questions addressed by reading two tiers together (Discussion). FT, Fischer–Tropsch; FM2-CF, Forest Management Model for Cyclical Forestry; UCO-HEFA, hydroprocessed esters and fatty acids from used cooking oil.

Results

Overview of the framework

Figure 1 summarizes the framework and places the tiers on the Wood-FT value chain. Tier 1 screens potential social risk with the PSILCA v4 database (GreenDelta, 2025), which assigns risk through country–sector averages within a multiregional input–output model, and aggregates 102 risk indicators into 35 risk subcategories. Results refer to a functional unit of 1 MJ of fuel and are expressed on two activity bases: worker hours, which weight the risk of the labor that a route mobilizes along its supply chain, and output value, which weights the risk of the economic activity that it generates. Each route is compared with fossil jet refined in Japan through subcategory ratios, and the Wood-FT result is divided among its foreground inputs and between Japan and overseas. Sawmill residue is assigned to the Japanese logs sector, and results with the residue assigned to the Japanese timber sector are reported alongside.

Tier 2 takes the forestry labor requirements and eligible chip supply of each prefecture from the Forest Management Model for Cyclical Forestry (FM2-CF; Han et al., 2026a) and allocates a fixed share of that supply to SAF. It expresses the attributed forestry work relative to the prefectural labor force as forestry employment potential (FEP), the value retained in the prefecture relative to gross prefectural product as regional added value (RAV), and the balance between eligible chip supply and incumbent chip demand from combined heat and power as resource headroom. Four socioeconomic scenarios

based on the Shared Socioeconomic Pathways (O'Neill et al., 2017) differ in working-age population, regional output, incumbent chip demand and the declining value of SAF, while the wood supply is common to all four, and results refer to the business-as-usual (BAU) scenario unless another is named. Tier 3 derives conduct families from the largest risk indicators of Wood-FT in Tier 1 and assesses six companies with functions from feedstock supply to off-take, each in its own operations and in its governance of suppliers. Their documented conduct is judged against a reference point for each family and domain on an ordinal scale from −2 to +2, using one public document per company and official records of labor-law violations (Methods).

The route performs a large share of its work in Japan while relying on overseas supply chains for most of it

Wood-FT draws a large share of its supply-chain work from Japan, although most of this work remains in overseas supply chains. Japan accounts for 42.7% of the worker hours that the route requires per MJ, compared with 19.0% for fossil jet refined in Japan. This share covers the whole supply chain, including the upstream suppliers represented in the database as well as the conversion plants and residue feedstock that the assessment places in Japan. Wood-FT requires 2.4 times the worker hours of the fossil reference per MJ and generates 2.4 times its gross output, so that despite its larger domestic share it draws more overseas work in absolute terms, at 1.79×10^{-3} hours per MJ against 1.07×10^{-3}. An even larger part of its screened risk lies overseas (Fig. 3c). Japanese sectors carry low risk levels in the database, which assigns risk through country–sector averages, so that the median share of the Wood-FT result located in Japan across the 35 subcategories is only 1.7% on the worker-hour basis and 15.7% on

the output-value basis. On the output-value basis, the route's own plants in Japan account for 63.1% of its gross output but a median of only 5.2% of its risk result.

With sawmill residue assigned to the Japanese logs sector, most of the screened risk comes from the methanol and hydrogen bought for Fischer–Tropsch synthesis (Fig. 3a,b). Among the 35 risk subcategories, methanol and hydrogen are the largest contributor in 33 on the worker-hour basis and in 25 on the output-value basis. The largest worker-hour hotspots lie in Russian upstream activities, led by energy mining, which accounts for 13.9% of upstream worker hours and is flagged at very high risk on 14 indicators.

Under the logs assignment, Wood-FT screens lower than UCO-HEFA on both activity bases, whereas its comparison with fossil jet depends on how activity is measured (Fig. 2; Table 1). Among the 35 risk subcategories, Wood-FT screens lower than UCO-HEFA in 32 on the worker-hour basis and in 28 on the output-value basis. Against fossil jet refined in Japan, it is lower in only 6 on the worker-hour basis but in 19 on the output-value basis, so the comparison changes direction with the basis. This reversal is consistent with the distribution of work described above. The additional overseas work of Wood-FT is likely to weigh on the worker-hour comparison, whereas the large and low-risk output of its Japanese plants lowers the output-value result.

The reversal persists when the inventory and conversion yield are sampled jointly (Methods). The central 90% interval of the median wood-to-fossil ratio stays above parity on the worker-hour basis (1.40–2.24) and below parity on the output-value basis (0.60–0.94) (Table 1). The comparison depends instead on how the sawmill residue is represented in the database. When the residue is assigned to the Japanese timber sector,

it is the largest contributor in 28 of the 35 risk subcategories on the worker-hour basis (Fig. 3a,b). On the output-value basis, methanol and hydrogen remain the largest in 19. Against fossil jet, Wood-FT is then lower in only 1 subcategory on the worker-hour basis and in 15 on the output-value basis (Table 1). The output-value interval now spans parity (0.86–1.40). Against UCO-HEFA, it is lower in 4 and 15 subcategories. The mapping also changes the concerns passed to Tier 3. Child labor, for which Wood-FT has its largest worker-hour ratio to fossil jet (5.59), enters the selected conduct families in place of fair salary. The input that carries the screened risk thus depends on the mapping. Its location does not, since the Japanese share of the risk result remains small under both assignments (Fig. 3c).

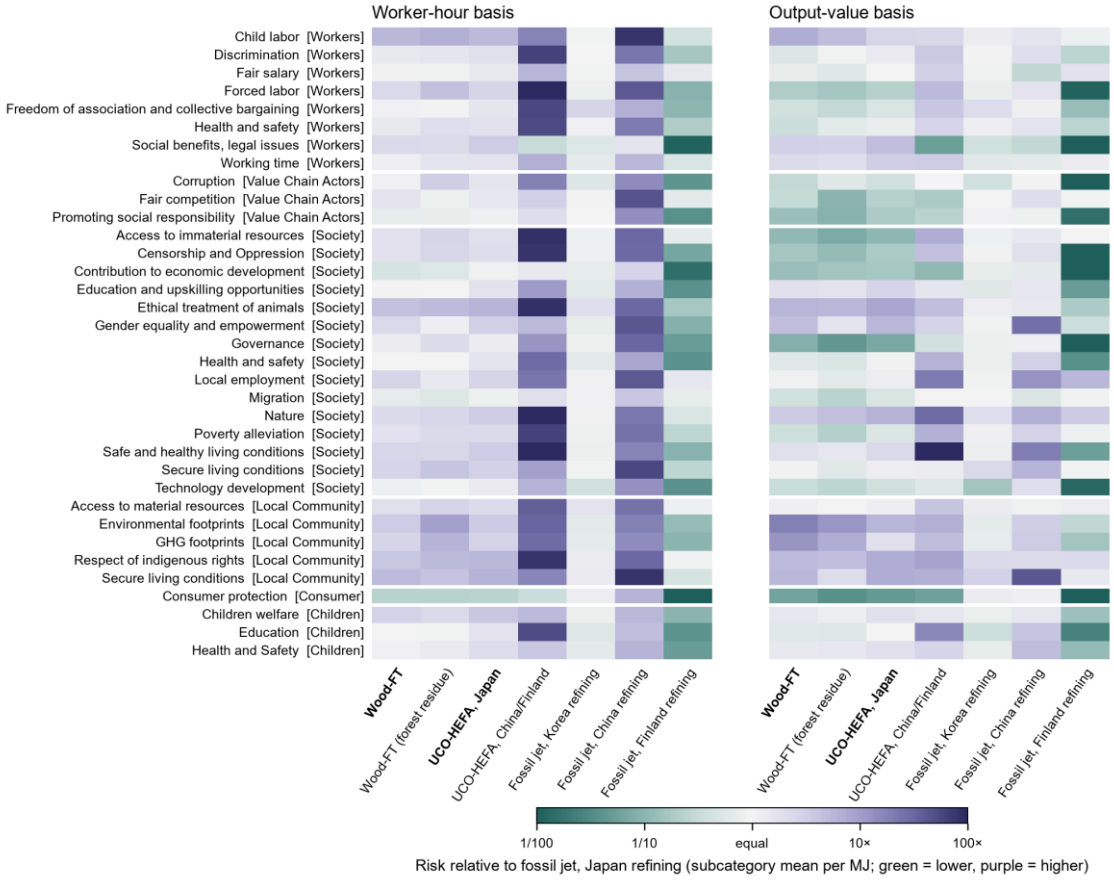


Figure 2 Route comparison. Potential social risk of each route relative to fossil jet refined in Japan, for 35 risk subcategories on the worker-hour and output-value bases. Each ratio compares the arithmetic means of the indicators within a subcategory. Green indicates a lower result and purple a higher result; the color scale is logarithmic and saturates at 1/100 and 100 times the reference. Results are per MJ (LHV) of unblended fuel at the plant gate, using PSILCA v4. Summary ratios and counts of favorable comparisons are reported in Table 1, and results per subcategory in Supplementary Table 1.

