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Review Paper

Forest Bioenergy and Climate-Smart Forestry, A Carbon-Constrained World: Integrating Mitigation, Biodiversity, And Social Forestry Perspectives

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ABSTRACT

Forest bioenergy is increasingly central to net-zero strategies, yet its real contribution to climate mitigation and biodiversity conservation remains highly contested. Building on the earlier literature review and systematically integrating recent work on forest biomass, climate-smart forestry (CSF), bioenergy with carbon capture and storage (BECCS), and social forestry, this article reassesses the role of forest-based bioenergy within a broader climate-resilient bioeconomy. New studies on life-cycle greenhouse gas (GHG) emissions and carbon parity at combined heat and power plants, wood pellet supply chains, and stand-level biomass procurement show that mitigation outcomes depend critically on feedstock type (primary versus secondary biomass), additionality and substitution assumptions, and silvicultural intensity (e.g., plantations versus unmanaged forests). Parallel work on CSF highlights the need to enhance forest resilience, reduce emissions, and support rural livelihoods through digital technologies, intelligent operations, and forest bioeconomy approaches. New evidence on biodiversity-conscious forest management and global policy frameworks reveals substantial trade-offs between intensive biomass production, long-term forest carbon stocks, and biodiversity adaptation, prompting calls to restrict eligibility of forest bioenergy in renewable energy and "negative emissions" policies. At the same time, social forestry and geospatial planning on degraded land can expand sustainable bioenergy options while strengthening community participation and energy justice. Synthesizing these strands, the review proposes a framework that embeds forest bioenergy within climate-smart, biodiversity-safe, and socially inclusive forest landscapes. It underscores the importance of transparent carbon accounting, robust sustainability criteria, and region-specific governance to avoid over-reliance on forest bioenergy and to prioritize truly low-carbon alternatives. Finally, it outlines a research agenda on carbon parity metrics, biodiversity-inclusive modeling, social license, and just transitions in forest-dependent communities.

Keywords: (SEO-optimised) forest bioenergy; climate-smart forestry; BECCS; biodiversity trade-offs; social forestry; sustainable biomass; negative emissions

INTRODUCTION

Forest bioenergy has moved from a niche option to a headline instrument in many decarbonisation pathways. In the European Union (EU) and other temperate and boreal regions, policies and subsidies have driven a sharp increase in the use of woody biomass for electricity and heat, and more recently for BECCS, with the promise of dispatchable "carbon-neutral" or even carbon-negative power. At the same time, growing evidence challenges the assumptions underlying this narrative, particularly regarding carbon accounting, biodiversity impacts, and competition with other renewable technologies. Earlier reviews highlighted the technical feasibility of forest bioenergy and the potential of biomass markets to support rural economies and the forest sector. Recent literature strongly updates this picture in three ways:

1. Carbon and climate performance. Detailed life-cycle assessments now quantify carbon parity times for a range of feedstocks and management regimes, revealing that short-term mitigation is far from guaranteed.
2. Biodiversity and ecosystem integrity. New modeling work links bioenergy expansion to biodiversity loss and resilience declines, even when overall mitigation goals are achieved.
3. Climate-smart and social forestry. CSF and social forestry studies offer alternative configurations of forest landscapes in which bioenergy is one component of broader strategies grounded in resilience, equity, and local participation.
4. This review synthesizes these developments to answer a central question: Under what conditions, if any, can forest bioenergy contribute meaningfully and responsibly to climate-resilient development? Building on the earlier review and the extended dataset of recent articles (DOKUMEN and DAPUS), we integrate insights from forest science, life-cycle modeling, policy analysis, and social research.

METHODS

The review draws on the curated corpus summarized in the earlier extraction tables and expanded with recent publications from 2023–2025. These include:

- Empirical and modeling studies of forest bioenergy systems (e.g., combined heat and power (CHP) plants, pellet supply chains, stand-level procurement).
- Conceptual and policy analyses on BECCS, carbon dioxide removal (CDR) portfolios, and renewable energy regulation.
- Reviews and case studies on CSF, agricultural residues and energy crops, and lignocellulosic biofuels including sustainable aviation fuel (SAF).
- Research on biodiversity-conscious forest management, global biodiversity–climate frameworks, and forest governance in EU and BRICS contexts.
- Socio-economic analyses of forest product markets, energy forest products, and social forestry-based bioenergy optimization.