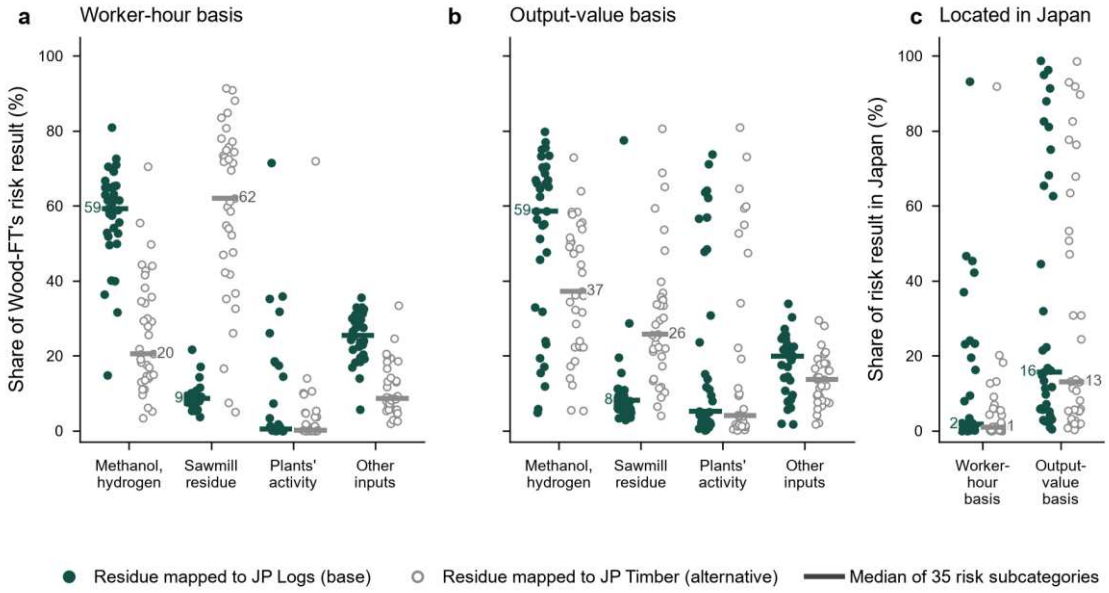


Figure 3 Input contributions and location of risk. Contributions to the Wood-FT risk result and its location under two assignments of sawmill residue. Panels a and b show the shares contributed by foreground input groups on the worker-hour and output-value bases. Panel c shows the Japanese share. Each point represents one of 35 risk subcategories; horizontal marks indicate medians. Filled points assign the residue to Japanese logs (JP Logs) and open points to Japanese timber (JP Timber). Input shares

sum to 100% within each subcategory, whereas the separate medians need not sum to 100%. Results are per MJ of unblended fuel.

Table 1 Screened social risk of Wood-FT relative to the reference routes under two assignments of sawmill residue.

Reference route	Activity basis	Residue as Japanese logs (base)			Residue as Japanese timber		
		Lower in (of 35)	Median ratio	90% interval	Lower in (of 35)	Median ratio	90% interval
UCO-HEFA, Japan	Worker hour	32	0.765	–	4	1.85	–
	Output value	28	0.776	–	15	1.04	–
Fossil jet, Japan	Worker hour	6	1.78	1.40–2.24	1	4.27	3.21–5.65
	Output value	19	0.748	0.60–0.94	15	1.08	0.86–1.40

Ratios compare Wood-FT with the reference route per MJ (LHV) of unblended fuel at the plant gate. For each risk subcategory, the ratio compares the arithmetic means of its indicators; the median is taken across the 35 risk subcategories, and a ratio below 1 indicates a lower screened risk for Wood-FT. The 90% interval is the central 90% range of the median ratio when the price and quantity of each purchased input and the monetary amount of each own activity are sampled within ±25% and conversion yield within ±10% (Methods); the comparison with UCO-HEFA was not sampled (–). Results per subcategory are reported in Supplementary Table 1.

Forestry work gains weight in shrinking labor forces, much of it where chip demand exceeds supply

Part of the work that Tier 1 places in Japan is forestry work in the regions that would supply the wood. Tier 2 assesses whether the labor and wood resources of the host regions could support the regional contribution attributed to the route. The forestry work

attributed to SAF, counted in full-time equivalents (FTE), is a labor requirement as well as a potential source of employment. RAV expresses the potential economic outcome, and resource headroom expresses the constraint arising from competing demand for chips.

Under BAU, the attributed forestry work becomes more significant to regional labor markets in all 47 prefectures, while its attributed value becomes a declining share of regional output (Fig. 4a,b). The median FEP rises from 1.04 to 5.69 basis points (bp) of the labor force. Over the same period, the median ceiling of RAV, which assumes conversion within the prefecture, falls from 0.170 to 0.0918 bp of gross prefectural product (GPP). Across prefectures, the median change is a 4.82-fold rise in FEP and a 39.0% fall in the RAV ceiling (Fig. 4d).

The rise in FEP reflects the contraction of the regional labor force more than the growth of the attributed work. Between 2025 and 2120, the attributed forestry FTE increase by a median 56.3%, whereas the labor force decreases by a median 67.9%. In a logarithmic decomposition, labor-force contraction accounts for more than half of the growth in FEP in every prefecture. With labor-force participation in 2120 set 50% above its 2020 level, FEP still rises 3.22-fold, and contraction still accounts for more than half of the growth in 38 prefectures (Supplementary Table 10). The attributed FTE are identical across the four scenarios, because the modeled wood supply is common to them. The median FEP ratio consequently varies with the labor force alone, from 3.18 under the Green Society to 7.26 under the Shrinking Society (Supplementary Table 2). A rising FEP thus means that the attributed work would occupy a larger share of a smaller workforce, as a growing demand on the regional labor force as well as a growing employment

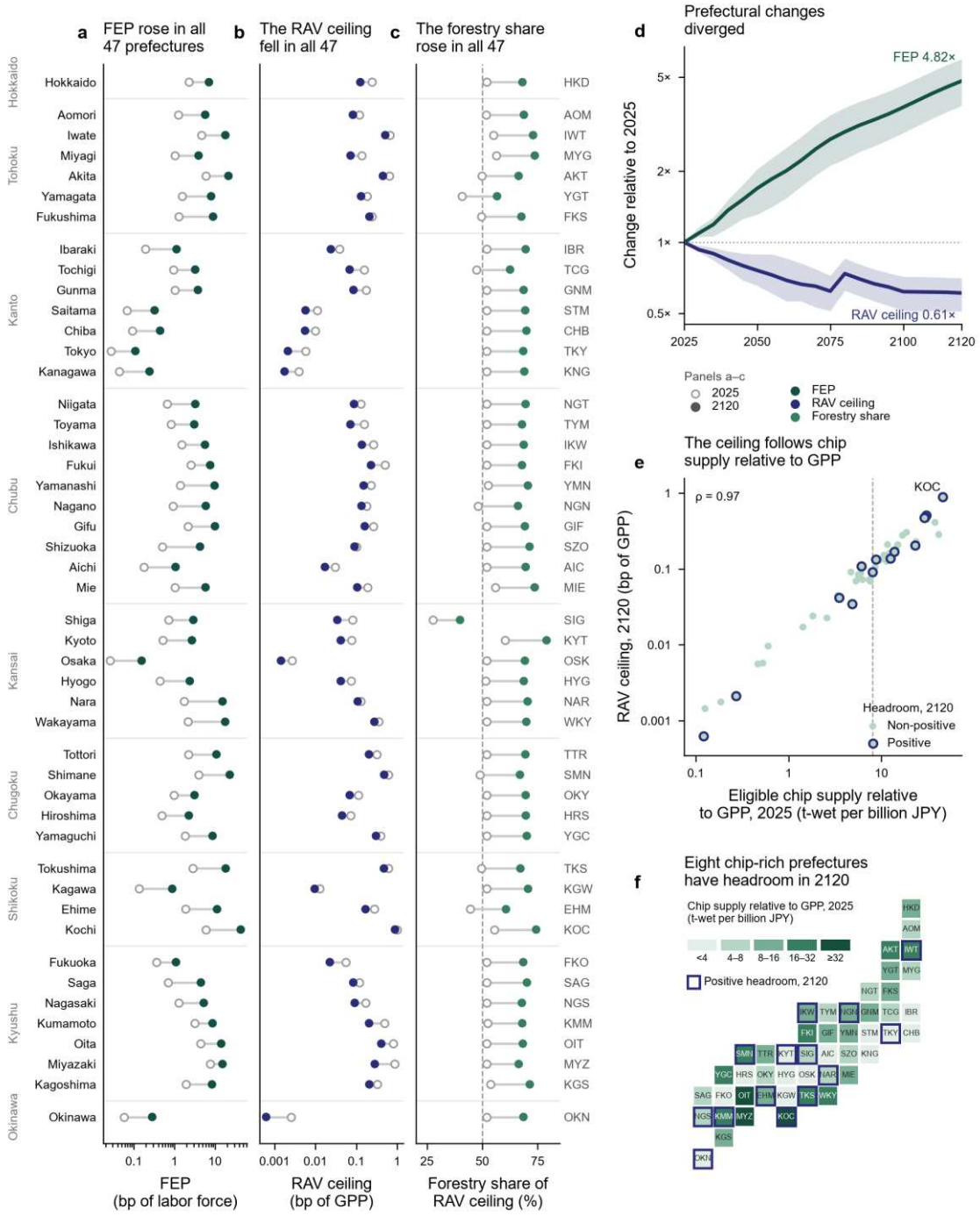
opportunity. Most of this regional work is forestry work. With conversion sited in the prefecture, conversion employment potential (CEP) rises from a median 0.186 to 1.10 bp of the labor force, about a fifth of FEP in both years.

The RAV ceiling declines relative to GPP even though it grows in absolute terms. Summed across prefectures, it rises from JPY 8.91 billion to JPY 11.5 billion, and it increases in 42 prefectures. GPP, however, grows faster, by a median 2.23-fold against 34.3% for the ceiling. Growth in GPP per labor-force member accounts for more than half of the divergence between FEP and the RAV ceiling in every prefecture. The direction of this outcome depends on the economic path of the host regions. Under the Shrinking Society, the ceiling relative to GPP rises instead, by a median 41.8% (Supplementary Table 2). Within the ceiling, the forestry component, which forms the RAV floor, gains weight as the assumed decline in SAF value reduces the conversion margin (Fig. 4c). Its share rises in every prefecture and exceeds half of the ceiling in 46 prefectures in 2120, against 38 in 2025. A growing part of the attributed value thus arises where the chips are produced, independently of where the conversion plant is sited.

Most of the attributed forestry work lies in prefectures where incumbent combined heat and power (CHP) chip demand from all origins exceeds eligible domestic chip supply. In 2120, headroom remains non-positive in 33 of the 47 prefectures (Fig. 5e). The number of prefectures with positive headroom rises from six in 2025 to 14 in 2120, and their share of attributed forestry FTE from 6.6% to 33.7% (Fig. 5a,b,e). Much of this increase follows the entry of reclaimed chips from 2076 under the fixed 55-year lifetime case. Across the scenarios, this share in 2120 ranges from 20.8% under the Green

Society to 51.1% under the Shrinking Society (Fig. 5c–f). The scenarios differ in how many prefectures reach positive headroom by 2120. The prefectures themselves are nested, as each scenario with more headroom contains all those that are positive under a scenario with less.

The prefectures where the attributed work is most significant are nevertheless among those where the resource balance improves. In 2120, six of the ten prefectures with the highest FEP have positive headroom and together hold 61.2% of total positive headroom (Supplementary Table 3). This coincidence suggests that the regional opportunity depends on when the resource balance becomes positive as well as on the eventual weight of the attributed work. Across prefectures, the RAV ceiling relative to GPP and FEP both rank with eligible chip supply relative to GPP (Spearman $\rho = 0.93$–1.00 in 2025 and 2120; Fig. 4e). They do not rank with GPP per labor-force member ($\rho \leq 0.21$). Among the 23 prefectures where this chip supply lies above the median, eight have positive headroom in 2120 (Fig. 4f; Supplementary Data 2). Read as conditions of regional feasibility, the results indicate that the attributed work grows relative to the regional workforce in every prefecture. The resource constraint eases only in a minority of prefectures, much of it after reclaimed chips enter the supply, and the potential economic outcome comes increasingly from forestry.



306

307 **Figure 4 Forestry employment potential, regional added value and chip supply of**
308 **wood-based SAF by prefecture under business as usual, 2025–2120. a**, Forestry
309 employment potential (FEP), in basis points of the prefectural labor force. **b**, Ceiling of
310 regional added value (RAV), in basis points of gross prefectural product (GPP). **c**,

Forestry share of the RAV ceiling. In a–c, open circles show 2025 and filled circles 2120, and prefectures are grouped by region. The axes of a and b are logarithmic, and the dashed line in c marks 50%. **d**, Change in each prefecture's FEP and RAV ceiling relative to 2025, shown as the median and interquartile range across the 47 prefectures on a logarithmic axis. The step after 2075 follows the entry of reclaimed chips from 2076. **e**, RAV ceiling in 2120 against eligible chip supply relative to GPP in 2025, both on logarithmic axes. Outlined points mark positive headroom in 2120, the dashed line marks the median chip supply relative to GPP, and ρ is the Spearman rank correlation. **f**, Eligible chip supply relative to GPP in 2025 by prefecture, with outlines marking positive headroom in 2120. The three darker classes lie above the median of 8.01 t-wet per billion JPY. Assumptions: 10% of eligible chips allocated to SAF, 240 working days per full-time equivalent, and conversion sited in each prefecture for the ceiling.

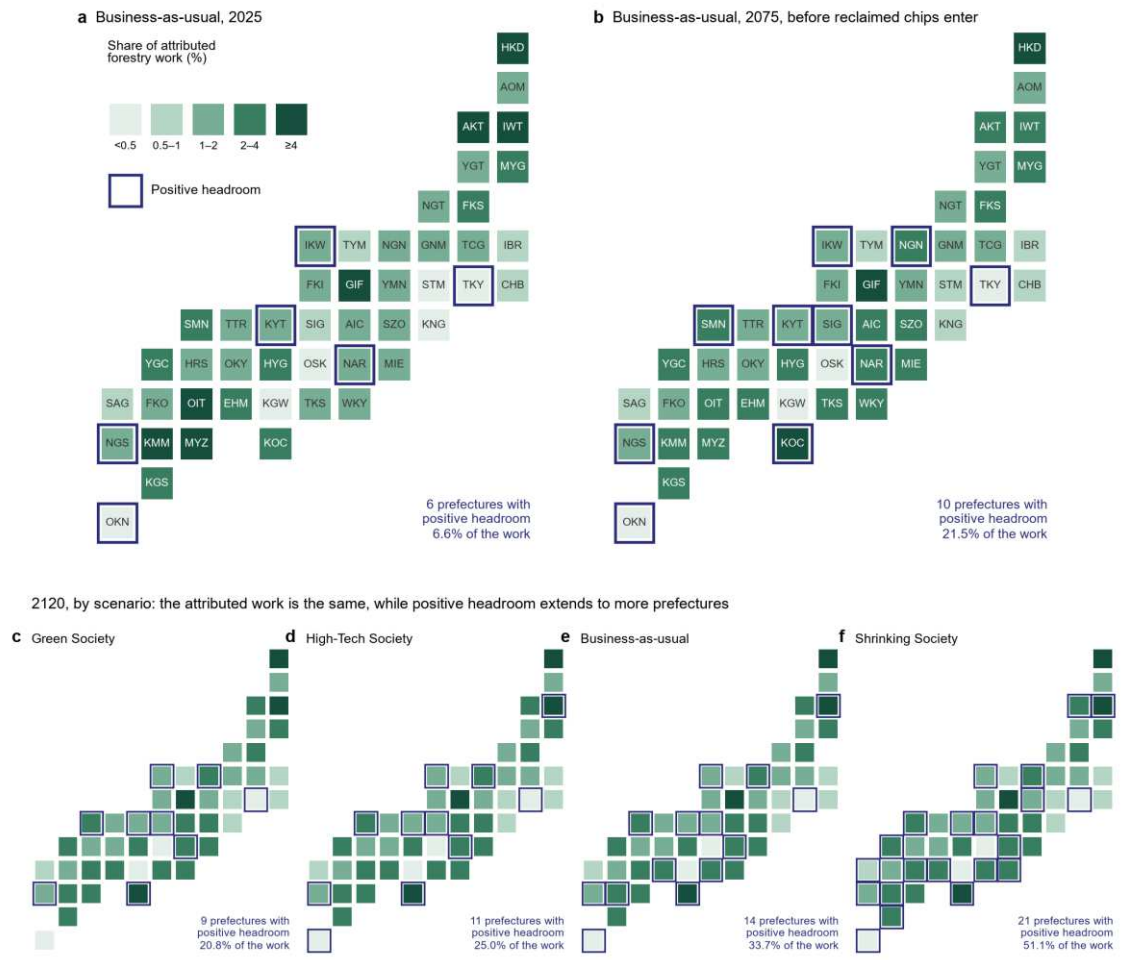


Figure 5 Positive headroom and the location of the forestry work attributed to wood-based SAF. Each tile is a prefecture. Fill shows the prefecture's share of the national attributed forestry work in that year, and an outline marks positive headroom, that is, eligible domestic chip supply exceeding incumbent CHP chip demand from all origins (H = Q − D). **a, b**, Business-as-usual in 2025 and in 2075, before reclaimed chips enter the supply from 2076 under the fixed 55-year lifetime case. **c–f**, 2120 under the four scenarios, ordered by the number of prefectures with positive headroom. The attributed work is the same in all scenarios because the modeled wood supply is common to them. The text in each map gives the number of prefectures with positive headroom and their share of the attributed work. Assumptions: 10% of eligible chips

allocated to SAF and 240 working days per full-time equivalent. CHP, combined heat and power.