This is focus on work that explicitly links forest biomass to climate mitigation, biodiversity, and socio-economic outcomes, allowing us to map trade-offs, synergies, and policy implications. Studies are grouped thematically rather than by geography, while highlighting regional specificities where they strongly shape outcomes.

RESULT

Forest biomass resources and feedstock quality

A central theme in the new literature is the distinction between primary biomass (e.g., additional harvesting of stemwood) and secondary biomass (mill residues, thinnings, harvest residues that would otherwise decay or be burned). Life-cycle studies of CHP plants in Nova Scotia show that GHG outcomes differ markedly between these feedstock categories. When mill residues are used, carbon parity can be achieved within about a decade, though still sensitive to plant efficiency and substitution assumptions. In contrast, using additional roundwood leads to parity times ranging from several decades to over a century, especially when harvests are truly additional to existing demand rather than substituting pulp and paper production. Similar conclusions hold for pellet supply chains sourcing from Canada's boreal forests, where residues scenarios deliver more favourable GHG profiles than increased harvest of standing trees. These results challenge policies that treat all forest biomass as equally "renewable" and highlight the importance of feedstock hierarchy, where genuine residues and waste streams are prioritized over additional harvesting.

Agricultural residues, energy crops, and degraded land

Recent work extends the biomass portfolio beyond forests, emphasising that agricultural residues and dedicated energy crops can displace some pressure from forest ecosystems if managed carefully. Reviews of agricultural residues and energy crops classify major feedstocks, their properties, and the food–energy nexus, illustrating how low-grade biomass waste (e.g., urban tree prunings) can be upgraded into high-value energy sources aligned with environmental and social directives. At the landscape scale, geospatial fuzzy–multicriteria analyses on small islands show that integrating degraded land and social forestry greatly increases the area technically suitable for bioenergy development, while respecting environmental and social constraints. By mapping raw material availability, infrastructure proximity, and demand centres alongside restrictions such as protected areas and steep slopes, these studies identify bioenergy "hotspots" that align with community-based forest management and just transition objectives.

Tree species and wood quality for bioenergy

Species-level studies continue to refine our understanding of wood quality for bioenergy. For example, analyses of Eucalyptus pellita in Malaysia compare leaves, bark, and trunk sections, revealing moisture, ash, volatile matter, lignin, cellulose, hemicellulose, and calorific values consistent with solid biofuel applications. Comparable work on the wood properties of Catalpa bungei at the cell level provides insights into moisture-driven swelling and shrinkage behaviour relevant for drying, storage, and combustion performance. These studies underline that feedstock heterogeneity—both between and within species—matters for process efficiency, emissions, and logistics, reinforcing the need to match feedstock characteristics with appropriate conversion technologies.

Table 1. Representative biomass feedstocks and their roles in emerging bioenergy systems

Feedstock / Source	Region / Case study	Key properties or insights	Dominant bioenergy / bioeconomy use	Ref.
Forest residues, mill by-products	Nova Scotia, Canada (CHP plants)	Large variation in carbon parity depending on primary vs secondary biomass and additionality assumptions	CHP electricity and heat	Steenberg et al., 2023
Harvest residues / roundwood	Boreal forests, Canada–UK pellet trade	Residues scenarios improve GHG profile; additional stemwood can prolong parity beyond 80–100 years	Utility-scale pellets replacing coal	Ter-Mikaelian et al., 2023
Eucalyptus pellita components	Malaysia	Calorific values 15.3–19.4 MJ kg^{-1}; ash and volatile matter suitable for solid biofuel applications	Domestic and industrial solid biomass	Abdullah et al., 2025
Agricultural residues and energy crops	Brazil and global synthesis	Classification of crops and residues; case study shows valorisation potential of urban	Bioelectricity, heat, advanced biofuels	Errera & Silva Lora, 2025

		tree prunings		
Degraded land and social forestry biomass	Bali, Indonesia and national mapping	Integrated geospatial-fuzzy analysis identifies 36,527 ha degraded land and 21,671 ha social forestry as bioenergy potential	Community-based bioenergy facilities	Rahayu et al., 2024
Mixed lignocellulosic biomass & residues	Global overview	Wide range of forestry and agro-industrial residues, emphasis on matching feedstock and technology	Biorefineries, power, heat, liquid biofuels	Hart et al., 2024