Documented supplier governance follows overseas concerns, while forestry safety lacks assessable evidence

The assessed companies document conduct beyond the reference point more often in their governance of suppliers (Indirect domain) than in their own operations (Direct domain) (Fig. 6). Level +1 is reached in 14 of the 42 Indirect cells and in 10 of the 42 Direct cells. Of all 84 cells, 41 are at the reference point (Level 0), 24 at +1 and one at −1, and none reaches +2. The other 18 cannot be assessed, 17 for lack of sufficient assessable evidence (NA-E) and one because of unresolved conflicting evidence (NA-C).

In the two families with the most +1 cells, the emphasis of documented governance follows where Tier 1 places the concern. Forced labor has 0.7% of its Tier 1 result in Japan, and five of its six +1 cells are in supplier governance. There, every company except Toyo Engineering reaches that level. Access to material resources has 84.9% of its result in Japan, and five of its eight +1 cells are in own operations. Legal and regulatory compliance departs from this pattern, as its result lies 93.2% in Japan while its three +1 cells are all in supplier governance. Because every family is assessed in both domains, this correspondence originates in the companies' documented governance.

None of the three feedstock companies has assessable supplier-governance evidence on worker health and safety in the assessed documents (Fig. 6). Their supplier governance in other families does reach wood suppliers, through supplier surveys, certification

schemes and legality checks. Oji Holdings and Sumitomo Forestry name overseas or directly imported wood suppliers among those they assess. The only worker health and safety verdict at the feedstock companies that departs from the reference point is adverse. It is a −1 in the own operations of Oji Holdings and concerns a paper mill rather than forestry work. The verdict rests on the Ministry of Health, Labour and Welfare's record that the Kasugai mill of Oji Paper was referred to prosecutors in March 2026 (MHLW, 2026). The conditions of the forestry contractors whose work Tier 2 counts as regional contribution thus lie outside the conduct that the assessed companies document.

The selection of companies also bounds what Tier 3 covers. The six companies are selected for their functions, from feedstock supply to refining and off-take, and none of them was selected for the supply of methanol or hydrogen. Read on its own, Tier 3 shows that documented supplier governance reaches forced labor, a concern located overseas, while the health and safety of the forestry work that supplies the wood remain without assessable evidence.



Figure 6 Company conduct levels by conduct family and domain. Each cell gives the level of one company's documented conduct in its own operations or in its governance of suppliers, judged against the reference point defined for that family and domain (Methods). Of the 84 cells, 41 are at Level 0, 24 at +1, one at −1 and none at +2. Seventeen cells are NA-E and one is NA-C. NA-E, insufficient assessable evidence; NA-C, unresolved material conflict. Document coverage and selected supporting findings are provided in Supplementary Tables 4 and 5.

Discussion

The results of our framework indicate that domestic wood-based SAF relies on overseas supply chains for most of its work. The domestic part of its work gains regional weight, yet it is the part on whose working conditions the framework holds the least direct evidence. Tier 1 assigns this work little risk, because the database applies low risk levels to Japanese sectors. Tier 2 shows it gaining weight as regional labor forces contract, and

the feedstock companies' documents contain no assessable evidence on the health and safety of the forestry work. The overseas supply chains carry most of the screened risk and are reached by the supplier governance that the assessed companies document, most clearly for forced labor. Under the logs assignment, however, most of that risk lies with methanol and hydrogen, for whose supply no company was selected. Each tier read alone would give a reassuring picture of the route, with low screened risk for its domestic work, a growing regional contribution and documented governance of suppliers. Reading the tiers in pairs locates the points at which social conditions could be attached to domestic SAF (Fig. 1b).

Replacing fossil jet with Wood-FT would not reduce screened social risk on the worker-hour basis. Wood-FT is lower in only 6 of the 35 subcategories and mobilizes 2.4 times the worker hours per MJ, including more overseas work in absolute terms. The two activity bases are complementary, and the reversal between them is informative in itself. The worker-hour basis weights risk by the labor a route mobilizes and speaks to the workers along its supply chain. The output-value basis weights risk by the economic activity a route generates and links the screening to where value is created, as Tier 2 does for the host regions. Read together, they show that Wood-FT mobilizes more labor per MJ than fossil jet while concentrating much of its economic activity in low-risk Japanese plants. Because the output-value result reflects the route's present cost structure, both bases should be tracked as the value chain matures.

The need for routes such as Wood-FT is likely to grow as SAF supply expands beyond waste oils. Used cooking oil and animal fats supplied about 98% of the feedstock for SAF in the EU in 2024, and more than two-thirds of it was imported (EASA, 2025). The

availability of these waste oils limits further expansion (O'Malley and Baldino, 2024). Against domestic UCO-HEFA, Wood-FT screens lower in most subcategories under the logs assignment and in a minority under the timber assignment. It screens lower than UCO-HEFA from Chinese feedstock converted in Finland in 34 of the 35 subcategories on the worker-hour basis. On the output-value basis, it is lower in 24 (Supplementary Table 6). The social risk of additional SAF thus depends on where its feedstock is collected and processed, which screening can indicate without settling.

The regional feasibility of the domestic value chain depends less on the economic structure of a prefecture than on the size of its chip supply relative to its economy. Both the attributed value relative to GPP and the attributed work relative to the labor force follow this ratio, whereas output per labor-force member plays no role. The value chain would thus matter most in small, forest-rich economies, where its potential benefit and its demand on the workforce coincide. Of the 23 prefectures whose chip supply is large relative to their economy, eight also have eligible supply exceeding incumbent demand by 2120 (Fig. 4f). In the other fifteen, the attributed value is high but the wood is contested. Within this structure, the decision that a host region controls is whether conversion is sited there. This decision carries the most weight early, because the share of conversion in the attributed value declines over time.

Tiers 1 and 3 together show that the documented supplier governance of the assessed companies follows overseas concerns such as forced labor. The input that carries most of the screened risk, however, lies outside their functions. Methanol and hydrogen carry most of the risk under the logs assignment and remain the largest contributor on the output-value basis under the timber assignment. Their sourcing is thus a social decision

as well as a carbon decision. The sustainability criteria of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) include respect for human and labor rights, verified through approved certification schemes (ICAO, 2025). In ISCC CORSIA 202, one of these schemes, the employment criteria are written for biomass production (ISCC, 2023), so it remains unclear whether audits reach the purchased methanol and hydrogen. Social conditions on the conversion inputs can instead be set at the point of purchase. They can be set by a national program that supports the route, by the plant operator or by the fuel buyer.

Tiers 1 and 2 together show that whether the regional contribution and the screened risk rest on the same input depends on how the residue is represented. Under the logs assignment, the residue carries the regional work and methanol and hydrogen most of the risk. Under the timber assignment, the residue also carries most of the worker-hour risk, although the Japanese share of that risk stays small. Because both assignments describe Japanese forestry through sector averages, the conditions of the work that host regions would gain cannot be judged from the screening alone. For a prefecture considering whether to host production, the attributed work is a demand on a shrinking workforce as well as an opportunity. Much of it lies where incumbent demand already exceeds eligible chip supply, and siting decides how much of the attributed value the prefecture retains. An indicator that relates attributed work to the labor force registers a shrinking labor force as rising significance. In contracting regions, its change has to be decomposed into the growth of the work and the contraction of the labor force before it is read as growing opportunity.

Tiers 2 and 3 together show that the forestry work counted in Tier 2 as growing regional contribution lacks assessable health and safety evidence in the feedstock companies' documents. At these companies, health and safety in own operations is at the reference point or adverse, whereas supplier governance holds no assessable evidence on it (Fig. 6). The forestry contractors whose work Tier 2 counts thus fall between the two domains, as they are neither the companies' employees nor suppliers screened on their health and safety. Forestry has the highest rate of work-related casualties per 1,000 workers of any industry in Japan (Forestry Agency, 2026b). The gap thus concerns the most hazardous part of the route's domestic work. The instruments that apply to the feedstock address other questions. The revised Clean Wood Act requires covered businesses to confirm the legality of the wood they handle (Forestry Agency, 2025c). This concerns the origin of the wood rather than the working conditions in its supply. Japan's guidelines on human rights in supply chains extend due diligence to indirect suppliers but remain non-binding (Inter-Ministerial Committee, 2022). Corporate disclosure is organized by company and domain, whereas the social performance of the route runs along its chain. A route-level social claim therefore needs evidence organized along that chain. Supplier-specific evidence becomes available once supply relationships exist, which makes procurement the stage at which it can be required. It would be most informative from the suppliers that carry the screened hotspots and the attributed regional work. These need not be the companies at the main stages of the process chain.

Distributional justice concerns how the benefits and burdens of an energy system are allocated (McCauley and Heffron, 2018). Read in these terms, the results show who would carry the social consequences of the route. It places its regional contribution in

Japanese forestry regions and most of its screened risk with workers in overseas supply chains, two groups that no single tier presents together. The first group is not only a beneficiary, as the forestry work it would carry lacks assessable health and safety evidence. Policy documents in Japan describe the social case for domestic woody biomass mainly in terms of rural employment and income (MAFF, 2022; Forestry Agency, 2026a; ANRE and MLIT, 2026). This framing covers the benefits to the first group, leaving out its working conditions and the second group.

Existing governance of biofuels and biomass takes a similarly partial view. Under the EU Renewable Energy Directive, the mandated sustainability criteria for biofuels centered on environmental performance, and social provisions were left to approved voluntary schemes (German and Schoneveld, 2012). Several of these schemes lacked such provisions and most were limited in scope (German and Schoneveld, 2012). Public regulation and private certification are closely intertwined in this regime (Schleifer, 2013). Japan's support for biomass power expects labor items such as the elimination of child and forced labor to be verified for imported woody biomass (ANRE, 2026). Domestic wood for power is instead verified through a chain of certificates on its origin (Forestry Agency, 2026c). For the route assessed here, the overseas workers lie in the supply of conversion inputs, beyond criteria attached to the feedstock. The domestic forestry work is checked for the origin and legality of its wood.

Because domestic, land-based wood is the feedstock for which national governance might be expected to reach furthest, the pattern arises even without imported feedstock. It rests on conditions that are not specific to this route. These are conversion inputs bought on world markets, a regional contribution placed in shrinking regions, and

conduct evidence held by reporting companies. Where these conditions hold in other bioenergy and e-fuel routes, governance attached to the feedstock can be expected to leave the social implications of those routes in the same places. Zeug et al. (2023) reported a comparable pattern for a biomass-to-liquid concept in Brandenburg, Germany, where about 72% of the required working time lay outside Germany. The assessment locates the regional contribution and the screened risk on both sides of the national border. A judgment on the fairness of this distribution can thus take both groups into account.

The tiers rest on different forms of evidence, and their boundaries condition these results. Tier 1 assigns potential risk through country–sector averages, in which Japanese sectors carry low risk levels, and does not describe conditions at particular sites. The ranking of its inputs also depends on how they are represented in the database. Tier 2 covers the domestic stages of the route, which places the attributed work in Japan by construction. It reports modeled quantities, so the attributed work need not become additional employment and the added-value ceiling is not realized income. A non-positive headroom indicates a deficit within a defined comparison rather than an observed shortage. The forestry value per tonne is nearly uniform across prefectures, so Tier 2 does not resolve how local forestry or industrial structure would change the value a region retains. Tier 3 rests on one public document per company and on official records, for companies selected by function, without establishing that they would participate in the route. Supplier-specific information, observed employment in the host regions and an independent second assessment of the documentary judgments would each narrow these uncertainties.

Assessed in this way, the social performance of domestic wood-based SAF depends on the points where the route meets other sectors, regions and borders. A social assessment of such a route is therefore less a verdict on its feedstock than a way to locate these points. At each point, conditions on social performance can be set: the purchase of conversion inputs, the planning of host regions and the evidence required from suppliers.

Methods

Assessment design

The assessment examines domestic wood-based SAF through three tiers that address supply-chain exposure, regional deployment and company conduct. Tier 1 compares jet-fuel routes using the potential social risks associated with their country-sector supply chains. Tier 2 estimates the regional employment and added value attributable to wood-based SAF in Japan's prefectures, together with the resource conditions for its deployment. Tier 3 uses the concerns identified by the Tier 1 screen to assess documentary evidence of conduct among companies with relevant functions. The design extends the two-layer approach of Han et al. (2026b), which combined supply-chain screening with prefectural indicators for a single period, by projecting the regional indicators over time and adding company conduct as a third tier**.** Each tier retains its own units and evidential basis. Tier 3 takes its conduct concerns, and the Japanese share used to interpret them, from Tier 1, but the tiers are not combined into a single result, and the cross-tier findings in Results are interpretations based on comparing the separately reported results.

Tier 1: supply-chain screening

Tier 1 compares wood-based SAF with fossil jet refined in Japan, which serves as the reference, and with UCO-HEFA produced in Japan, the second main SAF route (Supplementary Fig. 1). Further routes with alternative production locations and fossil supply chains are reported in Supplementary Table 6. The functional unit is 1 MJ, on a lower heating value basis, of unblended fuel at the plant gate. The foreground includes feedstock acquisition and fuel production. Transport between foreground stages and from the plant to the airport is excluded, while transport embodied in the database supply chains remains in the background system. The main wood route, Wood-FT, comprises the acquisition and chipping of domestic sawmill residue followed by gasification and Fischer–Tropsch conversion in Japan (Corradini et al., 2023). An alternative inventory based on forest residue (Ahire et al., 2024) is used as a sensitivity case. UCO pretreatment uses the database process for purification of used vegetable cooking oil, whose underlying data carry a weak data-quality rating. For the fossil reference, refinery exchanges mapped to Japanese sectors are combined with crude supplies from the three largest origins in the 2023 import statistics, normalized to the included supply (METI, 2023), and crude-extraction inputs are assigned to the supplier countries (Supplementary Table 6).

Each route is represented by foreground purchases valued in 2023 US dollars and assigned to database country-sectors, together with the direct activities of its production stages. Purchases generate demand through the background supply chains, whereas each foreground production stage contributes its own activity in the country where it operates, represented by the relevant production sector and scaled by its output value.

Where the database distinguishes commodity and industry versions of a sector, purchases are assigned to the commodity version and direct activities to the industry version. In the baseline, sawmill residue is assigned to the Japanese logs sector. Purchase totals, output values and sector assignments are given in Supplementary Tables 7 and 8.

The monetary demands are evaluated with the professional worker-hour edition of PSILCA v4 (GreenDelta, 2025), which represents 14,839 country-sectors within an Eora-based multiregional input–output system (Lenzen et al., 2013). Foreground purchases are propagated through the input–output model, and direct foreground output is added in its assigned sectors. The resulting sector activity is characterized on two parallel bases. On the worker-hour basis, sector output is converted to worker hours using the sector-specific labor intensity and weighted by the indicator's characterization factor; on the output-value basis, the same factor is applied directly to gross output. Risk characterization follows the PSILCA scale, which increases by a factor of ten between successive classes from 0.01 for very low risk to 100 for very high risk, with 0.1 as the baseline factor for missing data. The 102 risk indicators are averaged with equal weights into 35 risk subcategories. Each route is compared with the fossil reference through subcategory ratios, summarized by the number of subcategories in which the route is lower and the median ratio across the 35 subcategories. Wood-FT is also compared directly with UCO-HEFA produced in Japan (Table 1). Results are separated between Japan and overseas and between the plants' own activities and their upstream supply chains, and the contributions of foreground input groups are calculated for each subcategory. These shares are summarized as medians across the 35 risk subcategories.

The sensitivity analysis varies each foreground line by ±10% and tests conversion yield separately (Supplementary Fig. 2). Joint variation is examined first through deterministic bounds, in which the monetary amounts of all foreground lines of Wood-FT and the fossil reference vary within ±10% or ±25% and, for each subcategory, the least favorable combination raises the Wood-FT contribution and lowers the fossil contribution. Monte Carlo sampling then draws independent factors from uniform ranges of ±10% or ±25% for the price and quantity of each purchased input and for the monetary amount of each own activity, while the conversion yield of each route varies within ±10%. Each range and each of four inventory and mapping specifications is sampled with 10,000 draws. In each draw, the median Wood-FT-to-fossil ratio across the 35 subcategories is calculated and its distribution is summarized by the 5th and 95th percentiles. Individual comparisons are classified by whether Wood-FT is lower in at least 95% of draws (Supplementary Fig. 3), and first-order variance contributions are calculated for the Wood-FT minus fossil difference. The characterization factor for missing data is varied from 0 to 100 with the set of missing cells fixed, and risk characterization factors derived from the Social Hotspots Database are applied within the PSILCA calculation (Benoît Norris and Norris, 2015). Inventory alternatives represent chip acquisition as a single purchase, substitute the alternative wood inventory, or assign the sawmill residue to the Japanese timber sector (Table 1; Supplementary Table 9).

Tier 2: regional assessment

Tier 2 examines three aspects of deployment: the labor required to support production, the economic value that can be retained within a region, and competition for wood

616 resources that already serve other uses. It covers all 47 prefectures in five-year steps
617 from 2025 to 2120 under four socioeconomic scenarios. Annual forestry labor
618 requirements and eligible chip supply, Q, are both derived from the Forest Management
619 Model for Cyclical Forestry (FM2-CF; Han et al., 2026a). Q covers forest, sawmill and
620 reclaimed chips. Reclaimed chips enter the supply from 2076 under a fixed 55-year
621 lifetime for wooden buildings (Omi and Kurita, 2010). Quantities are annual wet tonnes
622 (t-wet) at 15% moisture content. The assessment allocates a fraction a = 0.10 of each
623 prefecture's eligible supply to SAF, so that QSAF = aQ.