Conversion pathways and circular bioeconomy perspectives

Recent reviews reinforce that thermochemical routes (combustion, gasification, pyrolysis) remain dominant for power and heat, while biochemical routes (fermentation, anaerobic digestion) are crucial for advanced biofuels and value-added products. Biorefinery concepts are increasingly framed within a circular carbon economy (CCE), where process streams are integrated to maximise carbon, energy, and material efficiency. In the context of aviation decarbonisation, lignocellulosic biomass is a key feedstock for SAF. Chapters reviewing SAF pathways detail fuel compositions, certification processes, and approved technologies, and highlight R&D priorities around carbon yields, process integration, and competition with renewable diesel. Thermochemical and biochemical routes to SAF are evaluated using techno-economic analysis and life-cycle assessment, with sustainability constraints on feedstock sourcing tightly coupled to aviation climate goals.

Engineered microbes and lignocellulosic biofuels

On the biochemical side, recent reviews of engineered microbes emphasise advances in metabolic engineering, including CRISPR/Cas9, pathway optimisation, and modular engineering strategies for higher yields of bioethanol, biodiesel, and biohydrogen from lignocellulosic feedstocks. Microbial systems are positioned as complements rather than substitutes for forest bioenergy, enabling integrated biorefineries that valorise multiple biomass streams.

Circular carbon economy and systems integration

The circular carbon economy framing links forest bioenergy to broader strategies such as electrification, demand reduction, and carbon capture. Reviews on biomass conversion technologies stress the importance of matching feedstock characteristics to technology and integrating supply chains with material and energy recovery loops. CCE strategies underscore that forests should not be treated as unlimited “biomass mines” but as multi-functional ecosystems supplying a limited stream of sustainable residues.

Table 2. Major biomass conversion pathways and their roles in a circular bioeconomy

Conversion pathway	Typical feedstock	Main products / services	Key sustainability considerations	Ref.
Direct combustion (CHP)	Forest residues, mill by-products	Heat and power	Efficiency; carbon parity; substitution of fossil generation	Steenberg et al., 2023
Dedicated biomass power / pellets	Roundwood, residues	Utility power, co-firing fuels	Transport emissions; additionality; impacts on forest carbon stocks	Ter-Mikaelian et al., 2023
Gasification and synthetic fuels	Lignocellulosic biomass	Syngas, SAF precursors	Feedstock pre-treatment; process integration; fuel certification	Tao et al., 2025

Fermentation-based biofuels	Lignocellulose hydrolysates, residues	Bioethanol, biobutanol	Sugar release efficiency; microbial robustness; land-use effects	Saravanan, 2024
Engineered microbial platforms	Diverse organic wastes	Advanced biofuels, biochemicals	Metabolic engineering; containment; waste valorisation	Kamalesh et al., 2024
Integrated biorefineries	Mixed forest and agro-industrial residues	Energy, chemicals, materials	CCE design; cascading use; competition with material uses	Hart et al., 2024

Climate mitigation performance, carbon parity and BECCS

Life-cycle GHG analyses now provide a more granular view of when forest bioenergy can deliver net climate benefits. CHP case studies in Nova Scotia show that carbon parity is reached within 4–9 years when additional harvests displace pulp and paper production, and much later (up to and beyond 100 years) when harvests are purely additional. When secondary biomass such as mill residues is used, net benefits can occur within a decade, albeit with strong dependence on plant efficiency and the fossil reference scenario. Similar dynamics appear in analyses of pellets exported from Canada to the UK: residue-based pellets outperform stemwood-based pellets, while the carbon intensity of shipping and plant operation further modulate results. Stand-level modeling in eastern Canada reveals that increasing wood procurement intensity offers only limited carbon benefits relative to undisturbed stands, and that biomass for bioenergy can increase net emissions unless it displaces high-emission energy sources or enhances future stand yields. Collectively, these studies show that forest bioenergy is not inherently "carbon neutral"; its performance hinges on counterfactuals, temporal horizons, and the choice of feedstock.

BECCS and negative emissions portfolios

BECCS has become emblematic of negative emissions, but its real climate value in forest-based systems is far from settled. Scenario analyses of CDR portfolios emphasise land-use constraints and long-term sustainability as key limitations to scaling BECCS and other land-based options. Policy-oriented work on BECCS in Europe characterises the regulatory environment as a patchwork, spanning biomass sourcing, CO_2 transport and storage, and overlapping energy and climate regulations. Current policies often lack a standardised definition of negative emissions and fail to consistently account for upstream emissions from biowastes and residues, system boundaries, and long-term storage permanence. This creates a risk that BECCS claims overstate actual net removals, especially when forest biomass feedstocks already have contested carbon neutrality.