624 Forestry employment potential (FEP, in basis points (bp) of the labor force, where 1 bp
625 = 0.01%) expresses the forestry work attributed to SAF as a share of the prefectural
626 labor force. Annual forestry labor requirements, P, are converted from person-days to
627 full-time equivalents (FTE) at 240 working days per year and assigned to SAF in
628 proportion to the allocation, giving the attributed forestry FTE, M*, and

629 $$M^* = \frac{aP}{240}, \quad FEP = 10^4 \frac{M^*}{LF}. \tag{1}$$

630 where LF is the labor force, obtained by applying each prefecture's 2020 ratio of labor
631 force to working-age population (Statistics Bureau of Japan, 2022) to its projected
632 working-age population. Prefectural working-age populations follow the regional
633 projections of the National Institute of Population and Social Security Research to 2050
634 and are extrapolated to 2120 under the fertility and mortality assumptions of each
635 scenario (IPSS, 2023a, 2023b; Table 2). Conversion employment potential (CEP)
636 expresses the conversion work associated with processing the allocated chips in the
637 same prefecture, using a conversion employment intensity, lC, of 0.002069 FTE per
638 tonne of chips:

$$CEP = 10^4 \frac{l_C Q_{SAF}}{LF}. \quad (2)$$

Regional added value (RAV, bp of gross prefectural product (GPP), denoted G) is reported as an interval. The floor includes the forestry value attributed to the allocated chips, and the ceiling adds the conversion value retained when processing is located in the prefecture:

$$RAV_{floor} = 10^4 \frac{Q_{SAF} v_F}{G}, \quad (3)$$

$$RAV_{ceiling} = 10^4 \frac{Q_{SAF}(v_F + v_C)}{G}. \quad (4)$$

Forestry value per tonne, vF, is the chip price, p, multiplied by the prefecture-specific forestry value-added ratio, rF, both held constant through time. Chip prices are the January 2025 pulp-chip prices at the chip-mill gate (MAFF, 2025). Conversion value per tonne, vC, is 20% of the positive margin between the SAF value obtainable from a tonne of chips and the chip price.

Resource headroom, H, is the balance between eligible chip supply and incumbent combined heat and power (CHP) chip demand, D:

$$H = Q - D. \quad (5)$$

Incumbent CHP demand is taken from the Forestry Agency's survey of woody-biomass energy use (Forestry Agency, 2023). Its chip total covers all origins, including imported and construction-waste chips, whereas Q is the eligible domestic pool. A non-positive headroom therefore indicates a deficit within this defined comparison rather than an observed shortage. Headroom is reported alongside the labor and value indicators and does not constrain them in the calculation.

The four scenarios, defined for this study, follow the storylines of the Shared Socioeconomic Pathways (O'Neill et al., 2017): business-as-usual (BAU, SSP2), Green Society (SSP1), Shrinking Society (SSP3) and High-Tech Society (SSP5). They differ in working-age population, GPP, incumbent CHP demand and the learning rate of SAF value (Table 2), while forestry labor requirements and eligible chip supply are common to all four. Incumbent CHP demand changes linearly from its 2025 value to λ times that value in 2120, where the scenario-specific multiplier λ is an illustrative assumption applied proportionally to every prefecture:

Table 2 Scenario assumptions for the Tier 2 regional assessment, 2025–2120.

Assumption	Business-as-usual	Shrinking Society	Green Society	High-Tech Society
Adopted SSP storyline	SSP2	SSP3	SSP1	SSP5
Labor				
Fertility assumption	Medium	Low	High	Medium
Mortality assumption	Medium	Medium	Medium	Low
Labor-force participation	Constant at the prefectural 2020 ratio	Constant at the prefectural 2020 ratio	Constant at the prefectural 2020 ratio	Constant at the prefectural 2020 ratio
Economic contribution				
Gross prefectural product trajectory	SSP2-based	SSP3-based	SSP1-based	SSP5-based
SAF output-value learning rate	10%	5%	15%	12%
Resource scarcity				
SAF allocation as a share of eligible chip supply	10%	10%	10%	10%
Incumbent CHP demand in 2120, relative to the 2025 baseline	0.90×	0.60×	1.40×	1.10×

The labor-force participation assumption uses each prefecture's 2020 ratio of labor force to working-age population throughout the assessment. The learning rate specifies the reduction in SAF output value per tonne of chips for each doubling of the cumulative

chip-supply index. Incumbent CHP demand changes linearly between the 2025 baseline and the specified 2120 endpoint. Forestry labor requirements and eligible chip-supply trajectories are common to all four scenarios.

$$D(t) = D_{2025}\left[1 + (\lambda - 1)\frac{t-2025}{95}\right]. \quad (6)$$

The SAF value per tonne of chips declines with the cumulative chip-supply index, C, calculated for each prefecture as the cumulative sum of the five-year chip-supply observations from 2025 divided by the 2025 quantity:

$$v_{SAF} = v_0 C^b, \quad b = log_2(1 - LR), \quad (7)$$

where LR is the scenario learning rate, the reduction in SAF value per doubling of C, and v0 is 66,317.5 JPY per tonne of chips, derived from the Corradini et al. (2023) yield and fuel value. Conversion value then follows as

$$v_C = max[(v_{SAF} - p) \times 0.20, 0]. \quad (8)$$

Results are summarized as medians across the 47 prefectures, with totals or counts where aggregation is required. Changes between 2025 and 2120 are reported both as the ratio of endpoint medians and as the median of prefectural ratios. Logarithmic decompositions separate the change in FEP into the change in attributed forestry FTE and the negative change in the labor force, and the divergence between FEP and the RAV ceiling into changes in GPP per labor-force member and in ceiling added value per attributed forestry FTE. The contributions are calculated for each prefecture and summarized as medians. Both decompositions are applied to each of the four scenarios (Supplementary Table 2). To relate employment significance to resource conditions, the attributed forestry FTE in prefectures with positive headroom are summed and

expressed as a share of the total. To relate the results to regional economic structure, Spearman rank correlations are calculated between FEP or the RAV ceiling and two prefectural characteristics in 2025. These are eligible chip supply relative to GPP and GPP per labor-force member. Prefectures are then divided at the median chip supply relative to GPP (8.01 t-wet per billion JPY) and grouped by the sign of headroom in 2120 (Fig. 4e,f; Supplementary Data 2). Sensitivity analyses cover 240 and 250 working days, two forms of labor attribution, fixed allocations of 5%, 10%, 20% and 30% and a scenario-specific allocation, and learning rates from 0 to 0.15 and value-capture ratios from 0.10 to 0.30. Labor-force participation in 2120 is also set 10%, 20% and 50% above the constant-2020 case, and the FEP decomposition is repeated for the 50% case (Supplementary Table 10).

Tier 3: company conduct assessment

The concerns assessed in Tier 3 are selected from the Tier 1 results for Wood-FT. The eight largest risk indicators in each assigned activity account are admitted, using the worker-hour account for worker-related indicators and the output-value account for community and societal indicators. Among the eight output-value indicators, three environmental footprint indicators are treated as environmental context, and the indicator for public expenditure on education is recorded as a gap in public provision rather than as company conduct. Each indicator is mapped to its stakeholder group and subcategory and retained where a company can respond through operational management, employment practices, procurement or supplier governance, and where public documents can support an assessment against a stated reference point. Indicators sharing a stakeholder group, subcategory and organizational response are grouped into

conduct families, giving seven families (Table 3). The Japanese share of each family's Tier 1 result, calculated for multi-indicator families as their combined Japanese contribution divided by their combined result, is recorded to interpret the companies' conduct, while every family is assessed in both domains. The company matrix is not rescored under the alternative residue mapping. Eight alternative selection specifications test which families enter or leave the selected set (Supplementary Table 11).

Table 3 Conduct families assessed in Tier 3 and the Tier 1 indicators from which they were derived.

Conduct family	PSILCA indicators (rank)	Activity basis	Share in Japan (%)
Forced labor	Trafficking in persons (2); frequency of forced labor (6)	Worker hour	0.7
Worker health and safety	Rate of fatal accidents at workplace (5); violations of mandatory health and safety standards (7)	Worker hour	0.9
Discrimination and gender	Women in the sectoral labor force (3)	Worker hour	11.3
Freedom of association and collective bargaining	Freedom of association and collective bargaining (4)	Worker hour	0.2
Legal and regulatory compliance	Evidence of violations of laws and employment regulations (1)	Worker hour	93.2
Access to material resources	Certified environmental management systems (1); extraction of industrial and construction minerals (4); industrial water use relative to renewable water resources (6); industrial water use relative to total withdrawal (7)	Output value	84.9
Fair salary	Sector average wage per month (8)	Worker hour	0.8

Indicators are those among the eight largest contributors to the Wood-FT risk result on each activity basis that companies can address in their own operations or supplier governance; ranks are given in parentheses. Three environmental footprint indicators and the indicator for public expenditure on education among the eight output-value contributors were not assigned to a conduct family. The share in Japan is the part of the Wood-FT result for the family's indicators located in Japan on the stated basis, with

sawmill residue assigned to the Japanese logs sector. When the residue is assigned to the Japanese timber sector, child labor enters the eight largest worker-hour contributors and fair salary leaves them; the company assessment was not rescored for this change.

Six focal companies are selected purposively for their functional relevance and the availability of public disclosure: Oji Holdings, Sumitomo Forestry and Nippon Paper Industries for forestry and feedstock functions, Mitsubishi Heavy Industries for gasification and conversion, Toyo Engineering for Fischer–Tropsch synthesis and ENEOS Holdings for refining, distribution and off-take. They are examined as holders of these functions, without assuming their participation in a realized value chain. The evidence comprises one specified public document per company available by 15 June 2026, recorded with its coverage and file hash (Supplementary Table 4).

The unit of assessment is one company, one conduct family and one domain. The own-operations domain covers the company's own employees and operations, and the supplier-governance domain covers its governance of suppliers. Either domain can include activities in Japan and overseas. Six companies, seven families and two domains give 84 assessment cells. Performance is assessed against a reference point defined for each family and domain, following the reference-scale logic of ISO 14075 (ISO, 2024), with substantive criteria drawn from the ILO fundamental conventions, the UN Guiding Principles on Business and Human Rights, the OECD Due Diligence Guidance and Japanese labor law and supply-chain guidance (Supplementary Table 12). An ordinal scale runs from −2 to +2. Level 0 requires evidence that the relevant management process operates in practice. Level +1 requires company-specific evidence of outputs beyond the reference point, and +2 additionally requires sustained outcomes,

753 a comparator or effectiveness test, and corroboration. Negative levels require a
754 substantiated adverse finding. Cells without sufficient assessable evidence are recorded
755 as NA-E, and unresolved material conflicts as NA-C. Evidence extraction and judgment
756 are conducted as separate stages, and evidence maturity, assurance and corroboration
757 are recorded separately from performance. Official records of labor-law violations
758 published by the Ministry of Health, Labour and Welfare for 1 September 2025 to 31
759 August 2026 are searched for all six companies (MHLW, 2026). Official records can
760 originate a negative level, while positive judgments require evidence in the company
761 documents, and every negative level and every +2 requires corroboration.

762 *Use of generative AI*

763 The three-tier framework, the scenario design, the selection rules for conduct families
764 and companies, and the reference scale were defined by the authors. Generative AI tools
765 (Claude, Anthropic; ChatGPT, OpenAI) were used to write code for the Tier 1 and Tier
766 2 calculations and to produce the figures, and, in Tier 3, to extract evidence from the
767 company documents. The authors take full responsibility for the work.

768 *Data availability*

769 The foreground inventories, sector assignments and Tier 1 subcategory results, the Tier
770 2 prefectural results for all scenarios and sensitivity cases, and the Tier 3 evidence
771 ledger and verdict matrix are provided in the Supplementary Information and
772 Supplementary Data 1–3. Background social risk data are from the PSILCA v4 database
773 (GreenDelta, 2025), which is available under license and is not redistributed; the
774 derived subcategory results are provided in Supplementary Data 1. The company
775 documents assessed in Tier 3 are publicly available and are identified, with their file

776 hashes, in Supplementary Table 4. The population, economic and chip-price statistics
777 are publicly available from the sources cited in Methods.

778 *Code availability*

779 The code used for the Tier 1, Tier 2 and Tier 3 analyses and for the figures is available
780 from the corresponding authors on reasonable request.

781 *Acknowledgements*

782 This work contains the results of projects supported by the New Energy and Industrial
783 Technology Development Organization (NEDO, Grant number JPNP20009), JST COI-
784 NEXT JPMJPF2003, and the Environment Research and Technology Development
785 Fund (JPMEERF20243004 and JPMEERF20253G03) of the Environmental Restoration
786 and Conservation Agency provided by Ministry of the Environment of Japan. The
787 activities of the Presidential Endowed Chair of the “Platinum Society” at the University
788 of Tokyo are supported by Mitsui Fudosan Corporation, Sekisui House, Ltd., East Japan
789 Railway Company, and Toyota Tsusho Corporation. The work was supported by JST
790 SPRING, Grant Number JPMJSP2108. The funders played no role in study design, data
791 collection, analysis and interpretation of data, or the writing of this manuscript.

792 *Author contributions*

793 Z.H.: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data
794 curation, Visualization, Funding acquisition, Writing – original draft. H.Y.T.:
795 Conceptualization, Methodology, Supervision, Writing – review & editing. Y.
796 Kanematsu: Supervision, Writing – review & editing. Y. Kikuchi: Supervision, Project
797 administration, Funding acquisition, Writing – review & editing.

Competing interests

The authors declare no competing interests.

References

Ahire, J. P., Bergman, R., Runge, T., Mousavi-Avval, S. H., Bhattacharyya, D., Brown, T., & Wang, J. (2024). Techno-economic and environmental impacts assessments of sustainable aviation fuel production from forest residues. Sustainable Energy & Fuels, 8, 4602–4616. https://doi.org/10.1039/d4se00749b

ANRE [Agency for Natural Resources and Energy]. (2026). Sustainability of woody biomass power generation (presentation, July 2026). https://www.gef.or.jp/wp-content/uploads/2026/07/day2_08_METI-Presentation_english.pdf

ANRE & MLIT [Agency for Natural Resources and Energy; Civil Aviation Bureau, Ministry of Land, Infrastructure, Transport and Tourism]. (2026). Supplementary explanation of the interim summary of the Task Force on Further SAF Promotion (Material 3, 8th Public-Private Council for Sustainable Aviation Fuel, 28 January 2026). https://www.mlit.go.jp/koku/content/001979009.pdf (in Japanese)

Benoit-Norris, C., Cavan, D. A., & Norris, G. (2012). Identifying social impacts in product supply chains: Overview and application of the Social Hotspot Database. Sustainability, 4, 1946–1965. https://doi.org/10.3390/su4091946

Benoît Norris, C., & Norris, G. A. (2015). The Social Hotspots Database. In J. Murray, D. McBain, & T. Wiedmann (Eds.), The sustainability practitioner's guide to social analysis and assessment (pp. 52–73). Common Ground Publishing.

Bouillass, G., Blanc, I., & Perez-Lopez, P. (2021). Step-by-step social life cycle assessment framework: A participatory approach for the identification and prioritization

821 of impact subcategories applied to mobility scenarios. The International Journal of Life
822 Cycle Assessment, 26, 2408–2435. https://doi.org/10.1007/s11367-021-01988-w
823 Corradini, L. L., Heiho, A., Kanematsu, Y., Shimono, R., Ohara, S., & Kikuchi, Y.
824 (2023). Simulation-based design of regional biomass thermochemical conversion
825 system for improved environmental and socio-economic performance. Computer Aided
826 Chemical Engineering, 52, 2363–2368. https://doi.org/10.1016/B978-0-443-15274-
827 0.50375-9
828 EASA [European Union Aviation Safety Agency]. (2025). ReFuelEU Aviation annual
829 technical report 2025: 2024 in review. https://www.easa.europa.eu/en/document-
830 library/general-publications/refueleu-aviation-annual-technical-report-2025
831 Forestry Agency. (2023). 2023 survey on trends in woody biomass energy use:
832 Prefectural tables of wood chips used for energy. e-Stat (statistics code 00501008).
833 https://www.e-stat.go.jp/stat-
834 search/files?page=1&layout=datalist&toukei=00501008&tstat=000001095155&cycle=
835 7&year=20230&month=0&tclass1=000001095156&tclass2=000001224500 (in
836 Japanese)
837 Forestry Agency. (2025c). The Clean Wood Act system: Act on Promotion of
838 Distribution and Use of Legally-harvested Wood and Wood Products, as amended in
839 2023 (in force 1 April 2025).
840 https://www.rinya.maff.go.jp/j/riyou/goho/summary/summary.html (in Japanese)
841 Forestry Agency. (2026a). Annual report on forest and forestry in Japan, FY2025,
842 Chapter 3, Section 2: Trends in wood use.
843 https://www.rinya.maff.go.jp/j/kikaku/hakusyo/r7hakusyo/attach/pdf/zenbun-18.pdf (in
844 Japanese)

Forestry Agency. (2026b). Current state of occupational accidents in forestry. Retrieved 9 November 2026, from https://www.rinya.maff.go.jp/j/routai/anzen/iti.html (in Japanese)

Forestry Agency. (2026c). Guideline for the certification of woody biomass used for power generation (2012; revised 1 April 2026). https://www.rinya.maff.go.jp/j/riyou/biomass/hatudenriyou_guideline.html (in Japanese)

Gan Yupanqui, K. R., Zeug, W., Thrän, D., & Bezama, A. (2024). A regionalized social life cycle assessment of a prospective value chain of second-generation biofuel production. Journal of Cleaner Production, 472, 143370. https://doi.org/10.1016/j.jclepro.2024.143370

German, L., & Schoneveld, G. (2012). A review of social sustainability considerations among EU-approved voluntary schemes for biofuels, with implications for rural livelihoods. Energy Policy, 51, 765–778. https://doi.org/10.1016/j.enpol.2012.09.022

GreenDelta. (2025). PSILCA: Product Social Impact Life Cycle Assessment database (Version 4.0). GreenDelta GmbH. https://psilca.net/

Han, Z., Oosawa, K., Kanematsu, Y., Teah, H. Y., & Kikuchi, Y. (2026a). Simulating forest transition for sustainable forestry planning in Japan: A backcasting model of roundwood supply and carbon stocks with operational and regional considerations. Resources, Conservation & Recycling Advances, 29, 200314. https://doi.org/10.1016/j.rcradv.2026.200314

Han, Z., Teah, H. Y., Kanematsu, Y., & Kikuchi, Y. (2026b). Social life cycle assessment of domestic wood-based aviation fuel in Japan. In Planetary sustainability and actionable strategies (World Sustainability Series). Springer Nature. Accepted.