Critical reassessments of forest bioenergy as mitigation

- Several recent contributions offer systematic critiques of forest bioenergy as a climate mitigation tool. Analyses of EU and UK policies show that renewable energy incentives have driven a more than ten-fold increase in forest biomass use for electricity since 1990, while residential heating—often unregulated—remains the largest consumer. These studies argue that treating forest biomass as carbon-neutral, particularly in the context of BECCS, undermines efforts to restore the forest carbon sink and can crowd out lower-impact renewables such as wind and solar.
- A comprehensive review of the climate and biodiversity implications of burning forest biomass concludes that:
- Forest bioenergy, including logging residues, increases atmospheric CO_2 over relevant policy horizons.

- Land-sector net accounting obscures the real impact of harvests on ecosystem carbon stocks.
- Bioenergy is likely to displace other renewables rather than fossil fuels in many systems.
- Cascading negative effects on forest integrity and species' adaptive capacity conflict with climate-resilient development goals.

These findings underpin calls to remove forest biomass from renewable energy target eligibility and to reallocate bioenergy subsidies toward genuinely low-carbon technologies.

Table 3. Summary of climate mitigation findings for key forest bioenergy systems

System / case	Feedstock & regime	Carbon parity / GHG outcome	Main drivers of performance	Ref.
Local forest CHP (Nova Scotia)	Roundwood vs mill residues; intensive vs extensive silviculture	Parity 4–9 yrs when substituting pulp/paper; 86–100+ yrs when additional harvest; ~10 yrs for residues	Additionality, feedstock type, plant efficiency	Steenberg et al., 2023
UK power station with imported pellets	Canadian boreal stemwood vs residues	Residue scenarios yield lower life-cycle emissions; stemwood parity far in future	Source forest dynamics; residue treatment; shipping distance	Ter-Mikaelian et al., 2023
Stand-level biomass procurement	Stemwood, treetops, pulpwood	Limited carbon benefits relative to undisturbed stands; pulpwood most favourable	Harvest intensity, product substitution, stand characteristics	Canuel et al., 2025
European BECCS power plant	Forest biomass with CCS	Negative emissions contingent on upstream accounting and biomass sustainability	Policy definitions, system boundaries, storage permanence	Tanzer et al., 2025
EU & UK forest bioenergy policy	Power, CHP, household heating	Bioenergy expansion linked to declining forest carbon sink and policy misalignment	Subsidy design, renewable targets, land-sector accounting	Booth, 2025; Mackey et al., 2025

Biodiversity, ecosystem integrity and land-use trade-offs

New integrated modeling connects global economic models of forest bioenergy expansion with biodiversity indicators, using countryside species–area relationships to constrain species loss. Under stringent climate mitigation scenarios (e.g., RCP1.9), increased forest bioenergy demand leads to greater biodiversity loss than in a higher-emissions reference scenario, illustrating how aggressive mitigation can conflict with conservation if poorly designed. However, biodiversity-conscious forest management can partially alleviate this trade-off by:

1. Shifting biomass production from natural forests to energy crops where appropriate.
2. Expanding unmanaged secondary forests.
3. Reducing management intensity in biodiversity-rich regions.
4. Reallocating biomass production spatially to minimise species loss.

These interventions can reduce projected global biodiversity loss by around 10% with only minor impacts on economic outcomes, though local outcomes remain heterogeneous.

Policy frameworks: restoration, biodiversity and forests

At the governance level, cross-walks between the EU Nature Restoration Regulation and the Kunming-Montreal Global Biodiversity Framework reveal gaps in alignment on habitat restoration, species protection, and sustainable resource use, particularly in forest ecosystems. This work underscores the need for coherent policy architectures that integrate biodiversity, climate, and bioenergy objectives rather than treating them in isolation.

Forest integrity and adaptive capacity

Critical assessments of forest bioenergy emphasise that intensive harvesting—even of residues—can degrade forest ecosystem integrity and reduce species' adaptive capacity to climate change, through fragmentation, structural simplification, and altered disturbance regimes. From this perspective, maintaining and restoring intact, mature forests is central to climate resilience, and any additional biomass extraction must be evaluated against its impact on long-term adaptation. Taken together, these studies argue for a biodiversity-first hierarchy in forest landscapes: conservation and restoration of high-integrity forests, cautious multi-use management in production forests, and careful targeting of bioenergy to waste streams and lower-value residues.

Climate-smart forestry, social forestry and socio-economic dimensions

CSF explicitly seeks to align three objectives: enhancing forest carbon stocks, reducing GHG emissions, and supporting sustainable forest-based livelihoods. Comparative reviews of CSF practice in Europe and the Americas highlight strategies such as:

- Diversifying species and structures to increase resilience.
- Integrating GIS, remote sensing, IoT, and AI for monitoring and precision management.
- Promoting intelligent harvesting and wood processing, including bioeconomy value chains. These approaches position bioenergy as one possible outlet for by-products of CSF-aligned management, rather than a primary driver of harvest decisions.

Social forestry and community-based bioenergy

Social forestry emerges as a powerful lever for aligning bioenergy development with local rights and priorities. Geospatial fuzzy–multicriteria analyses in Indonesia show that combining social forestry areas with degraded land can dramatically increase technically suitable land for bioenergy facilities, while involving tens of thousands of households in community-based energy transitions. These studies demonstrate how participatory mapping, sustainability criteria (e.g., proximity to roads, ports, transmission, demand), and restriction layers (protected areas, slope, land-use limitations) can be integrated to design bioenergy systems that support, rather than undermine, local livelihoods and environmental justice.

Perceptions, justice and social license

Ethnographic research with rural forest landowners in the southeastern US reveals complex attitudes toward climate change and wood-based bioenergy. While some actors present bioenergy as inevitable regardless of climate "truth", environmental advocates and many landowners question its climate-mitigating role and highlight social and ecological risks. The assumption that landowners will always act in their economic best interest is challenged by place-based identities, cultural values, and concerns about long-term forest stewardship. These findings underscore that social license for bioenergy projects cannot be taken for granted and must be built through transparent communication, fair benefit-sharing, and respect for local values.

Forest products markets, energy forest products and macro-governance

On the macro scale, analyses of the international market for energy forest products (EFP) and forest products for energy (FPE) show increasing concentration in a few producer and exporter countries, with implications for energy security, forest governance, and trade balances. Small islands and regions with limited land may face constraints, while large forested countries weigh opportunities to expand exports against domestic environmental impacts. Emerging economies aligning with BRICS explore strategies to integrate forest management, renewable energy production, and carbon markets. Panel analyses suggest that forest area, renewable energy production, and trade in forest products interact with carbon emissions in complex ways, highlighting the need for careful policy design to avoid locking in high-emissions pathways.

Table 4. Governance and socio-economic instruments shaping forest bioenergy outcomes

Instrument / context	Main features	Implications for forest bioenergy and CSF	Ref.
EU Renewable Energy Directives & BECCS policies	Incentives for renewable power and negative emissions; forest biomass often treated as carbon-neutral	Drives large-scale biomass demand; risks misaligned carbon accounting	Booth, 2025; Tanzer et al., 2025
EU Nature Restoration Regulation & KM-GBF	Targets for habitat restoration and species protection; partial alignment with global biodiversity goals	Need for integrated climate–biodiversity–bioenergy planning	Aggestam, 2024
CSF strategies in Europe and Americas	Technological innovation, digital monitoring, diversified silviculture, forest bioeconomy	Positions bioenergy as a by-product of resilient forest management	Xie et al., 2025
Social forestry and geospatial planning	Multi-criteria site selection on degraded land and community forests	Expands sustainable bioenergy options, strengthens local participation	Rahayu et al., 2024
Global EFP/FPE market concentration	Long-term shift-share and concentration analyses of energy forest products trade	Highlights geopolitical risks and opportunities in forest bioeconomy	Coelho Junior et al., 2025; Diniz et al., 2024
BRICS-aligned forest–energy strategies	Integration of forest area, renewable energy, trade and emissions in emerging economies	Potential for coordinated low-carbon forest and energy policy, but also risks of intensified extraction	Bayramoğlu et al., 2025

Forest biomass in EU and global energy transitions

The EU remains a focal region for forest bioenergy debates. Strategic analyses of forest biomass in the EU's changing geopolitical environment argue for accelerating energy transformation while positioning forest biomass as one among several renewable options, subject to constraints on resource availability and competition from other energy sources. These studies stress the need to revise assumptions that uncritically promote wood use for energy and to align policies with forest industry needs and sustainability criteria.