ICAO [International Civil Aviation Organization]. (2025). CORSIA sustainability criteria for CORSIA eligible fuels (ICAO document 05, June 2025 edition). https://www.icao.int/sites/default/files/environmental-protection/CORSIA/Documents/CORSIA%20Eligible%20Fuels/ICAO-document-05-Sustainability-Criteria-June-2025.pdf

Inter-Ministerial Committee on Policy Promotion for the Implementation of Japan's National Action Plan on Business and Human Rights. (2022). Guidelines on respecting human rights in responsible supply chains (13 September 2022; provisional English translation). Ministry of Economy, Trade and Industry. https://www.meti.go.jp/english/policy/economy/biz_human_rights/1004_001.pdf

IPSS [National Institute of Population and Social Security Research]. (2023a). Population projections for Japan: 2021–2070, with long-range population projections: 2071–2120 (Population Research Series No. 347). (in Japanese)

IPSS [National Institute of Population and Social Security Research]. (2023b). Regional population projections for Japan: 2020–2050 (released December 2023; Population Research Series No. 349, 2024). (in Japanese)

ISCC. (2023). ISCC CORSIA 202 sustainability requirements (Version 2.0). ISCC System GmbH. https://www.iscc-system.org/wp-content/uploads/2023/12/ISCC_CORSIA_202_Sustainability-Requirements_2.0.pdf

ISO [International Organization for Standardization]. (2024). ISO 14075:2024 Environmental management: Principles and framework for social life cycle assessment. https://www.iso.org/standard/61118.html

Kostidi, E., & Lyridis, D. (2024). Social impact assessment of biofuel production for maritime and aviation sectors: A case study of a pilot biorefinery project. Frontiers in Energy Research, 12, 1454862. https://doi.org/10.3389/fenrg.2024.1454862

LeBaron, G., & Lister, J. (2015). Benchmarking global supply chains: The power of the 'ethical audit' regime. Review of International Studies, 41, 905–924. https://doi.org/10.1017/s0260210515000388

Lenzen, M., Moran, D., Kanemoto, K., & Geschke, A. (2013). Building Eora: A global multi-region input–output database at high country and sector resolution. Economic Systems Research, 25, 20–49. https://doi.org/10.1080/09535314.2013.769938

Macombe, C., Leskinen, P., Feschet, P., & Antikainen, R. (2013). Social life cycle assessment of biodiesel production at three levels: A literature review and development needs. Journal of Cleaner Production, 52, 205–216. https://doi.org/10.1016/j.jclepro.2013.03.026

MAFF [Ministry of Agriculture, Forestry and Fisheries, Japan]. (2022). Basic plan for the promotion of biomass utilization (3rd; Cabinet decision, 6 September 2022). https://www.maff.go.jp/j/shokusan/biomass/attach/pdf/index-22.pdf (in Japanese)

MAFF [Ministry of Agriculture, Forestry and Fisheries, Japan]. (2025). Wood distribution statistics survey, preliminary results: Wood prices, January 2025. e-Stat. (in Japanese)

Marquis, C., Toffel, M. W., & Zhou, Y. (2016). Scrutiny, norms, and selective disclosure: A global study of greenwashing. Organization Science, 27, 483–504. https://doi.org/10.1287/orsc.2015.1039

Mattila, T. J., Judl, J., Macombe, C., & Leskinen, P. (2018). Evaluating social sustainability of bioeconomy value chains through integrated use of local and global

915 methods. Biomass and Bioenergy, 109, 276–283.
916 https://doi.org/10.1016/j.biombioe.2017.12.019
917 McCauley, D., & Heffron, R. (2018). Just transition: Integrating climate, energy and
918 environmental justice. Energy Policy, 119, 1–7.
919 https://doi.org/10.1016/j.enpol.2018.04.014
920 METI [Ministry of Economy, Trade and Industry, Japan]. (2023). Resource and energy
921 statistics 2023: Crude oil imports by country of origin. (in Japanese)
922 MHLW [Ministry of Health, Labour and Welfare, Japan]. (2026). Published cases of
923 violations of labor standards laws, cases published 1 September 2025 to 31 August
924 2026. Labour Standards Bureau. https://www.mhlw.go.jp/content/001725374.pdf (in
925 Japanese)
926 Miyamoto, M., Sasaki, R., Nakao, A., & Yoshida, N. (2022). Business feasibility and
927 regional economy impacts of tri-generation system utilizing woody biomass: Focusing
928 on regional vitalization through workcation. Journal of Japan Society of Civil
929 Engineers, Ser. G (Environmental Research), 78, II_237–II_250.
930 https://doi.org/10.2208/jscejer.78.6_ii_237
931 Moon, D., Isa, A., Yagishita, T., & Minowa, T. (2013). The regional economic impacts
932 on the development of wood chip utilization in Maniwa city. Journal of Wood Science,
933 59, 321–330. https://doi.org/10.1007/s10086-013-1334-6
934 NEDO [New Energy and Industrial Technology Development Organization]. (2021,
935 June 18). SAF made from wood waste and microalgae supplied to scheduled flights
936 (Press release). https://www.nedo.go.jp/news/press/AA5_101442.html (in Japanese)
937 O'Malley, J., & Baldino, C. (2024). Availability of biomass feedstocks in the European
938 Union to meet the 2035 ReFuelEU Aviation SAF target. International Council on Clean

939 Transportation. https://theicct.org/publication/low-risk-biomass-feedstocks-eu-refueleu-
940 aug24/
941 Omi, Y., & Kurita, N. (2010). Simulation of building residual ratio under the trends in
942 longer life of buildings. Journal of Architecture and Planning (Transactions of AIJ),
943 75(656), 2459–2465. https://doi.org/10.3130/aija.75.2459 (in Japanese)
944 O'Neill, B. C., Kriegler, E., Ebi, K. L., Kemp-Benedict, E., Riahi, K., Rothman, D. S.,
945 van Ruijven, B. J., van Vuuren, D. P., Birkmann, J., Kok, K., Levy, M., & Solecki, W.
946 (2017). The roads ahead: Narratives for shared socioeconomic pathways describing
947 world futures in the 21st century. Global Environmental Change, 42, 169–180.
948 https://doi.org/10.1016/j.gloenvcha.2015.01.004
949 Schleifer, P. (2013). Orchestrating sustainability: The case of European Union biofuel
950 governance. Regulation & Governance, 7(4), 533–546.
951 https://doi.org/10.1111/rego.12037
952 Statistics Bureau of Japan. (2022). 2020 population census: Basic complete tabulation
953 on labour force status. Ministry of Internal Affairs and Communications.
954 https://www.stat.go.jp/data/kokusei/2020/kekka.html
955 Tsalidis, G. A., Xevgenos, D., Ktori, R., Krishnan, A., & Posada, J. A. (2023). Social
956 life cycle assessment of a desalination and resource recovery plant on a remote island:
957 Analysis of generic and site-specific perspectives. Sustainable Production and
958 Consumption, 37, 412–423. https://doi.org/10.1016/j.spc.2023.03.017
959 UNEP [United Nations Environment Programme]. (2020). Guidelines for social life
960 cycle assessment of products and organizations 2020 (C. Benoît Norris, M. Traverso, S.
961 Neugebauer, E. Ekener, T. Schaubroeck, S. Russo Garrido, M. Berger, S. Valdivia, A.

Lehmann, M. Finkbeiner, & G. Arcese, Eds.).
https://wedocs.unep.org/20.500.11822/34554
Zeug, W., Gan Yupanqui, K. R., Bezama, A., & Thrän, D. (2023). Holistic and integrated life cycle sustainability assessment of prospective biomass to liquid production in Germany. Journal of Cleaner Production, 418, 138046.
https://doi.org/10.1016/j.jclepro.2023.138046

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryInformation.docx