Parallel assessments of wood pellet feedstock harvesting in the southeastern US reveal significant knowledge gaps around the sustainability of wood pellet operations, particularly regarding residue removal, soil characteristics, biodiversity, carbon, and water quality. Existing biomass harvesting guidelines and best management practices appear adequate at current thresholds but require regionalised updates under intensified biomass demand.

Global analyses of forest products for energy and energy forest products show longstanding trends toward concentration of production and trade, suggesting that a small group of countries will bear disproportionate forest and land-use impacts of global bioenergy demand. This raises questions of equity and responsibility in the international distribution of environmental burdens and benefits.

Synthesis: Towards a climate-resilient, biodiversity-safe forest bioeconomy

Synthesising the updated literature, several key insights emerge:

1. Conditional mitigation value. Forest bioenergy can contribute to climate mitigation only under restrictive conditions: priority use of genuine

residues and wastes; high-efficiency conversion; short supply chains; robust substitution of high-carbon energy; and careful consideration of temporal dynamics and counterfactuals.
2. Biodiversity and adaptation constraints. Even where climate metrics look favourable, forest bioenergy may undermine biodiversity and ecosystem resilience, especially when it incentivises intensified harvesting in biodiversity-rich or carbon-dense forests.
3. Policy misalignment and accounting gaps. Current renewable energy and BECCS policies often treat forest biomass as carbon-neutral and focus on stack emissions, ignoring upstream impacts, land-sector accounting artefacts, and the risk of displacing other renewables.
4. Promise of CSF and social forestry. Climate-smart forestry and social forestry provide promising frameworks where bioenergy is secondary to goals of resilience, livelihoods, and biodiversity, with degraded land and community forests as priority locations for development.
5. Geopolitical and market dynamics. Concentration of forest bioenergy supply in a few regions raises questions of global justice and long-term socio-ecological stability; diversified portfolios including agricultural residues, energy crops, and non-biological renewables are essential. From a systems perspective, forest bioenergy should be reframed from a cornerstone of net-zero strategies to a niche, carefully governed option within a broader climate-smart, biodiversity-safe, and socially just energy transition.

Research agenda

The updated literature points to several priority research directions:

1. Standardised carbon parity metrics. Develop transparent, policy-relevant metrics and tools for carbon parity and GHG performance, including sensitivity to additionality, substitution, and temporal discounting.
2. Biodiversity-inclusive modeling. Integrate species–area relationships, habitat quality, and functional diversity into global and regional bioenergy scenarios, building on recent GLOBIOM-Forest and biodiversity-constrained modeling efforts.
3. Landscape-scale experiments. Implement long-term experimental landscapes comparing CSF regimes, bioenergy harvesting intensities, and conservation options, monitoring carbon, biodiversity, hydrology, and socio-economic outcomes.
4. Social license and justice. Expand ethnographic and participatory research with forest-dependent communities and landowners, focusing on perceptions of climate risk, intergenerational equity, and acceptable forms of bioenergy development.
5. Policy coherence and governance innovation. Analyse how biodiversity, climate, energy, and rural development policies interact; design instruments that explicitly cap forest bioenergy within ecological limits and prioritise residues and waste.
6. Integration with non-biological renewables. Evaluate scenarios where reduced reliance on forest bioenergy is compensated by accelerated deployment of wind, solar, geothermal, and demand-side measures, assessing implications for land use and justice.
7. Circular carbon economy design. Further develop and test CCE-based biorefinery concepts that minimise primary biomass extraction, maximise cascading use, and internalise social and ecological costs.

CONCLUSION

The emerging evidence base fundamentally reshapes how forest bioenergy should be understood within climate mitigation and bioeconomy strategies. Rather than a default "green" solution, forest bioenergy is a highly conditional option whose desirability depends on feedstock type, management context, policy design, and interactions with biodiversity and social systems.

Climate-smart forestry and social forestry offer promising pathways to embed bioenergy within resilient, equitable, and biodiversity-aware landscapes. However, achieving this vision requires tight governance, robust accounting frameworks, and an explicit willingness to limit forest bioenergy where it conflicts with climate resilience and conservation objectives.

For policymakers and practitioners, the implication is clear: forest bioenergy must be de-exceptionalised—treated neither as a blanket solution nor as an inherent threat, but as one tool among many, deployed cautiously within a science-based, justice-oriented, and biodiversity-compatible transition.

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